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SURFACE INTEGRITY OF MACHINED STRUCTURAL COMPONENTS

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Metcut Research Associates Inc.
Cincinnati, Ohio

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Air Force Materials Laboratory
MATF
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

Technical Report AFML-TR-70-11

March 1970

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MMP Project Nr. 721-8

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361

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FOREWORD

This final technical report covers experimental effort under Contract F33615-68-C-1003 performed from 1 February 1968 to 30 November 1969. The report was released by the authors in April 1970.

This contract with Metcut Research Associates Inc., Cincinnati, Ohio, was initiated under Manufacturing Methods Project Nr. 721-8, "Surface Integrity of Machined Structural Components." Effort during this contract period was accomplished initially under the technical direction of Mr. Max Guenther and later under Lt. Raymond H. Coe, Jr., of the Fabrication Branch (MATF), Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

Dr. William P. Koster, Director of Metallurgical Engineering at Metcut, was the engineer in charge. Others at Metcut who participated in this program were: Dr. Michael Field, Dr. John F. Kahles, Luciano R. Gatto, and Louis J. Fritz who served as the manager of the experimental effort. This project was given the Metcut Internal Number 970-11700.

Metcut was assisted in this program by two subcontractors: The Boeing Company/Commercial Airplane Division, Seattle, Washington, under the direction of Birger Anderson and Ian Slater and the General Electric Company/Aircraft Engine Group, Evendale, Ohio, under the direction of Guy Bellows and Roger Niemi.

This project has been accomplished as a part of the Air Force Manufacturing Methods Program, the primary objective of which is to develop, on a timely basis, manufacturing processes, techniques and equipment for use in economical production of USAF materials and components.

Your comments are solicited on the potential utilization of the information contained herein as applied to your present or future production programs. Suggestions concerning additional manufacturing methods development required on this or other subjects will be appreciated.

This technical report has been reviewed and is approved.

JACK R. MARSH
Chief, Fabrication Branch
Manufacturing Technology Division

ABSTRACT

A program has been run to evaluate the effects of different metal removal methods and variations of these methods on surface integrity. Three alloys were studied: beta rolled Ti-6Al-4V; AISI 4340, quenched and tempered, 50 R_c; and Inconel 718, solution treated and aged.

Various grinding procedures caused the titanium alloy to exhibit a fatigue strength range of 13 to 62 ksi. The fatigue strength of 4340 due to grinding variables ranged from 62 to 102 ksi, while Inconel 718 showed a range of 24 to 60 ksi. Abusive grinding conditions always resulted in fatigue strengths at the minimum of these ranges.

The variables in end milling-end cutting exhibited a fatigue strength range of 64 to 77 ksi in the beta rolled titanium alloy. On the other hand, peripheral cutting produced a fatigue spread of from 32 to 70 ksi.

Both EDM and ECM exhibited fatigue strengths lower than that associated with gentle grinding. EDM of Inconel 718 yielded a fatigue strength of 22 ksi under both roughing and finishing conditions. ECM of Inconel 718 yielded a fatigue strength of 39 ksi under both gentle and abusive conditions. These are in contrast to a fatigue strength level of 60 ksi for Inconel 718 when finished by gentle grinding.

The presence of untempered martensite and the presence of overtempered martensite in hardened steel are equally detrimental to the surface integrity of hardened steel. Both caused a fatigue strength depression of approximately 35 percent. Other metallographic features found detrimental include recast surface layers, tears, laps, and intergranular attack.

Correlation studies have shown a lack of relation between surface finish (within the range studied) and fatigue strength. On the other hand, residual stress in the surface layer does show a trend of a correlation with fatigue strength, although it is neither complete nor consistent.

Guidelines for processing of aerospace hardware in such a way as to assure good surface integrity have been developed and presented in this report. Control of cutting tool sharpness as well as proper selection of processing parameters are prime requirements.

The distribution of this report is limited because it contains technology identifiable with items on the strategic embargo lists excluded from export or re-export under U.S. Export Control Act of 1948 (63 STAT. 7), as amended (50 U.S.C. Appn. 2020-2031), as implemented by AFR 400-10, AFR 310-2, and AFSCR 80-20.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF TABLES

LIST OF ABBREVIATIONS
USED IN THIS REPORT

CHM	Chemical Machining
ECM	Electrochemical Machining
EDM	Electrical Discharge Machining
ELP	Electropolishing
UTM	Untempered Martensite
OTM	Overtempered Martensite

1. INTRODUCTION

The design of structures for modern aerospace application has created stringent reliability and safety requirements. The development of advanced design techniques is permitting the use of more highly loaded, hence more efficient, structures for both static and dynamic applications. This trend is widespread. In situations where higher strength materials are needed and where these materials are loaded to a greater percentage of their available strength, the achievement of high uniform quality during the manufacturing process becomes a prime requirement. The need for the ultimate in available reliability is intensified by severe long-life requirements of the large, high-performance aircraft now undergoing prototype development.

In order to meet environmental demands, aerospace structural components are being manufactured in increasing quantities from materials such as titanium alloys, high strength steels, high temperature alloys, high strength aluminum alloys, refractory alloys, and beryllium. While materials such as these are selected because they have basic properties necessary to meet service requirements, the consistent preservation of their inherent strength characteristics during manufacturing can be difficult to achieve. Serious service failures have already occurred, resulting from surface damage inflicted by machining during manufacturing of aerospace parts. Since surfaces of these components are frequently highly stressed, it becomes increasingly important to specify manufacturing procedures to avoid surface damage and, if possible, to specify processing which will enhance part performance.

Surface integrity is a subject covering the description and control of the many possible alterations produced in a surface layer during manufacturing, including their effect on the performance of components in service. More precisely, surface integrity has been defined as the unimpaired or enhanced surface condition which is developed in a component by controlled manufacturing processes.

A wide variety of new as well as conventional material removal techniques is required for the efficient manufacture of aerospace components. In order to meet the design requirements set forth by engineering, surface integrity effects must be evaluated generally by the same methods normally used in the qualification of aerospace materials and components. These include fatigue; stress corrosion; stress rupture and creep; tensile strength, including in particular the ductility of materials during tensile failure; residual stress and the resulting distortion; microstructural changes; such as phase changes and recrystallization and plastic deformation; microhardness changes; chemical changes (relating to interaction of fluids, formation of oxides, nitrides, and carbon and other element depletion); and macro-and microcracking. Most of the above property evaluations must also take into consideration specific ranges of temperature as well as other environmental conditions.

1. INTRODUCTION (continued)

An extensive experimental program has been initiated to study aspects of surface integrity behavior of three different aerospace materials. The classes of materials covered under this contract were as follows:

Titanium 6Al-4V, beta rolled
AISI 4340 steel, quenched and tempered, 50 R_C
Inconel 718, solution treated and aged

Metal removal variables ranged from gentle to abusive conditions for the following operations: milling, grinding, drilling, electrical discharge machining (EDM), electrochemical machining (ECM), electrolytic polishing (ELP), and chemical machining (CHM). The effects of these variables have been studied in terms of alterations of microstructure, microhardness, residual stress, stress corrosion behavior, and fatigue strength of the test materials.

Three types of surface integrity evaluation programs have been developed providing three different depths of study. These designations, along with the scope of each, are as noted below.

Surface Metallography

- Microstructure
- Phase Transformations
- Plastic Deformation
- Microcracks
- Macrocracks
- Microhardness
- Surface Roughness

Standard Data Set

- Surface Metallography
- Residual Stress
- Fatigue - Screening Tests
- Stress Corrosion

Extended Data Set

- Surface Metallography
- Residual Stress
- Fatigue - Screening Tests - Design Data Tests
- Stress Corrosion
- Other Mechanical Tests - Ductility, Tensile, Stress Rupture

1. INTRODUCTION (continued)

In describing the various machining conditions, arbitrary terms of gentle, conventional, and abusive have been extensively used in this report. Broadly speaking, gentle conditions are those which involve metal removal under conditions expected to produce a minimum of surface damage. Abusive conditions are those which are intentionally damaging to the surface, such as the use of dull tools in milling or the use of high speeds and hard wheels in grinding.

In the case of EDM, the terms finishing and roughing have been used, in that these describe the standard conditions for metal removal at low rates and high rates, respectively. These two conditions were chosen as being representative of the range of surface characteristics that could be produced by EDM.

In describing other processes such as ECM and CHM, terms such as standard and off-standard might have been used as counterparts for gentle and abusive, respectively. However, to avoid confusion between the various sets of terminology, gentle and abusive have been used throughout this report as being nominally descriptive of the characteristics of the process, except in the case of EDM.

Data presented in this report are for information purposes only and are not to be considered suitable for design or other materials engineering purposes.

2. OBJECT OF PROGRAM

The overall objectives of this program were as follows:

1. To provide an initial review and summary of available information on aspects of surface integrity which would permit an assessment of the current state of the art. This review in turn would lead to the development of a logical experimental program in the surface integrity field.

2. To establish proposed test methods and evaluation procedures for the systematic gathering of surface integrity information.

3. To develop and carry out a specific experimental program which would serve to obtain initial high priority surface integrity information and also serve to assess the merit of the methods and procedures referred to in Item 2 above.

The first and second of these objectives were achieved upon the completion of Phase I and have had their influence on the direction and scope of the experimental work which followed. The various procedures selected as techniques for obtaining surface integrity data (object 2) have come to be designated as "surface metallography", "standard data set", and "extended data set". The definition of these test methods is summarized in Section 1, the introduction to this report.

The third objective of this program consisted of developing data relating the effect of several different metal removal methods and variables within each of these methods to changes in metallography, residual stress, stress corrosion behavior, and fatigue strength of selected aerospace alloys. The particular materials, metal removal conditions, and type of analyses conducted under the present contract are as summarized in the following table:

.2. **OBJECT OF PROGRAM** (continued)

Operation	Titanium Alloy Ti-6Al-4V Beta Rolled	High Strength Steel 4340 Steel 50 R_c	Nickel Base Alloy Inconel 718
Mill - End Cutting	Extended Data*	Metallography*	Metallography
Mill - Peripheral Cutting	Extended Data	Metallography	Metallography
Surface Grind	Standard Data	Standard Data	Standard Data
Drill	Metallography	Metallography	Metallography
Hand Grinding	Standard Data	Standard Data	Metallography
EDM	Metallography	Metallography	Standard Data
ECM	Metallography	Metallography	Standard Data
ELP	Metallography	Standard Data	Standard Data
CHM	Standard Data	Metallography	Metallography

In some instances data developed in connection with surface integrity effort sponsored internally by Metcut and also by G. E. /Evendale have been included in this report. These data have been selected in order to enhance the conclusions which have been drawn and to add perspective to data which were produced under this contract.

* See Section 1 for explanation of terms.

3. CONCLUSIONS

3.1 Summary Statements

General

1. An extensive literature search covering over 1200 references produced little useful data on the subject of surface integrity. Virtually no information was available relating variables in machining methods to resulting mechanical properties. The industrial survey, which was part of the Phase I study under this contract, revealed some information in company files. This material, however, was usually hardware oriented, of limited scope, and not generally available to the aerospace industry.

2. Testing carried out under this contract has demonstrated that metal removal methods and variables within these methods have an enormous effect on surface integrity of materials, principally as measured by changes in fatigue strength. The overall ranges of fatigue strength observed were approximately 5 to 1 for Ti-6Al-4V beta rolled, 1.6 to 1 for AISI 4340, and 2.5 to 1 for Inconel 718. The ranges stated above for titanium and 4340, which happen to be the maximums observed, were exhibited by variations in grinding alone. The range expressed for Inconel 718 takes into account all of the processes studied for this material. (Figures 29-31, 48-49, 79-81)

3. A ranking of characteristic fatigue strength as a function of the metal removal procedure used may be possible. Considering that nominally good or well-controlled machining procedures are used for each of the processes, the ranking of resulting characteristic fatigue strengths based collectively on the three materials studied, from highest to lowest, is as follows:

   Milling
   Grinding
   Electropolishing (ELP)
   Chemical Machining (CHM)
   Electrochemical Machining (ECM)
   Electrical Discharge Machining (EDM)

3.1 Summary Statements (continued)

General (continued)

4. A characteristic surface finish is generally produced for a given material and a given type of operation. Within those normal ranges of surface finish, there is no relationship between the fatigue strength and surface finish as measured by standard stylus techniques. This is true for all of the methods of metal removal studied under this contract.

   The fatigue strength rather is related to the process itself and parameters within a particular metal removal process. This program did not include the study of extremely fine or ultra-high finishes nor did it evaluate surfaces having extremely coarse finishes. Additional effort would be required to determine the effects of finishes in these extreme ranges. (Section 6.4.1)

5. A qualitative correlation between residual stress and fatigue strength has been found in some instances. It is, however, neither totally conclusive nor consistent. Data available indicate that a fatigue correlation exists with the peak stress in the surface layer which may be at the surface or a few thousandths of an inch below the surface. There is no apparent correlation, however, with the stress at the very surface of the material. Due to the complexity of this relationship, it would at this time be hazardous to use residual stress alone to predict fatigue behavior. On the other hand, there is an indication that residual stress measurement may offer the basis for development of quality control techniques for evaluating surface integrity on an NDT basis. (Section 6.4.3)

6. Residual stress data indicate that abusive conditions can lead to significant problems with distortion. In general, the distortion in a machined surface has been found to be proportionate to the area under the residual stress curve. Usually, abusive conditions exhibit much larger areas than their gentle counterparts. (Figures 20-27, 44, 46, 47, 69-72)

7. Under the salt exposure conditions studied, titanium showed no consistent relation between metal removal method and stress corrosion sensitivity (Figure 9). The stress corrosion tests on 4340 steel yielded widely scattered data. One significant trend, although not entirely consistent, was the low life, hence high stress corrosion susceptibility, exhibited by abusively ground samples. (Figure 10)

3.1 Summary Statements (continued)

General (continued)

8. Metallography, including measurement of surface microhardness variation, has demonstrated itself to be a valuable tool in evaluating surface integrity. This procedure is capable of revealing areas of concern with regard to surface integrity insofar as characteristics of a particular material-process combination are concerned. Incidence of such things as intergranular attack, redeposited surface layers, surface depletion, untempered and overtempered martensite, tears and laps can be consistently revealed by metallographic means. (Sections 6 and 7)

9. Data available now, although very limited in scope compared to total aerospace manufacturing requirements, do permit the development of both general and specific guidelines to be used as a means of achieving and controlling surface integrity. These have been included in this report as Section 4.1.

Grinding

10. Abusive grinding caused a significant depression in fatigue strength (compared to gentle grinding) on all three alloys evaluated. To a lesser extent, conventional grinding also showed a fatigue strength depression on the two materials which studied this particular condition, 4340 and Inconel 718. (Figures 29, 48, 49, 79)

11. Hand grinding characteristics are generally similar to those exhibited by surface grinding. Abusive hand grinding was particularly detrimental to Ti-6Al-4V, although the drop in fatigue strength was not quite as great as had been exhibited by abusive surface grinding of titanium. Hand grinding appears to be less prone to producing surface damage under abusive conditions although this indication may well be due to inherent poor controlability of the process. Nevertheless, there is a certainty of significant fatigue strength loss if the grinding is done improperly. (Figures 29 and 48)

12. The fatigue strength depression in martensitic steels due to abusive grinding may be attributable directly to the presence of overtempered martensite in the surface in addition to the presence or quantity of fully hard untempered martensite which may also be found in the surface layer. The fatigue strength due to

3.1 Summary Statements (continued)

Grinding (continued)

12. (continued)

abusive grinding on 4340 was approximately the same whether the quantity of untempered martensite varied from trace patches, .0005 in. deep, up to a continuous layer, .004 in. deep. Even when these quantities of untempered martensite were removed by gentle grinding, exposing the underlying layer of overtempered martensite, the fatigue strength remained at about the same depressed level. (Figures 82 and 83)

Milling

13. Variations in milling Ti-6Al-4V cause a wide spread in resulting fatigue strength. In end milling-end cutting, fatigue strengths ranged from 64 to 77 ksi, compared to 62 ksi for gentle grinding. In this operation, tool sharpness is the most influential variable. As the tool becomes duller, hence the operation more abusive, the fatigue strength increases. (Figure 30)

In end milling-peripheral cutting, tool sharpness is also the biggest factor, but as the tool becomes duller the fatigue strength decreases. The range of endurance limits associated with peripheral cutting was found to be from 70 ksi down to 32 ksi. (Figure 31)

In both types of milling, conditions using dull tools generally showed larger areas under curves on the residual stress plots, indicating a tendency toward greater distortion. The response to variations in milling over the range studied, however, was smaller than potential distortion differences observed for abusive versus gentle grinding. (Figures 22-27)

EDM

14. The EDM of Inconel 718 under both finishing and roughing conditions resulted in a low endurance limit of 22 ksi, compared to a level of 60 ksi exhibited by gentle grinding. The magnitude of this fatigue strength depression is significant as is the fact that both finishing and roughing conditions produced the same

3.1 Summary Statements (continued)

EDM (continued)

14. (continued)

low value. The behavior of Inconel 718 which was EDM in the solution treated condition followed by aging in vacuum is very similar. In this case, both finishing and roughing EDM exhibited an endurance limit of 29 ksi, as compared to 74 ksi exhibited by gentle grinding (Figures 79 and 81)

ECM

15. The ECM of fully heat treated Inconel 718 under both gentle and abusive conditions resulted in an endurance limit of 39 ksi, approximately two-thirds that of the level of 62 ksi exhibited by the baseline condition, gentle grinding. It is again interesting to note that both gentle and abusive ECM processing yield the same endurance limit. This level was very close to the 42 ksi exhibited by Inconel 718 in the ELP condition. ELP is considered as a neutral or stress-free surface, and is essentially similar to ECM.

The ECM of Inconel 718 in the solution treated condition followed by aging in vacuum resulted in an endurance limit of 42 ksi. This was observed as a result of both abusive and gentle conditions. This again is somewhat low compared to the 74 ksi endurance limit determined for the gentle ground condition of Inconel 718 in the same heat treated condition. (Figures 79 and 81)

Post Treatments

16. Shot peening appears to be effective in elevating fatigue strength to the upper part of the range exhibited by each of the materials studied. Shot peening over surfaces which initially exhibited good fatigue strength will lead to higher levels of fatigue strength than shot peening over surfaces which previously exhibited relatively poor fatigue strength. For example, shot peening will elevate fatigue strength of gently ground 4340 from 102 to 112 ksi, while shot peening will elevate the fatigue strength of abusively ground 4340 from 62 to 92 ksi. On a percentage basis, shot peening applied to surfaces which contain

3.1 Summary Statements (continued)

Post Treatments (continued)

16. (continued)

damage frequently affords spectacular results. Nevertheless, the total effect of the prior damage is not completely overcome by the peening operation. All work done on this program was at room temperature. The effect of shot peening at elevated service temperatures where stress relief and relaxation may occur has yet to be systematically explored. (Figures 6 and 8)

17. Shot peening as a post processing operation gave scattered evidence of being effective in decreasing stress corrosion sensitivity of 4340. Shot peening at Level 1 resulted in significant improvement in average specimen life as applied to gentle and abusive grinding. Shot peening at Level 2, however, showed a slight decrease in specimen life when applied to an abusively ground surface. (Figure 10)

18. Post heat treatment consisting of complete reprocessing and also stress relieving shows moderate ability to correct surface damage. The complete resolutioning and aging in vacuum as applied to Inconel 718 is more effective than a stress relief cycle. Complete reheat treatment raised the endurance limit of Inconel 718 (EDM, roughing = 22 ksi) to 38 ksi, while the stress relief cycle caused a slight increase to 25 ksi. In either case, however, reheat treatment is much less effective than peening (66-75 ksi) as a means of restoring fatigue strength to a nickel alloy part which has experienced surface damage due to EDM. (Figure 80)

3.2 Mechanical Properties

3.2.1 Variations in Fatigue Strength

A table summarizing the variations or differences in endurance limit for the three materials studied under this contract are shown below. These data indicate the percentage changes from the endurance limit value obtained for gentle grinding each of the materials. This comparison has been made assuming that gentle grinding is a nominal baseline for comparative purposes.

Machining Condition*	Percent Change in Endurance Limit From That Exhibited by Gentle Grinding: Ti-6Al-4V (Beta Rolled, 32 R_c)	AISI 4340 (Quenched and Tempered, 50 R_c)	Inconel 718 (Solution Treated and Aged, 44 R_c)
Surface Grinding			
Gentle	0	0	0
Conventional	--	-31	-60
Abusive	-79	-39	--
Gentle + Shot Peen (Level 1)	--	+10	--
Abusive + Shot Peen (Level 1)	--	-10	--
Abusive + Shot Peen (Level 2)	--	-14	--
Conventional + Resolution and Age	--	--	-17
Hand Grinding			
Gentle	-8	-8	--
Abusive	-52	-4	--
Abusive + Shot Peen (Level 1)	--	+16	--
End Milling (Carbide)			
End Cutting			
Sharp Tool	+3 to +16	--	--
Dull Tool	+3 to +24	--	--
Peripheral Cutting			
Sharp Tool	-2 to +13	--	--
Dull Tool	-11 to -48	--	--
Electrical Discharge Machining (EDM)			
Finishing	--	--	-63
Roughing	--	--	-63
Finishing + Shot Peen (Level 1)	--	--	+10

3.2.1 Variations in Fatigue Strength (continued)

Machining Condition *	Ti-6Al-4V (Beta Rolled, 32 R_c)	AISI 4340 (Quenched and Tempered, 50 R_c)	Inconel 718 (Solution Treated and Aged, 44 R_c)
	Percent Change in Endurance Limit From That Exhibited by Gentle Grinding		
Electrical Discharge Machining (EDM)			
Roughing + Shot Peen (Level 1)	--	--	+25
Roughing + Resolution and Age	--	--	-37
Roughing + Stress Relief	--	--	-58
Electrochemical Machining (ECM)			
Gentle	--	--	-35
Abusive	--	--	-35
Gentle + Shot Peen (Level 1)	--	--	+30
Gentle + Glass Bead Peen	--	--	+30
Abusive + Shot Peen (Level 1)	--	--	+12
Abusive + Shot Peen (Level 2)	--	--	+25
Chemical Machining			
Gentle	-18	--	--
Abusive	-27	--	--
Electropolishing			
Conventional	--	-12	-30
Conventional + Shot Peen (Level 1)	--	-6	+30

* See Tables II through X for machining conditions, Table XI for shot peening conditions.

3.2.2 Summary of Properties Obtained on Beta Rolled Titanium 6Al-4V, $32R_c$

Machining Conditions*	Endurance Limit (ksi)	Average Surface Finish (AA)	Residual Stress (ksi)	Stress Corrosion Sensitization:** Before	After
Surface Grinding					
Gentle	62	35	+35	10.5	2.0
Abusive	13	65	+90	8.5	4.0
Hand Grinding					
Gentle	57	80	+45	--	--
Abusive	30	80	+70	--	--
End Milling					
Condition 1	64	74	-25	10.0	2.3
Condition 2	70	53	-20	--	--
Condition 3	72	82	-20	--	--
Condition 4	72	57	-15	11.0	4.3
Condition 5	64	67	-25	--	--
Condition 6	70	42	-30	11.0	5.7
Condition 7	72	66	+15	--	--
Condition 8	75	87	-30	9.2	4.7
Condition 9	64	56	-20	--	--
Condition 10	55	35	+20	6.0	4.8
Condition 11	64	22	-5	--	--
Condition 12	40	43	+25	4.0	3.3
Condition 13	66	41	-15	--	--
Condition 14	61	40	+20	7.8	5.0
Condition 15	47	45	+25	--	--
Condition 16	32	59	+35	3.8	1.8
Condition 17	64	41	-20	--	--
Condition 18	38	63	+35	4.0	3.0
Condition X1	77	84	--	--	--
Condition X2	70	17	--	--	--
Chemical Machining					
Gentle	51	20	+35	9.0	2.8
Abusive	45	165	+40	8.8	4.8

*See Tables II through X.
**Measured as average tensile ductility (%) before and after exposure.

3.2.3 Summary of Properties Obtained on AISI 4340, Quenched and Tempered, 50 R_c

Machining Conditions*	Endurance Limit (ksi)	Average Surface Finish (AA)	Peak Residual Stress (ksi)	Average Life In Stress Corrosion Environment (hours)
Surface Grinding				
Gentle	102	45	-30	410
Conventional	70	40	+90	369
Abusive	62	50	+105	203
Gentle + Shot Peen (Level 1)	112	25	-230	877
Abusive + Shot Peen (Level 1)	92	40	-105	1000
Abusive + Shot Peen (Level 2)	88	76	-160	158
Hand Grinding				
Gentle	94	115	-40	360
Abusive	98	105	-70	164
Abusive + Shot Peen (Level 1)	118	56	--	297
Electropolishing				
Conventional	90	15	-5	287
Conventional + Shot Peen (Level 1)	96	46	--	432

*See Tables II through XI.

3.2.4 Summary of Properties Obtained on Inconel 718, Solution Treated and Aged, 44 R_c

Machining Conditions*	Endurance Limit (ksi)	Average Surface Finish (AA)	Peak Residual Stress (ksi)
Inconel 718 Fully Heat Treated Before Machining			
Surface Grinding			
Gentle	60	15	-40
Conventional	24	26	+100
Conventional + Re-solution and Age	50	26	+15
Electrical Discharge Machining (EDM)			
Finishing	22	60	+100
Roughing	22	170	+70
Finishing + Shot Peen (Level 1)	66	43	-110
Roughing + Shot Peen (Level 1)	75	125	-160
Roughing + Resolution and Age	38	175	-5
Roughing + Stress Relief	25	221	--
Electrochemical Machining (ECM)			
Gentle	39	43	0
Abusive	39	74	0
Gentle + Shot Peen (Level 1)	78	74	-160
Gentle + Glass Bead Peen	78	69	-100
Abusive + Shot Peen (Level 1)	67	119	-100
Abusive + Shot Peen (Level 2)	75	90	--
Electropolishing (ELP)			
Conventional	42	15	0
Conventional + Shot Peen (Level 1)	78	43	-120

3.2.4 Summary of Properties Obtained on Inconel 718, Solution Treated and Aged, 44 R_c (continued)

Machining Conditions*	Endurance Limit (ksi)	Average Surface Finish (AA)	Peak Residual Stress (ksi)
Inconel 718 Machined And Solution Treated Followed by Aging in Vacuum			
Surface Grinding			
Gentle	74	17	-10
Electrical Discharge Machining (EDM)			
Gentle	29	65	+10
Abusive	29	155	+20
Electrochemical Machining (ECM)			
Gentle	42	19	0
Abusive	42	55	-5
Electropolishing			
Conventional	28	15	+5

*See Tables II through XI.

3.3 Analysis of Extended Data Set

A test program suitable for evaluation of extended data was designed specifically to study the interplay of a number of variables in the milling process. The program was applied specifically to the end milling of beta rolled Ti-6Al-4V. Initially, nine different combinations of variables in end cutting and nine different combinations in peripheral cutting were planned. Later, an additional combination of conditions was added to each method of cutting, making a total of 20 in all. Details of the design of the experimental program as well as the analysis are summarized in Appendix II-4.

An analysis of the results indicates that in end cutting only the wearland on the tool is significant in affecting fatigue strength. In peripheral cutting, four of the variables studied were found to be significant, although again the tool wear was the most important. A summary of the relative influence of these variables, as determined by the analysis made, is as follows:

Variable	Level 1	Level 2	Effect on Fatigue Strength of Level 2 vs. Level 1
End Milling - End Cutting			
Wearland	.003 in.	.018 in.	+6.0 ksi
Cutting Fluid	None	Hocut	nil
Feed	.004 in.	.008 in.	nil
Speed	100 rpm	150 rpm	nil
Depth of Cut	.005 in.	.030 in.	nil
End Milling - Peripheral Cutting			
Wearland	.003 in.	.018 in.	-20.4 ksi
Cutting Fluid	None	Hocut	+8.56 ksi
Feed	.004 in.	.008 in.	-4.81 ksi
Speed	100 rpm	150 rpm	-4.35 ksi
Depth of Cut	.005 in.	.030 in.	nil

3.4 Methods of Evaluating Surface Integrity

1. The standard data set is considered to be the most useful general approach in the evaluation of surface integrity of a metal removal/material combination. The most significant part of the standard data set analysis is the fatigue data developed. Metallography including microhardness data and residual stress information, however, are useful in providing a more complete description of the surface condition exhibited by a particular metal removal/material combination.

2. The addition of low cycle fatigue data at room temperature as well as both low and high cycle fatigue data at elevated temperatures are considered to be useful supplements to the room temperature high cycle fatigue evaluations performed under the subject contract as part of a standard data set analysis. This additional testing, however, would be desirable only where particular materials and potential applications justify the information provided.

3. The extended data set type of evaluation has merit for studying the surface integrity characteristics of a production situation once a specific component-material-manufacturing method has been selected. For purposes of providing information of general value and interest to the aerospace industry as a whole, the benefits of this study could, in the future, be accomplished by evaluating well-chosen extreme conditions to identify sensitive areas. This procedure would accomplish appropriate evaluations at a cost somewhat lower than would be required to test a number of variables over a large matrix of conditions.

4. RECOMMENDATIONS: GUIDELINES FOR MATERIAL REMOVAL AND POST PROCESSING

Reliable surface integrity data are needed for a large number of alloys subjected to many types of metalworking operations and intended for varied service requirements including fatigue and stress corrosion at elevated temperatures. Unfortunately, the demands for specific data cannot all be met on a timely basis. Therefore, extensive effort in this program has been directed toward gathering any information which may establish trends useful to designers and manufacturing engineers.

Initially, in Phase I of this study, an extensive literature search was conducted. Also, in March of 1969, "Surface Integrity Guidelines for Machining" (Ref. 1)* was published and presented for critical review by industry, especially the aerospace industry. In addition to the general publication by the Society of Manufacturing Engineers (formerly American Society of Tool and Manufacturing Engineers), copies of Reference 1 were specifically directed for comment to more than 100 key people associated with manufacturing in industry and government. From the 50 replies received, it was clearly evident that there is a high level of interest in surface integrity data. Also, it was judged that surface integrity guidelines are important and should be kept up to date. A number of good suggestions were received for adding to and modifying the guidelines. These were reviewed and incorporated herein.

Also, during the course of this surface integrity program, the Air Force Materials Laboratory had specific and urgent need for data on "Machining of High Strength Steels with Emphasis on Surface Integrity" (Ref. 2). A report bearing this title was produced and published by the Air Force Machinability Data Center. It presented additional general and specific guidelines on some of the material removal operations not covered in earlier publications. These data were also used in preparing the guidelines presented in the sections which follow.

4.1 Precautions for Use of Surface Integrity Guidelines

Several important precautions should be noted in applying surface integrity guidelines:

Precaution 1

The following guidelines are meant to serve as general or starting recommendations only. Data and experience gathered to date indicate that these practices will lead to increased

*This and other References in Section 4 are listed on page 348.

4.1 Precautions for Use of Surface Integrity Guidelines (continued)

surface integrity. However, the state of knowledge of surface alterations at this time is such that general recommendations are not always applicable to all specific surface integrity situations. For highly critical parts, it is mandatory to make individual specific evaluations. A suggested approach is set forth in Guideline No. 29.

Precaution 2

Surface integrity control generally results in increasing manufacturing costs and decreasing production rates. Therefore, surface integrity practices should not be implemented unless the need exists. Process parameters which provide surface integrity should be applied selectively to critical parts or to critical areas of given parts to help minimize cost increases. Processing analyses made in the interest of achieving surface integrity can lead to overall cost savings in production because a detailed study of surface requirements may make it possible to relax the finish and dimensional requirements in noncritical areas. Key indications of need for surface integrity control are:

1. Distortion in thin parts.

2. Cracking in processing or in service.

3. Short service life.

4. Requirements for manufacturing parts using sensitive alloys such as high strength steels, nickel and cobalt base high temperature alloys, titanium alloys, beryllium, and refractory alloys.

5. New or indeterminant environmental conditions including stress, temperature, and atmosphere.

6. Hazards to life and/or the possibility of high economic property loss.

7. Requirements for designs which approach more complete utilization of material properties.

4.1 Precautions for Use of Surface Integrity Guidelines (continued)

Precaution 3

These surface integrity guidelines are intended primarily for application to metal removal processes used for final surface generation rather than for roughing cuts. It is important, however, to know the type and depth of surface alterations produced during roughing so that adequate provisions may be made for establishing surface integrity during finishing operations by removing damaged surface layers.

Precaution 4

It is important to recognize that the field of surface integrity is in a state of rapid development, and therefore even its terminology is in a state of flux. By definition, surface integrity is the unimpaired or enhanced surface condition which is developed in hardware by controlled manufacturing processes. In the formulation of surface integrity parameters and guidelines, the intent is to apply the term surface integrity when special steps are being taken to control manufacturing processes in generation of surfaces designed to meet severe stress or environmental conditions.

Terminology is also required to describe specifically the set of conditions or material removal parameters which are used to achieve surface integrity. Any type of material removal operation in which parameters are especially selected in order to achieve improved service performance is modified by terms such as low stress or gentle, for example, low stress grinding, gentle grinding, gentle milling, etc. Removal parameters or conditions which are known to be damaging are often referred to as abusive, such as abusive grinding, abusive milling, etc. In the surface integrity literature, data are frequently obtained under so called conventional machining and grinding conditions. Removal parameters which are commonly used or generally accepted in industry are referred to as conventional. It should be pointed out that use of conventional machining and grinding practices sometimes leads to a lack of surface integrity. It should also be emphasized that ultimately abusive and gentle processing can only be differentiated by mechanical testing (fatigue, stress corrosion, etc.) and/or service performance.

4.2 General Guidelines for Material Removal

1. Tool Life

During material removal, it is important to produce a surface which has a minimum or preferably an absence of surface alterations, that is, the surface layer should be similar to the bulk material below the surface. In order to achieve this objective in chip removal operations such as turning, milling, etc., the best general rule is to select machining conditions which are recommended to produce long tool life and a low rate of tool wear. By using these recommendations and by removing the tool when the tool wear reaches a relatively low value, the tendency for surface alterations to be produced will be minimized.

For all chip removal operations, the tool should be removed from service when the tool wear reaches .005 to .008 inches. A good rule of thumb is to remove the tool when the wearland becomes visible to the naked eye since the aforementioned wearland is just barely visible to the naked eye.

2. Tool Life Data

In order to determine machining conditions which will provide long tool life, it will be necessary to refer to tool life data for specific materials and material removal operations. (See Refs. 3 to 9). If tool life data are not available, a material closest in characteristics to the actual work material can be used for initial consideration of machining parameters. In addition, it is recommended that tool life data be studied carefully in order to develop the relationship of machining parameters to tool life. In this way one can get an idea of the effect of changes in speeds, feeds, tool materials, etc., on the tool life and be in a better position to decide on departures from the recommended machining parameters.

3. Machine Tools

Rigid, high quality machine tools are essential. These must have ranges of speeds and feeds necessary to meet surface integrity requirements.

4. Cutting Tools

Cutting tools must be processed carefully. The most rigid tool design should be employed. An example would be using a stub

4.2 General Guidelines for Material Removal (continued)

4. Cutting Tools (continued)

length drill instead of a jobber's length wherever possible. Cobalt or premium grade high speed steel should be used wherever carbide is not feasible. All tools should be inspected after grinding to insure that previous wear, chipping, galling, etc., have been corrected and meet tool specifications. After grinding, the cutting edges of all tools should be protected to prevent accidental damage in transit or handling. Tools should be double checked by the machine tool operator for obvious defects.

5. Cutting Fluids

During machining, a proper and adequate supply of cutting fluid should be used. This fluid should be washed off the part after machining by using well controlled, conventional cleaning practices. If the cutting fluid contains sulfur or chlorine, the part should be cleaned immediately after machining. If it is not possible to completely wash the entire part after machining, the cutting fluid may have to be omitted.

6. Grinding

Grinding should be done generally using a soft wheel, low wheel speeds, light infeeds, and a highly active cutting fluid. In cylindrical grinding as well as other forms of grinding, high work speeds are also desirable. The above combination of conditions tends to minimize surface alterations. The entire width of grinding wheels should be flooded with coolant. Under no circumstances should the grinding fluid be cut off during the grinding process.

To insure against wheel loading, frequent dressing of grinding wheels should be performed. Diamond dressing tools should be turned frequently to present a sharp edge to the wheel for turning and dressing.

Any evidence of burning either during the normal process of grinding or because of an accidental interruption or mishap during the grinding process should be reported to supervision. Even burning during the grinding process before finish grind should be reported because the "burn" effects may extend several thousandths below the surface and the finish grind may not remove these effects.

Grinding specifications set up by manufacturing engineering should be religiously carried out by the machine operator.

4.2 General Guidelines for Material Removal (continued)

7. **Processing Parameters**

All parameters for material removal should be specified by manufacturing engineering. These include tool material, tool geometry, cutting speed, feed, cutting fluid, and tool life (maximum number of parts per tool grind) for chip removal operations. Similarly, appropriate parameters must be set up for operations such as grinding, EDM, and ECM.

8. Metallography

When critical sections of a component are to be machined or ground, it is recommended that the operation in question be done on either a trial piece or on sections of the actual work material using the same tools and conditions contemplated for the actual component. The operation should be performed with both sharp and dull tools or under gentle and abusive grinding conditions, and then the surface layer should be checked by macroetch and metallographic sectioning for surface conditions to determine whether undesirable surface alterations are present. Microhardness checks should be made to help identify soft and hard layers. These metallographic practices can also be used to specify the extent of secondary processing for removal of undesirable alterations.

9. Deburring

All parts should be carefully deburred after machining since burrs and sharp edges are common sources of component failure. Manufacturing engineering should set careful specifications for the radius, chamfer or break-edge, especially on holes.

10. Post Processing

Shot peening is a process which should be considered seriously for improving surface integrity. It has been widely used and has also been successfully used in tests conducted in this program.

11. Protection of Parts

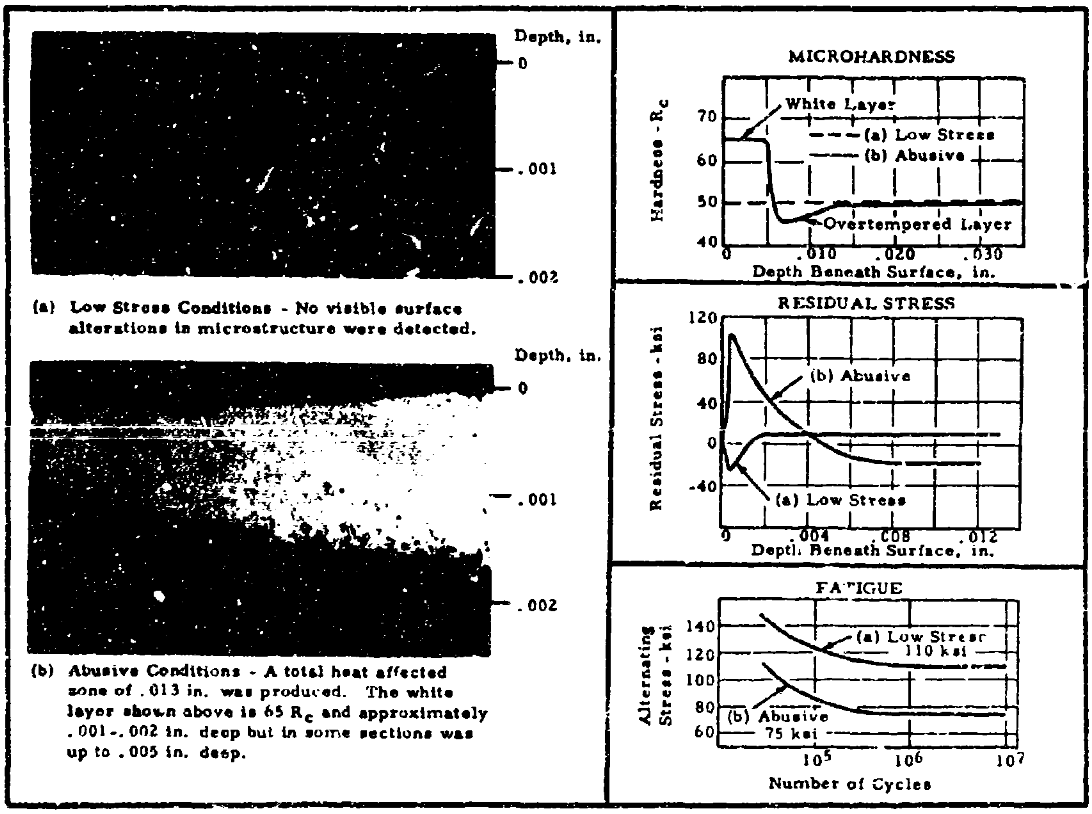
Parts should not be stored for extended periods without being covered with a coating or oil for corrosion prevention.

4.2 General Guidelines for Material Removal (continued)

12. Specifications

Preparation of processing specifications is most highly recommended for highly stressed parts. Some of the aerospace producers have in fact already written detailed manufacturing specifications incorporating machining parameters and procedures in an effort to maintain surface integrity. These specifications, even though widely used in subcontract work, are generally considered proprietary and under the control of the prime contractor. It is suggested that manufacturing engineering departments of the large prime aerospace producers be contacted directly concerning the availability of their specifications.

In the absence of specifications, data disseminated in a convenient form can be extremely helpful. A suggested format is shown below:



(a) Low Stress Conditions - No visible surface alterations in microstructure were detected.

(b) Abusive Conditions - A total heat affected zone of .013 in. was produced. The white layer shown above is 65 R_c and approximately .001-.002 in. deep but in some sections was up to .005 in. deep.

SURFACE CHARACTERISTICS PRODUCED BY GRINDING
AISI 4340 STEEL, QUENCHED AND TEMPERED, 50 R_c

4.2 General Guidelines for Material Removal (continued)

12. Specifications (continued)

The figure on the previous page is a typical display showing photomicrographs of surface layers machined under different conditions along with hardness, residual stress, and fatigue data. Displays of this type, which should be varied to meet specific needs, are effective in that they present a great deal of information conveniently and convincingly. Specific processing instructions should be written, preferably in tabular form, listing the material, the material removal operation, all removal parameters and post-processing requirements. It has been found helpful to add some general notes which may list additional instructions, alternate procedures, and precautions.

13. Education and Training

Manufacturing and engineering personnel are not sufficiently acquainted with the many types of surface alterations which can be produced during material removal operations. Engineers generally do not realize that high temperatures prevail at work-piece and tool interfaces, while manufacturing people often do not realize the extent to which metallurgical changes occur and how seriously they lower mechanical properties.

Programs should be set up relative to handling of surface integrity data. When a specific surface integrity situation has been investigated and the process operating parameters selected, it is essential that these selected operating values be maintained. Machine operators should be thoroughly trained to follow the proper procedures outlined by manufacturing engineering. Machinists should be informed as to the reason and necessity for maintaining good surface integrity and surface quality. Management needs to be ever alert to the desire on the part of operators to try "just one more notch" on the control. Without requalification, this relaxation of standards may result in loss of surface integrity.

Operators should be instructed to notify supervision of all accidents or damage including all visual evidence of damage, for example grinding burn. Cleanup of surface discoloration is not necessarily sufficient to remove all of the damage below the surface. In case of damage, parts should be subject to systematic review action.

4.2 General Guidelines for Material Removal (continued)

13. Education and Training (continued)

Breaking of drills, reamers or taps in holes, and sparking during EDM, are examples of the type of mishaps requiring special treatment.

14. Source of Surface Integrity Data

The Air Force Machinability Data Center (AFMDC), Cincinnati, Ohio, has and will continue to collect information and data on surface integrity. Specific inquiry services are available without charge to the aerospace industry, Department of Defense (including all of the military services and their contractors), and other Government agencies, technical institutions, and nonmilitary industries in a position to assist the defense effort. Inquiries should be directed to Supervisor, Technical Inquiries, Air Force Machinability Data Center, 3980 Rosslyn Drive, Cincinnati, Ohio 45209, Telephone: 513-271-9510, TWX: 810-461-2840.

4.3 Specific Guidelines for Material Removal

Abrasive Processes

1. Reduce Grinding Distortion and Surface Damage by Using "Low Stress" Grinding

To minimize grinding distortion and to reduce the possibility of producing extensive surface alterations, including cracking, conventional finish grinding practices can be replaced by low stress grinding procedures. Low stress grinding, in comparison with conventional practices, employs softer grade grinding wheels, reduced grinding wheel speed, reduced infeed rates and chemically active cutting fluids.

A typical comparison of conventional versus low stress conditions is shown on the following page.

4.3 Specific Guidelines for Material Removal (continued)

1. Reduce Grinding Distortion and Surface Damage by Using "Low Stress" Grinding (continued)

Grinding Conditions for Steels and for Nickel Base High Temperature Alloys

Surface Grinding

	Typical Conventional	Typical Low Stress
Wheel:	A46K8V	A46H8V
Wheel Speed:	5500 to 6500 ft./min.	2500 to 3000 ft./min.
Down Feed:	.001 to .003 in.	.0002 to .0005 in.
Table Speed:	20 to 60 ft./min.	*20 to 60 ft./min.
Cross Feed:	.050 to .250 in./pass	.040 to .050 in./pass
Grinding Fluid:	Water base, soluble oil or chemical	Highly sulfurized oil

Cylindrical Grinding

	Typical Conventional	Typical Low Stress
Wheel:	A46K8V	A60I6V
Wheel Speed:	5500 to 6500 ft./min.	2500 to 3000 ft./min.
Infeed:	.0005 to .002 in.	.0002 to .0005 in.
Work Speed:	70 to 100 ft./min.	*70 to 100 ft./min.
Grinding Fluid:	Water base, soluble oil or chemical	Highly sulfurized oil

For certain sensitive alloys, no compromise should be permitted in selecting the low stress grinding parameters. In other situations, some of the low stress grinding parameters may be altered in the direction of increased productivity while still maintaining adequate surface integrity (see Guideline No. 5 of this Section). For a wide variety of metals, including high strength steels, high temperature alloys, titanium and refractory

*Increased work speeds even above those indicated are considered to be advantageous.

4.3 Specific Guidelines for Material Removal (continued)

1. Reduce Grinding Distortion and Surface Damage by Using "Low Stress" Grinding (continued)

alloys, low stress grinding practices develop very low residual tensile stresses, and in some materials the residual stress produced near the surface is actually in compression instead of tension.

In order to apply low stress grinding, it would be preferable to have a variable speed grinder, but since most grinding machines do not have wheel speed control it is necessary to add a variable speed drive or make pulley modifications.

2. If Low Stress Grinding is Specified for Finish Grinding, then Conventional Grinding Can be Used to Within .010 In. of Finish Size, Provided the Materials being Ground are Not Sensitive to Cracking (See Guideline Nos. 3, 4 and 5 Below)

During conventional grinding, the metallurgically altered layer, including stresses, is confined to approximately .005 in. of the surface. Thus all of the altered surface layer can be removed by using low stress conditions during finish grinding. Stock allowances greater than .010 in. should be considered to compensate for location inaccuracies in holding fixtures.

Crack detection tests should be made to see that rough grinding of materials does not create cracks, because it is entirely possible for cracks to penetrate more than .010 in. below the ground surface or to be pushed in deeper during finishing operations.

3. Conventional Grinding Conditions Should Not be Used for Grinding Highly Sensitive Alloys

Typical examples of extremely sensitive alloys are:

High Temperature Nickel and Cobalt Base Alloys (Cast)
In 100, 713C, MAR-M509
Beryllium
Columbium Alloys
Tungsten

4.3 Specific Guidelines for Material Removal (continued)

4. **Finish Grinding of Highly Stressed Surfaces of Sensitive Alloys Exposed to High Service Stresses Should be Performed Using Low Stress Grinding Instead of Conventional Grinding**

Sensitive classes of alloys include:
(Note: This is a partial list with typical examples.)

High Strength Steels
- 4340 at 40-56 R_c
- D6ac at 50-56 R_c
- Maraging Steels
- HP 9-4-45

High Temperature Nickel and Cobalt Base Alloys (Wrought)
- Rene' 41
- Udimet 700
- Waspaloy
- Inconel 718
- L-605

Titanium
- 6Al-4V
- 5Al-2.5Sn
- 6Al-2Sn-4Zr-2Mo

Molybdenum
- TZM
- Mo+0.5Ti

Note: Low stress grinding conditions recommended for these alloys differ from those of Guideline No. 1.

Abusive grinding has been shown to cause a significant drop in fatigue strength (compared to general grinding) of 4340 (50 R_c), Ti-6Al-4V, and Inconel 718. To a lesser extent, conventional grinding also showed a fatigue depression of 4340 (50 R_c) and Inconel 718. Abusive hand grinding showed similar effects but to a slightly lesser degree.

Fatigue depression in martensitic steels due to abusive grinding has been demonstrated to be approximately equal regardless of the quantity of untempered martensite (UTM) present. Traces of UTM as well as layers .004 in. deep were associated with the same fatigue depression. Depression of the endurance limit was about 30-35 percent. Even if UTM is removed by gentle grinding, fatigue life is still depressed. This suggests that overtempered martensite (OTM) may be the limiting factor influencing fatigue strength.

4.3 Specific Guidelines for Material Removal (continued)

5. Modification of the Low Stress Grinding Procedures Should Not be Attempted Unless Testing Programs in the Shop or Laboratory Confirm that Compromises Can be Tolerated

It is sometimes possible to make changes in low stress procedures in order to accommodate equipment limitations and/or to increase production rates. Two sets of conditions are compared below. Condition A resulted in scrap caused by cracks produced in the fir tree section of IN 100 turbine blades, while Condition B did not. Note that a feed as high as .002 in. did not cause cracking.

Grinding Parameters	A (Cracks)	B (No Cracks)
Wheel	38A10018VBE	38A8018VBE
Wheel Speed	6300-4700 ft./min.	2800 ft./min.
Table Speed	20 ft./min.	20 ft./min.
Infeed/Pass	.004 in.	.002 in.
Fluid	Sulfochlorinated Oil	Highly Sulfurized Oil
Grinding Cycle	Rough: .060 in. at .004 in./pass, dress. Leave .100 in. side for finish operation. Finish: .012 in. from finish size (3 passes at .004 in./pass) 2 free passes (no feed)	Dress, feed .060 in. at .002 in./pass. Dress, feed .060 in. at .002 in./pass. Dress, feed .010 in. at .002 in./pass to finish size.

6. Frequent Dressing of Grinding Wheels Can Reduce Surface Damage by Keeping Wheels Open and Sharp thus Helping to Reduce Temperatures at the Wheel-Workpiece Interface

Automatic dressing and wheel compensation contribute to the economic feasibility of frequent dressing. Crush dressing can also be used to minimize cost of frequent dressing.

4.3 Specific Guidelines for Material Removal (continued)

7. **Hand Grinding of Sensitive Alloys Should be Discouraged**

The inherent lack of control has been responsible for creating many surface defects. Abusive hand grinding of 4340 (50 R_c) on tests conducted in this program depressed fatigue strength.

8. Abrasive Cutoff Requires Special Surface Integrity Considerations

Abrasive cutoff operations generally provide deeper surface layer alterations than grinding, sometimes as much as .100 in. Also, capability for minimizing damage during cutoff operations varies from plant to plant. Therefore, it is recommended that if abrasive cutoff is used, steps should be taken to determine the extent of the disturbed layer and allow stock for cleanup. Also, the entire surface should be explored, because the temperatures generated are subject to extreme variation across the cut. Presently, some plants will not allow abrasive cutoff to be used on sensitive alloys. It is suggested that abrasive cutoff be considered in manufacturing, provided proper controls are maintained, because many of the newer alloys are very difficult to saw.

9. Controls for Hand Power Sanders Should be Maintained

Some of the important precautions to be taken are:

a. Reduce speed (2000 surface ft./min. maximum, for example).
b. Use a flexible (rubber) support for sanding disks or belts.
c. Use a finer abrasive grit, generally no coarser than 80, with coolant if feasible.

Chip Removal Operations

10. Sharp Tools Help Establish Surface Intregity in Turning and Milling

In turning and milling there are at least two very important steps which will improve surface integrity. First, machining conditions should be selected which will give long tool life and good surface finish. Second, all machining should be done with sharp tools. Section 6.1-Fatigue shows that the best fatigue life for end milling-end cutting Titanium 6Al-4V alloy was obtained when using dull tools. In spite of this exception, at this time sharp tools are still recommended even for milling of titanium alloys. Sharp tools minimize distortion and generally lead to better control during machining. The maximum flank wear in turning and milling

4.3 Specific Guidelines for Material Removal (continued)

10. Sharp Tools Help Establish Surface Integrity in Turning and Milling (continued)

should be limited to approximately .005-.008 in. Dull tools develop high compressive stresses which cause distortion, and they often produce metallurgical alterations of the surface including white layers such as untempered martensite in steels. Use of carbide tools makes it more feasible to maintain sharp tools in cut and at the same time meet reasonable production rates.

Throwaway carbide tools, in particular, should be used whenever possible. This will enable rapid change of cutting edges whenever tool wear reaches its specified limit.

Any evidence of burning as a result of a tool or cutter breakdown should be reported to supervision. Care must be taken to remove sufficient stock after tool breakdown to completely remove the effects of the burning which may extend to as much as .005 in. to .010 in. of the machined surface.

There is a tendency for more surface damage to occur in the transient surface than on generated surfaces in turning and milling. Likewise, there is a tendency for more surface damage to occur when a long cutting edge produces the final surface. This is the situation that usually exists when turning to a shoulder or when milling a radius into a component. Hence, when transitional surfaces or formed surfaces of the above type become finished surfaces, special care must be exercised to avoid surface damage. The use of especially sharp cutters for finishing is desirable to minimize the alterations in this case. Whenever possible in turning, a shoulder or large radius should be generated by a finishing tool rather than formed by the long cutting edge of a forming tool.

11. Sharp Drills Should be Used to Help Avoid Serious Surface Layer Alterations

Specified power speeds and feeds, as well as all other recommended drilling conditions, should be followed. Holes in highly stressed components should be free of tears, laps, and untempered martensite. To minimize defects, wearland in drills should be limited to .005 in. to .008 in. Wherever possible, all hand feeding during drilling should be avoided. When drilling

4.3 Specific Guidelines for Material Removal (continued)

11. **Sharp Drills Should be Used to Help Avoid Serious Surface Layer Alterations (continued)**

in assembly, a rigid machine tool or gantry type drill should be employed in preference to portable drilling equipment. Dwelling should also be avoided because it produces damage and may even friction weld the drill to the workpiece. The operator should visually check the hole and drill after each operation. If average or localized wear exceeds specifications, the drill should be replaced. If abnormal conditions develop in the hole, it should be marked and inspected thoroughly before assembly. Galling, torn surfaces, or discoloration due to overheating are causes for rejection. When a drill breaks in the drilling of sensitive alloys, the operator should notify appropriate personnel in order that remedial steps be taken. Accidents of this type indicate that proper machining conditions have not been selected and/or used properly. Coolant-fed drills may help minimize surface damage, but no supporting data are available.

12. Proper Drill Fixturing Assists in Minimizing Damage During Drilling

When drilling holes 1/4 in. or larger, a drill fixture or bushing should be used. Where accessibility permits, a drill backup should be used to minimize burring.

13. Finishing of Drilled Holes is Imperative

Entrance and exit of all holes should be carefully deburred and chamfered. All holes should be reamed after drilling whenever possible to insure better surface finish and surface integrity (see Guideline Nos. 14 and 15).

14. Special Precautions Should be Taken in Reaming of Holes in Sensitive Alloys

Since reaming often serves as a final hole finishing operation, all machining parameters must be controlled. Stock allowances must also be controlled. Hand feeding of straight reamed holes should be avoided, but may be acceptable for taper holes. Hand reaming of taper holes may be permissible after power reaming. If hand reaming is performed, special attention should be placed on selection of tool material, reamer geometry, and accuracy and alignment during the reaming process.

4.3 Specific Guidelines for Material Removal (continued)

14. Special Precautions Should be Taken in Reaming of Holes in Sensitive Alloys (continued)

Double ream all holes 5/16 in. or larger with a minimum metal removal of 3/64 in. on diameter. On smaller holes, the minimum metal removal should be 1/64 in. on the diameter. The operator should visually check the reamer after each operation. At the first sign of chipping, localized wear or average flank wear beyond specification, the reamer should be replaced and the hole inspected. Also, regardless of hole and reamer condition, a maximum number of holes should be specified for reamer replacement. Each reamed hole should be carefully inspected for surface finish, galling, smearing, scratches, etc. Entrance and exit of all holes should be carefully deburred and chamfered.

15. Drilled and Reamed Holes Should be Countersunk

To countersink, use power feed units if they are accessible. Use a countersink which completely avoids chattering. Generally, low spindle speeds are desirable. As for other operations, honing and chamfering tools should be kept sharp.

The operator should visually inspect the tool after each cut, and it should be replaced if any visual evidence of wear is observed.

The breaking of edges or radiusing may be done by abrasive deburring using a low speed, powered hand drill. In chamfering of a part, a minimum of .010 in. of material removal is advisable. The break-edges and chamfers should be carefully examined for compliance with good surface finish requirements. This is especially important on the entrance and exit of holes since it is here that fatigue failure has a tendency to start.

16. Honing is an Excellent Finishing Operation for Developing Surface Integrity

Honing is usually used only when finish requirements or tolerances are too close for practical use of other finishing operations such as reaming, grinding, etc. A multi-stone head is preferred; heads with steel shoes and/or steel wipers are not recommended. Honing produces less surface deformation and surface integrity damage than any other hole finishing process.

4.3 Specific Guidelines for Material Removal (continued)

17. Boring May be Used as a Finish Machining Operation if Roughness is Within the Manufacturing Engineering Limits

On finishing operations, the tool life should be limited to *one* finish pass per cutting edge. Throwaway carbide inserts should be used whenever possible. This will enable rapid change of cutting edge when going from the roughing cut to the finishing cut.

Electrical, Chemical, and Thermal Material Removal Processes

18. Whenever Electrical Discharge Machining (EDM) is Used in the Manufacture of Highly Stressed Structural Parts, the Heat Affected Layer which is Produced Should be Removed

The altered surface layer which is produced during EDM lowers fatigue strength of alloys significantly. Concern over the lowered fatigue strength is in reference to highly stressed structures. In many tool and die applications, the altered layer has not caused problems and there have even been reports of improved die life. Generally, during roughing EDM, the layer showing microstructural changes, including a melted and resolidified layer, is less than .005 in. deep, while during finishing EDM it is less than .001 in. See Guideline No. 23 below for suggested post-processing methods.

In electrical discharge machining of Inconel 718, both finishing and roughing practices yield low endurance limits--approximately one-third that exhibited in low stress grinding. These data strongly suggest that no heat affected layer produced by the EDM process should be tolerated on highly stressed parts.

19. Whenever Electrical Discharge Grinding (EDG) or Electrochemical Discharge Grinding (ECDG - sometimes referred to as ECDM) is Used in the Manufacture of Highly Stressed Parts, the Heat Affected Layer which is Produced Should be Removed

The removal conditions for EDG and ECDG essentially produce the same surface effects as EDM, however, the altered layers are very shallow and generally less than .001 in. deep.

4.3 Specific Guidelines for Material Removal (continued)

20. Electrochemical Grinding (ECG) Should be Controlled Carefully in Order to Establish and Maintain Surface Integrity

The ECG process, using a metal bonded abrasive wheel as an electrode, should be controlled to avoid shorting. Also, since some metal is removed by the abrasive grains, it is possible to locally overheat parts just as in ordinary grinding. The surface effects of properly ground parts are very shallow and generally less than .001 in. It is desirable to maintain a full flow of electrolyte and a good balance between feed rate and electrolytic cutting rate so mechanical removal is under 5 percent of total as shown by only light scratches being present.

21. Surface Integrity Evaluations Should be Made When Chemical and Electrochemical Processes are Used for Finishing of Critical Parts

Electrochemical and chemical material removal processes often provide optimum surface conditions. However, these processes when out of control can, in fact, damage surfaces and lower fatigue strength. Surface integrity is lowered by intergranular attack, preferential solution of microconstituents, and shorting. When shorting occurs, the high temperature arc melts and vaporizes a local spot. Below the spot, there are other microstructural changes which can also be detrimental. During ECM, parts should be fixtured in a way that will provide good electrical contact. Otherwise, there is a danger of localized overheating as a result of resistance heating. Cases have been observed where the damage in the form of discoloration is barely discernible on the surface. However, just below the surface the microstructure revealed the effects of extensive overheating including very large grain size. ECM, improperly applied, can also cause pitting as in the case of high strength aluminum alloys. Pits are often responsible for stress corrosion and fatigue failures.

The fatigue strengths of surfaces produced by controlled chemical and electrochemical processes can be lower than the ones produced by some of the more commonly used material removal processes. This is generally attributed to the unworked, stress-free surface produced by ECM. It is believed that processes such as milling and polishing may provide beneficial fatigue resistance as a result of cold working. Therefore, when substituting ECM for other machining

4.3 Specific Guidelines for Material Removal (continued)

21. **Surface Integrity Evaluations Should be Made When Chemical and Electrochemical Processes are Used for Finishing of Cri Critical Parts** (continued)

processes, it may be necessary to add post processing such as steel shot or glass bead peening or mechanical polishing. Some companies require peening of all electrochemically machined surfaces of structural parts (see Guideline Nos. 23 and 24). Gentle or abusive ECM of Inconel 718 gave a fatigue strength of 39,000 psi as compared with 60,000 psi for low stress grinding. Electrolytic polishing of Inconel 718 gave a value of 42,000 psi, virtually no improvement over ECM.

22. Electron Beam Machining (EBM) and Laser Beam Machining (LBM) Develop Surfaces Showing the Effects of Melting and Vaporization

Applications for use of EBM and LBM are not too common. Recently, however, LBM with oxygen assist is being investigated for cutting (instead of shearing) of various alloys including titanium. Wherever EBM or LBM are used in manufacturing highly stressed structural members it should be remembered that in the application of these methods the surface is subjected to melting and vaporization. Indications are that such surfaces should be removed. It becomes difficult, however, to apply secondary processing to parts containing very small diameter holes or narrow slots. As a first step, it is suggested that critical parts made by EBM and LBM be tested to see if surface alterations lower the critical mechanical properties.

Post Processing

23. All Heat Affected Layers Created During Material Removal Processing Should be Removed from Critically Stressed Parts

By microstructural examination and microhardness testing, the depth of the affected layer can generally be established. Certain critical situations may require mechanical testing to be certain that no alterations have been produced which cannot be detected by microexamination. Secondary removal processes which are currently being used include:

4.3 Specific Guidelines for Material Removal (continued)

23. All Heat Affected Layers Created During Material Removal Processing Should be Removed from Critically Stressed Parts (continued)

a. Mechanical polishing
b. Sanding
c. Low stress grinding
d. Honing
e. Chemical milling
f. Electrochemical milling
g. Electropolishing
h. Heat treatment

24. Steel Shot and Glass Bead Peening Can be Used to Improve Surface Integrity

A considerable number of studies, including those developed in this report, confirm that fatigue life determined in laboratory tests and proved by field performance is measurably enhanced by peening. Peening, which puts the surface layer into compression and cold works the surface, must be performed under controlled conditions.

Processing specifications for peening include consideration of factors such as cleanliness and surface roughness of the part being machined; type, geometry and hardness of the shot and its fluid carrier; peening time, intensity and coverage. Reports also indicate that peening confers improved resistance to corrosion and a large reduction in stress corrosion susceptibility. Indications are that cold working of drilled holes by burnishing is also beneficial. Some reports contain precautions warning against overpeening in order to avoid fatigue damage and to reduce the possibility of masking flaws such as fine cracks.

25. Post Heat Treatments Following Material Removal are of Limited Usefulness

Stress relief treatments used to soften hardened layers produced during grinding of steels do not restore the hardness of overtempered layers which are present immediately below the damaged surface layer. Also, heat treatment does not heal any cracks produced during material removal. Evidence

4.3 Specific Guidelines for Material Removal (continued)

25. **Post Heat Treatments Following Material Removal are of Limited Usefulness (continued)**

has also been presented to show that annealing treatments following EDM on nickel base alloys such as Rene' 41, Inconel 25, Inconel 718 and Monel K-500 seriously lower tensile strength and ductility as a result of carbon diffusion. Work in this report has shown that heat treatments in some cases have improved surface integrity of damaged surfaces but not nearly as effectively as shot peening. Low temperature heat treatments are helpful in eliminating embrittlement in operations where hydrogen may be picked up during processing. Elimination of hydrogen is time and temperature dependent and also depends upon the alloy being treated. Steels, for example, are often treated at 400°F.

26. Abrasive Tumbling is an Effective Process for Improving Surface Properties Including Fatigue

This process is less applicable than shot peening for many of the very large parts required for aerospace. Both abrasive tumbling and shot peening usually require an added polishing operation when very high finish requirements must be met. Care must be taken not to remove the favorable surface layer established by peening or tumbling. Abrasive tumbling can replace unfavorable tensile stresses by inducing a compression stressed surface layer.

27. Washing Procedures Should be Employed for Critical Parts and Assemblies in Order to Remove All Traces of Cutting Fluids Which May Cause Stress Corrosion

Typical compounds which are suspect are sulfur compounds on aluminum and nickel base alloys and chlorine compounds on titanium alloys. Currently, some companies do not allow any chlorine containing cutting fluids to be used in processing titanium parts which are to be used at room or elevated temperatures. Other companies use this precaution only for parts which are subjected to temperatures over 500°F. For applications at less than 500°F, carefully controlled washing procedures are often used to remove the chlorinated and sulfurized cutting oils. These fluids are particularly effective in chip removal operations such as drilling, tapping and broaching. Since no complete agreement exists among manufacturers regarding cutting fluid practices, subcontractors are obliged to follow the policies and procedures established by the prime contractor.

4.3 Specific Guidelines for Material Removal (continued)

Inspection

28. Inspection Practices Should be Reviewed and Amplified to Meet Surface Integrity Requirements

It must be recognized that there is no single test or combination of tests which can be employed for a nondestructive quality control surface integrity check of finished parts. However, there are some nondestructive as well as destructive testing practices which can be employed to help develop surface integrity:

a. Use microscopic examination including microhardness testing on a sampling basis in order to determine the kind of surface layer being produced plus the layer depth. Use this method to check for microcracks, pits, folds, tears, laps, built-up edge, intergranular attack, sparking, etc. Since many surface alterations are shallow, it is essential to use good edge retention techniques for microscopic examination. The term conventional as applied to various material removal operations simply indicates use of removal parameters which are in general use regardless of whether they are abusive or not.

b. White layer or overtempered martensite produced during grinding of steels can be detected by immersion etching using 3-5 percent aqueous nitric acid solution. Ammonium persulfate has also been used and has the advantage of removing less material than nitric acid. Compounds used for inspection should be free of constituents which may be harmful such as chlorine in the case of titanium or sulfur in the case of nickel base alloys. The procedures used are quite detailed, consisting essentially of appropriate and specific precleaning and post-preparation procedures. These vary among producers and are too detailed to be included in this paper.

c. Magnetic particle, penetrant inspection, ultrasonic testing, and eddy current techniques are recommended for detecting macrocracks. Most of the inspection techniques currently being used can be refined further by using more care in their application. Direct visual examination should be supplemented by macroscopic examination at low and medium magnification (5-20X).

d. X-ray diffraction methods are available to detect residual surface stresses. This method may be helpful in process development as well as for spot checking of finished parts. However, x-ray can only detect stresses within a few tenths of the surface.

4.3 Specific Guidelines for Material Removal (continued)

28. Inspection Practices Should be Reviewed and Amplified to Meet Surface Integrity Requirements (continued)

e. The scanning electron microscope is currently being used to provide detailed information on the surface condition of materials after machining. This instrument is capable of combining very high magnifications with high resolution and high depth of field, but to date it has not been used for quality control of finished parts.

Guidelines for In-House Surface Integrity Programs

29. Systematic Metallurgical and Mechanical Testing Programs for Establishing and Controlling Surface are Important

As noted previously, the guidelines outlined in this paper are simply general recommendations which should be supplemented by very specific data in order to accommodate individual critical design requirements. Three types of evaluation programs are suggested. These programs differ in the extent of data which they provide and must be tailored to meet a plant's specific needs. These are artitrarily designated as:

a. Minimum Data Set
b. Standard Data Set
c. Extended Data Set

a. The Minimum Data Set is essentially based upon metallographic information supplemented with microhardness measurements and the usual surface finish measurements.

Metallography affords a very simple approach for determining visual changes in the surface layer at higher magnification. Careful mounting and polishing techniques must be employed to achieve good edge preparation. In this way, heat affected layers can be identified, including melting or changes in the grain structure resulting from phase transformations or plastic deformation. Cracks are also detected readily and surface roughness, pits, tears, laps and built-up edge can be identified microscopically.

29. **Systematic Metallurgical and Mechanical Testing Programs for Establishing and Controlling Surface are Important** (continued)

a. (continued)

Microhardness measurements are extremely useful since they confirm visual alterations and help identify changes which are not discernible in a microscopic examination of the surface layer. While both microscopic and microhardness studies are destructive procedures, they are essential in selecting, setting up, and monitoring the processing of critical parts. Destructive testing, on a sampling basis, should be used to make surface integrity decisions in engineering and manufacturing today, because for most parts there is no set of nondestructive tests which will in a practical way serve as a quality control check on finished parts. At the present time, it is important to use appropriate nondestructive tests, such as magnetic particle and penetrant checks, to detect cracks, etching to detect burn, etc., but there is no substitute for in-process control which has been established upon systematic testing including destructive testing.

The surface metallography tests help to measure surface integrity, but they cannot be used to predict mechanical properties and service performance. After correlations have been established with performance, surface metallographic practices can be used for quality control purposes.

Minimum Data Set

Surface Finish

Macrostructure (10X or less)
- Macrocracks
- Macroetch Indications

Microstructure
- Microcracks
- Plastic Deformation
- Phase Transformations
- Intergranular Attack
- Pits, Tears, Laps, Protrusions
- Built-up Edge
- Melted and Redeposited Layers
- Depletion by Vaporization
- Selective Etching

Microhardness

29. Systematic Metallurgical and Mechanical Testing Programs for Establishing and Controlling Surface are Important (continued)

b. The Standard Data Set is designed to provide more in-depth data for the more critical applications which are influenced by surface integrity. It should be noted that the Standard Data Set includes surface metallography studies. In addition, three mechanical properties have bee selected for evaluation because they are generally significant in surface integrity situations. These are residual stress, fatigue, and stress corrosion. Distortion as related to residual stress becomes an important consideration because the emphasis on high-strength-to-weight ratios leads to fragile parts requiring high dimensional accuracy. Stress corrosion tests are very important because many highly stressed components are subjected to environments which can cause cracking in parts carrying residual surface tensile stresses. Screening type fatigue tests isolate the most important variables which should be considered, thereby providing a strong base for making manufacturing decisions.

Standard Data Set

Minimum Data Set

+

Fatigue Tests (Screening)

Stress Corrosion Tests

Residual Stress and Distortion

c. The Extended Data Set provides data gathered from a statistically designed fatigue program and yields data suitable for detailed designing. Screening tests (from the Standard Data Set) as well as extended fatigue studies take various forms, but always the extended programs can be expected to require many more tests in order to develop the necessary confidence limits. For highly critical parts, it may become necessary to run full-scale component tests.

To round out a surface integrity package, extended testing may logically require evaluation of surface integrity effects on tensile, stress rupture, creep, and other material properties under unusual environmental conditions.

4.3 <u>Specific Guidelines for Material Removal</u> (continued)

29. <u>Systematic Metallurgical and Mechanical Testing Programs for Establishing and Controlling Surface are Important</u> (continued)

c. (continued)

<u>Extended Data Set</u>

Minimum Data Set

Standard Data Set

+

Fatigue Tests (Extended to obtain design data)

Additional Mechanical Tests
- Tensile
- Stress Rupture
- Creep

5. PROCEDURE

5.1 Procurement and Certification of Test Materials

The three materials purchased for the experimental effort under the contract were ordered as 1/4 in. rolled plate. This thickness was selected as being representative of a reasonable volume of aerospace production and to be suitable for the experimental program. The majority of test specimens run under this program were less than 0.100 in. thick. Therefore, adequate stock removal was allowed in order to avoid the influence of various surface conditioning treatments as might be applied to these materials.

5.1.1 Titanium 6Al-4V, Beta Rolled

Applicable Specification: The Boeing Company, XBMS 7-174, Condition 1, mill annealed.

Source: Reactive Metals Inc., Heat No. 302493.

The specified melt chemistry of this material, in comparison with the check analysis determined by F. C. Broeman & Company, Cincinnati, Ohio, and Ledoux and Company, Teaneck, New Jersey, was as follows:

	Specification	Check Analysis
Titanium	Remainder	-
Aluminum	5.5 - 6.75	6.20
Vanadium	3.5 - 4.5	3.82
Iron	0.25 max.	0.12
Carbon	0.08 max.	0.07
Hydrogen	0.0125 max.	0.0135
Oxygen	0.175 max.	0.119
Nitrogen	0.03 max.	0.015
Other Impurities	0.40 max.	-

The heat treatment specified for Condition 1 of this alloy in comparison to that used for this material was as follows:

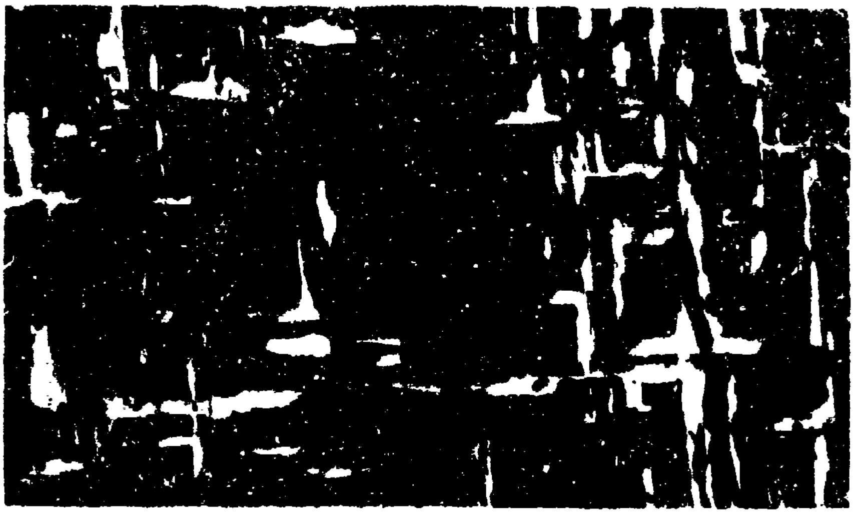
Specification	Heat No. 302493
1350 ± 25°F to 1450 ± 25°F/ 15 minutes to 8 hours/air or furnace cool	1450°F/15 minutes/air cooled (production annealed)

The tensile properties per the applicable specification in comparison with those actually measured by Metcut are summarized on the following page.

5.1.1 Titanium 6Al-4V, Beta Rolled (continued)

Specification	Measured Properties
Thickness: 0.188-2.000 in.	0.25
UTS, psi: 130,000 minimum	144,000*
0.2% Y.S., psi: 120,000 minimum	131,000*
Elongation, % in 4D: 10.0 minimum	12.5*

The applicable specification indicates that the microstructure shall consist of 100% acicular alpha phase when examined under conditions detailed in this specification. The microstructure shown below at 500X magnification, typical of the test material, conforms to this requirement.



The hardness range of Titanium 6Al-4V is not a stated requirement of this Boeing specification. For purposes of record, however, it was determined to be in the range of 31-33 R_c.

5.1.2 AISI 4340, Vacuum Melted

Applicable Specification: AMS 6415F

Source: Republic Steel Corporation, Heat No. 3922805.

The specified melt chemistry of this material, in comparison with the check analysis determined by F. C. Broeman & Company, Cincinnati, Ohio, is indicated on the following page.

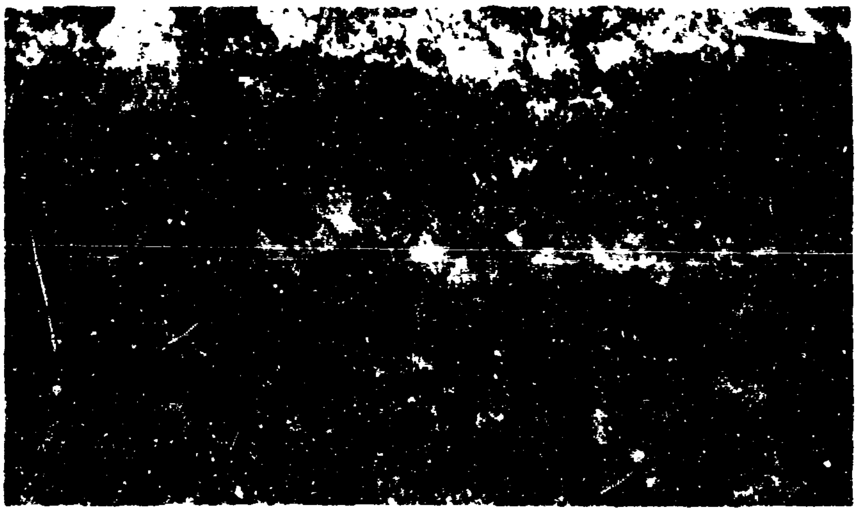
*Values reported are an average of 3 tests.

5.1.2 AISI 4340, Vacuum Melted (continued)

	Specification	Check Analysis
Carbon	0.38 - 0.43	0.42
Manganese	0.65 - 0.85	0.70
Silicon	0.20 - 0.35	0.25
Phosphorous	0.04 max.	0.015
Sulfur	0.04 max.	0.012
Chromium	0.70 - 0.90	0.78
Nickel	1.65 - 2.00	1.79
Molybdenum	0.20 - 0.30	0.27

The grain size as called out by the above specification was for predominantly ASTM 5 or finer with occasional grains as large as 3. The subject heat of material indicated an average grain size of 10.

The applicable specification indicated a maximum surface decarburization of 0.010 in. The subject heat of material, upon sampling the entire cross section of the 1/4 in. plate, indicated a maximum visible decarburization as judged by microstructure of 0.008 in. maximum. A photomicrograph of this microstructure at a magnification of 1000X is shown below:



No mechanical properties requirements were covered in the applicable specification for this alloy; no specific determinations were made on the as-received material.

5.1.3 <u>Inconel 718</u>

Applicable Specification: The General Electric Company, B50TF14-S4, Class A, mill annealed.

Source: Allvac Metals Company, Heat No. 6604.

The melt chemistry of this material as specified, in comparison with the check analysis determined by F. C. Broeman & Company, Cincinnati, Ohio, was as follows:

	Specification	Check Analysis
Carbon	0.02 - 0.08 max.	0.03
Manganese	0.35 max.	0
Silicon	0.35 max.	0.15
Sulfur	0.015 max.	0.007
Phosphorous	0.015 max.	0.01
Chromium	17.00 - 21.00	19.52
Iron	16.50 - 20.50	16.65
Cobalt	1.00 max.	0.35
Molybdenum	2.80 - 3.30	3.03
Columbium + Tantalum	4.75 - 5.50	5.11
Titanium	0.75 - 1.15	1.01
Aluminum	0.30 - 0.70	0.37
Boron	0.006 max.	0.005
Copper	0.30 max.	less than 0.05
Nickel	Remainder	-

The <u>hardness</u> of this material following a 1700-1800°F mill anneal is specified as 100 R_B maximum. The hardness of the subject heat of material was determined to be 93-94 R_B. A part of this G. E. specification involves converting the material from the mill annealed condition (Class A) to the solution treated and aged condition (Class B), and checking certain mechanical properties in the Class B condition. After conversion to the Class B condition the hardness is specified to fall in the range of 38-48 R_c. Following this procedure, the subject heat of material indicated a hardness of 43-44 R_c. The <u>tensile properties</u>, after heat treatment of samples converting them to B50TF14, Class B, are summarized as follows in comparison to the applicable specification:

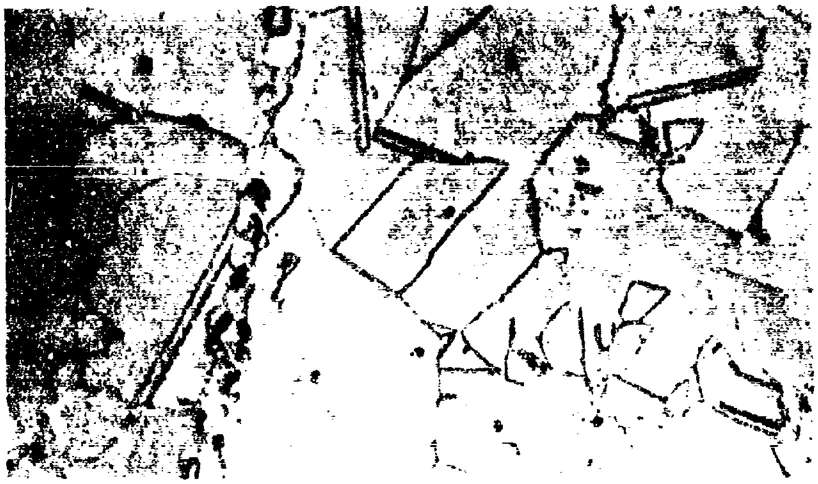
5.1.3 Inconel 718 (continued)

	Specification Minimums		Measured Properties	
	Room Temp.	1200°F	Room Temp.	1200°F
UTS, psi	180,000	140,000	208,000*	166,000*
0.2% Y.S., psi	150,000	120,000	160,000*	131,000*
Elongation, % in 4D	12.0	5	22*	25*

Stress rupture properties after conversion by heat treatment to Class B, and in comparison to the applicable specification, are as summarized below:

	Specification	Measured Properties
Temperature	1200°F	1200°F
Stress, psi	100,000	100,000
Life, hours	20 min.	70 hours removed without failure*

The grain size of the Inconel 718 in the Class A condition is specified as an average of ASTM 5 or finer, with a maximum permissable grain size of ASTM 3. This heat of material was judged as having an average uniform grain size of ASTM 5-6 in the as received condition (Class A), and ASTM 6-10 after conversion by heat treatment to Class B. A photomicrograph of the subject heat of material at 500X in the Class A as received condition is shown below:



*Values reported are an average of 3 tests.

5.2 Manufacture of Specimens

All test materials were procured as 1/4" plate in the conditions described in Section 5.1 of this report. The Ti-6Al-4V was tested in the beta rolled condition in which it was received without further heat treatment. The other two materials were heat treated as follows:

Heat Treatment of AISI 4340

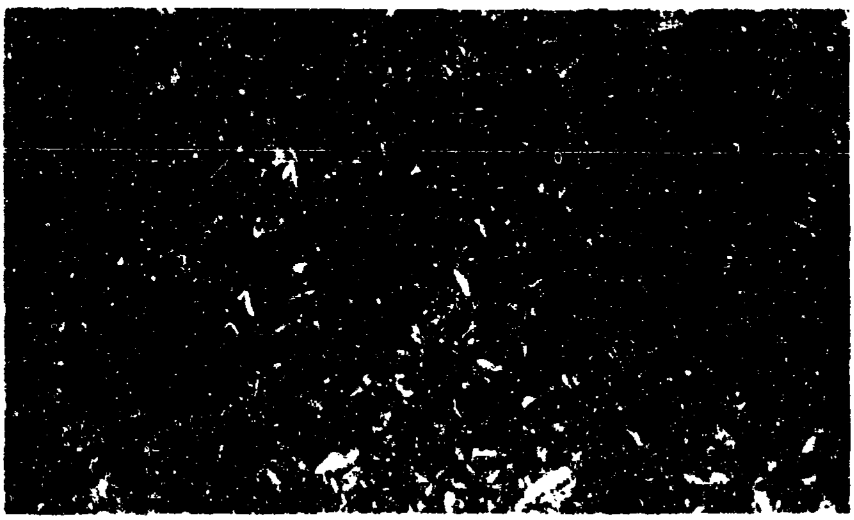
It was desired to work with this alloy in the quenched and tempered condition at a strength level in the 250-270 ksi range. The following heat treatment was used:

Normalize	1600°F/1 hour/air cool
Harden	1550°F/1 hour/oil quench
Temper	550°F/2 hours/air cool

Properties of samples of the AISI 4340 subjected to this heat treatment were measured to be as follows:

UTS:	259,000 psi	0.2% Y.S.:	219,000 psi
R.A.:	46.5%	Elongation:	11.5%
Hardness:	49-51 R_c		

A photomicrograph showing this heat treated condition is presented as follows at a magnification of 1000X:



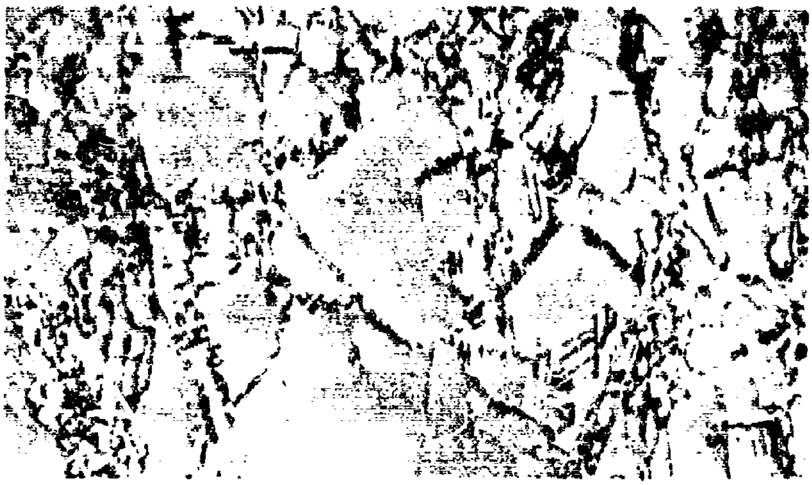
Heat Treatment of Inconel 718

The solutioning and aging treatment selected for use with this alloy coincides with the Class B heat treatment per the applicable G.E. Specification, B50TF14-S4. This heat treatment is as follows:

Solution treatment: 1700°F/1 hour/air cool

Age: 1325°F/8 hours/furnace cool at a rate of 100°F per hour to 1150°F. Hold 8 hours at 1150°F/air cool

The microstructure of Inconel 718 following this heat treatment is shown below at 500X:



The resulting mechanical properties, previously obtained in order to verify conformance of this alloy to the applicable specification, are summarized in Section 5.1.3. Test cuts were made on Inconel 718 in both the 1) solution treated and the 2) solution treated and aged condition. For those residual stress and fatigue samples on which the test cuts were made in the solution treated condition, the specimens were subsequently aged in vacuum at a pressure of approximately 10^{-6} torr prior to further evaluation. Metallographic coupons were examined, however, in the as-machined condition.

5.2 Manufacture of Specimens (continued)

Following heat treatment, specimens were manufactured in accordance with the adjacent figures, as follows:

Residual Stress Specimen, All Materials -	Figure 1
Fatigue Specimen, 4340 and Inconel 718 -	Figure 2
Fatigue Specimen, Titanium -	Figure 3
Stress Corrosion Specimen, Titanium -	Figure 4
Stress Corrosion Specimen, AISI 4340 -	Figure 5

Metallographic specimens were taken from fatigue specimens after failure or from the ends of residual stress specimens whenever available. In certain instances where only metallographic studies were to be made, mechanical test specimens were not prepared. Sketches of these metallographic coupons as well as the details for the manufacture of all of the test specimens used during this program are summarized in Appendix I. An outline of the cutting conditions used for the various test surfaces is contained in Tables I through X.

5.3 Evaluation Procedures

Standard metallurgical procedures were used to evaluate test specimens. All tests were run at room temperature. The types of techniques and equipment used are noted below.

Metallography

Microstructure - standard optical metallograph
Fracture Surface Examination - binocular macroscope, electron microscope using surface replication

Hardness - Rockwell and Knoop

Residual Stress

Surface layer removal technique

Fatigue

Cantilever bending, constant force at 1800-2000 cycles/minute

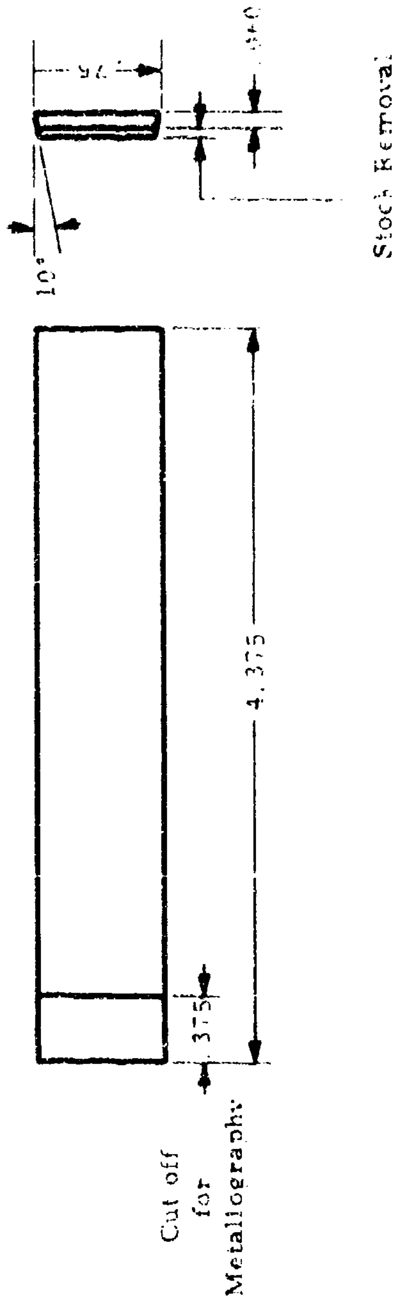
Stress Corrosion, Titanium

Salt coated specimens prestrained at 40 ksi/100 hours/ 800°F followed by room temperature tensile tests

Stress Corrosion, AISI 4340

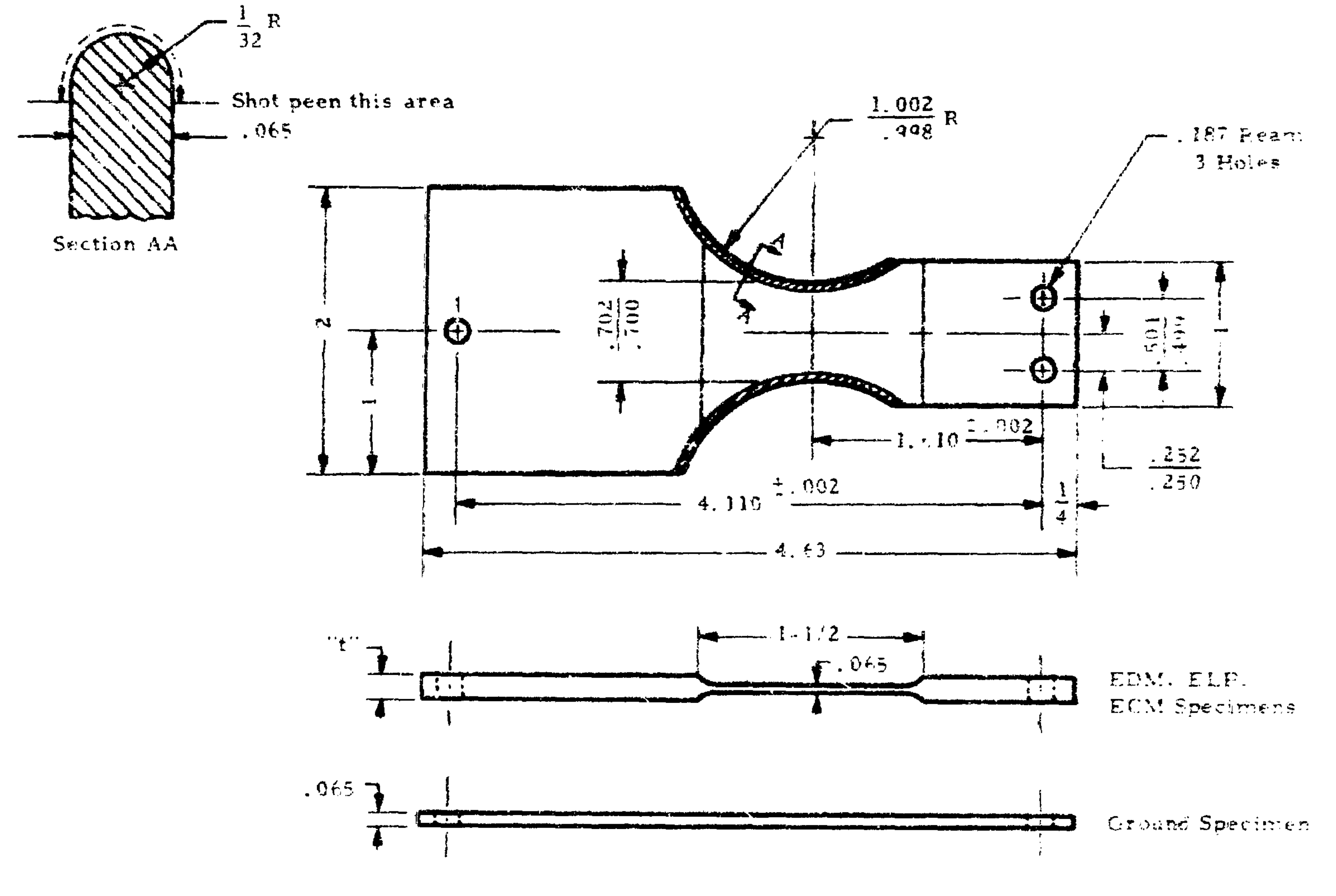
Salt fog exposure of bent beam specimens

Details of all of the test procedures involved are summarized in Appendix II.



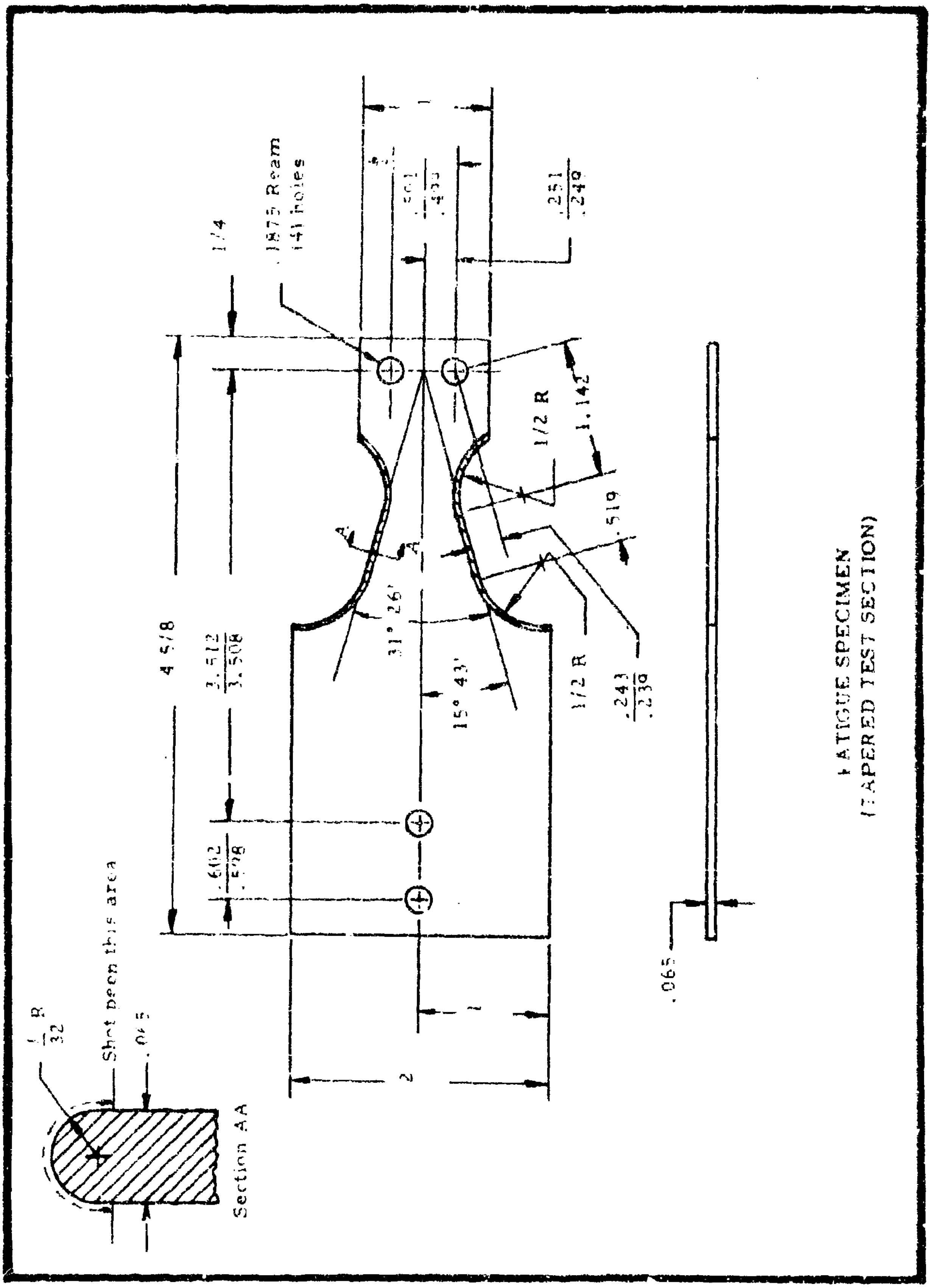
RESIDUAL STRESS SPECIMEN

Figure 1



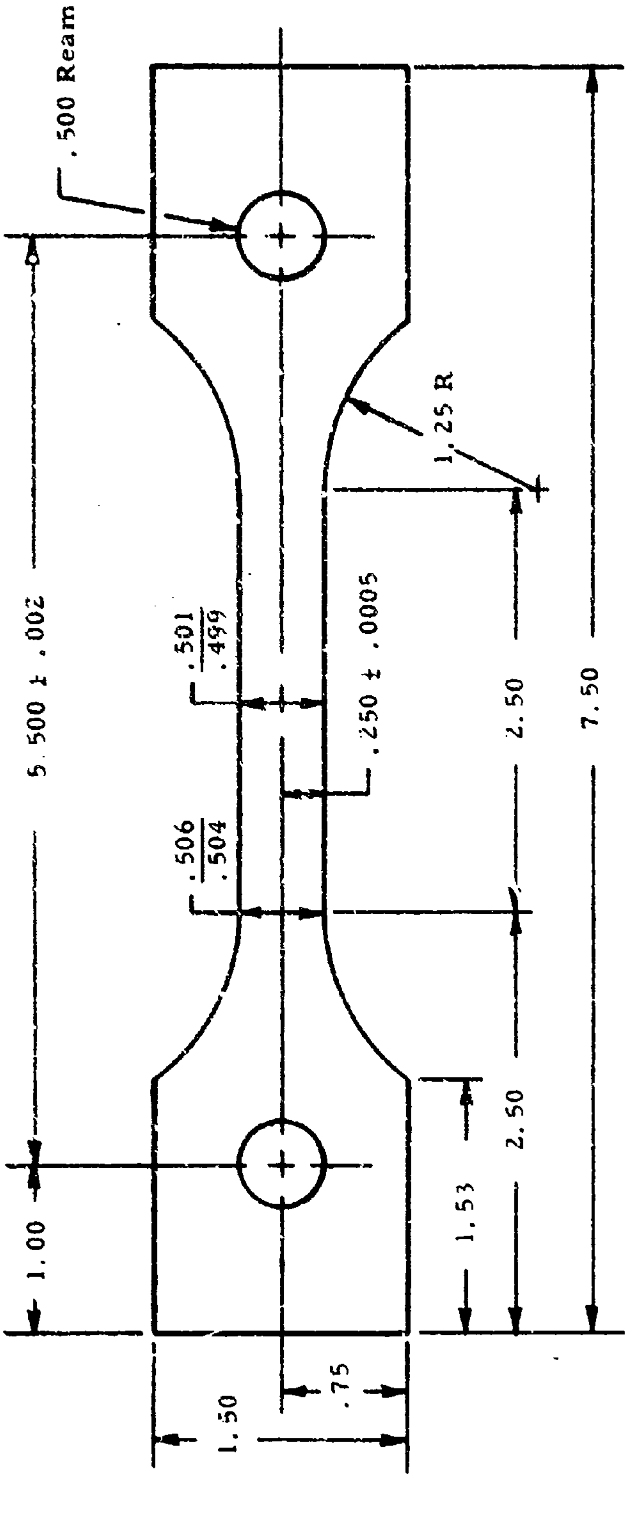
FATIGUE SPECIMEN
(HOURGLASS TEST SECTION)

Figure 2



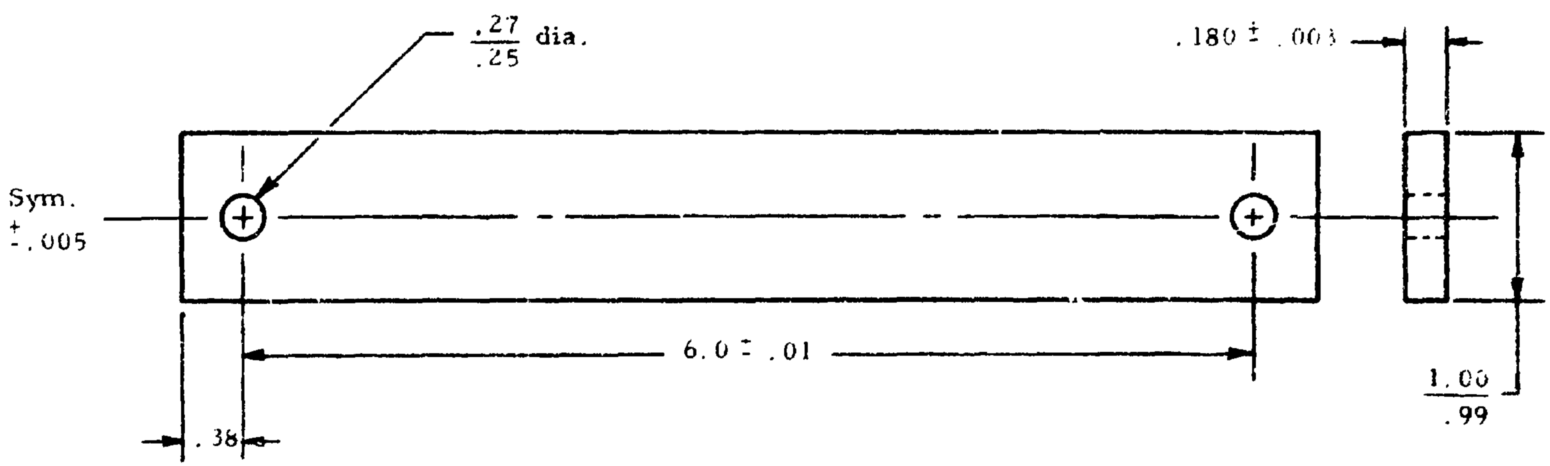
FATIGUE SPECIMEN
(TAPERED TEST SECTION)

Figure 3



STRESS CORROSION SPECIMEN FOR TITANIUM

Figure 4



STRESS CORROSION SPECIMEN FOR AISI 4340

Figure 5

6. SUMMARY OF RESULTS

All of the data developed under this contract for Ti-6Al-4V, AISI 4340, and Inconel 718 are presented graphically in Sections 6.1, 6.2, and 6.3, respectively. Additional correlations which have been made from these data, as well as the introduction of supplementary information available from other sources, are included as Section 6.4. Discussions regarding the significance of these correlations and inferences which may be drawn from them are presented in that section.

Identification of the data obtained under the subject contract has been incorporated into a cross-referencing index. This index, showing the location within this report of the resulting metallurgical data as a function of metal removal conditions is contained on the following page:

6. SUMMARY OF RESULTS (continued)

Material	Operation	Mfg. Procedure (Table)	Metallography (Figure)	Residual Stress (Figure)	Fatigue Summary (Figure)	Stress Corrosion (Figure)
Ti-6Al-4V	Surface Grinding	IV	11	20	29	32
	Hand Grinding	IX	12	21	29	--
	End Milling					
	End Cut	III	13-14	22-24	30	32
	Periph. Cut	III	14-15	25-27	31	32
	Drilling	X	16	--	--	--
	EDM	V	17	--	--	--
	ECM	VI	18	--	--	--
	CHM	VIII	19	28	29	32
4340	Surface Grinding	IV	33	44	48	50
	Hand Grinding	IX	34	46	48	50
	End Milling					
	End Cut	II	35	--	--	--
	Periph. Cut	II	36	--	--	--
	Drilling	X	37	--	--	--
	EDM	V	38	--	--	--
	ECM	VI	39	--	--	--
	CHM	VIII	40	--	--	--
	ELP	VII	41	47	48	50
	Peening	XI	42-43	45	49	50
Inconel 718	Surface Grinding	IV	51-52	69, 75	79	--
	Hand Grinding	IX	53	--	--	--
	End Milling					
	End Cut	II	54	--	--	--
	Periph. Cut	II	55	--	--	--
	Drilling	X	56	--	--	--
	EDM	V	57-58	70, 76	79	--
	ECM	VI	59-60	71, 77	79	--
	CHM	VIII	61-62	--	--	--
	ELP	VII	63	72	79	--
	Peening	XI	64-66	72-74	80	--
	Post Heat Treat		67-68	78	80	--

6. SUMMARY OF RESULTS (continued)

An overview of the response of the three principal test materials to surface integrity variables may be obtained by comparing fatigue and stress corrosion behavior.

Significant fatigue comparisons which may be drawn from available data are shown in Figures 6, 7, and 8. Figure 6 summarizes data obtained from both surface and hand grinding as well as the effects produced by the shot peening of ground surfaces. Specific behavior is discussed in the following sections where each alloy is dealt with separately. Note, however, that abusive grinding conditions almost always cause a significant drop in fatigue strength as compared to gentle grinding conditions. The only exception to this is in the case of hand grinding AISI 4340 where the fatigue strength due to abusive grinding was slightly higher than that exhibited by gentle grinding.

It has long been recognized that abusive grinding applied to martensitic steels results in fatigue damage. This damage has manifested itself either as grinding burn or (in extreme cases) as grinding cracks or checks in the surfaces of hardened steel dies. This grinding damage in steel, in turn, is attributed to the formation of brittle untempered martensite and/or softened overtempered martensite on the steel surface. It is significant to note from the comparisons shown in Figure 6, however, that abusive grinding is detrimental to other classes of materials as well, even though these materials do not exhibit the allotropic change which has been associated with the grinding damage susceptibility of steel.

It is also significant, as indicated in Figure 6, that the use of shot peening as a post-processing operation is quite effective in compensating for fatigue damage that has been caused by abusive grinding conditions. Note the significant elevation in fatigue strength imparted by the shot peening operation. In examining the data presented for gentle versus abusive grinding of 4340 followed by shot peening, it is equally worthy to note that the shot peening of the gently ground sample raised the endurance limit to 112 ksi, while the endurance limit of the abusively ground sample was only raised to 92 ksi (for the same level of shot peening). It can be seen that, even though the shot peening has masked or corrected to some degree the damage associated with abusive grinding, some loss of material strength is still present in spite of the peening operation.

Figure 7 summarizes fatigue strength associated with the 20 different end milling conditions applied to the titanium alloy. These have been grouped by type of cutting and cutter sharpness. In general, the use of a sharp cutter implies "gentle" cutting conditions, while the use of a dull cutter implies the use of "abusive" cutting conditions. Figure 7 indicates that cutter sharpness has little effect on fatigue strength, hence on surface integrity as measured by fatigue strength in end cutting. On the other hand, abusive cutting conditions associated with a dull cutter do result in degradation of fatigue strength during peripheral cutting.

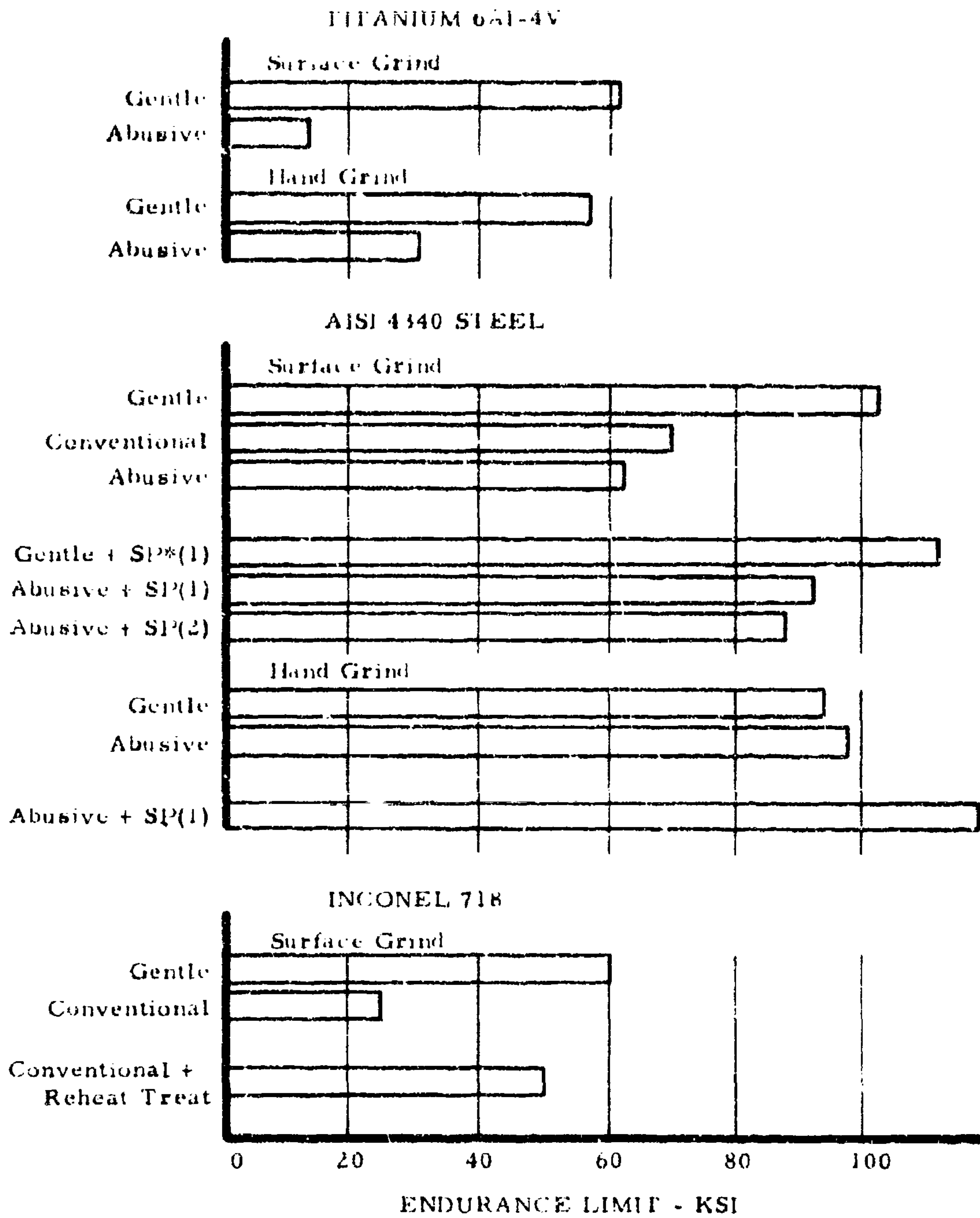
Figure 8 shows various comparisons that can be made on all three test materials as cut by the nonconventional metal removal methods. An examination of these bar chart comparisons shows that gentle versus abusive (or finishing versus roughing) variations of EDM, ECM, and CHM exhibit little or no difference in fatigue strength on these particular materials. It may also be seen that shot peening and glass bead peening as post-processing operations are effective in elevating fatigue strength to a significant degree. As was the case with samples which had been ground before shot peening, however, the fatigue strength level afforded by peening is greater when applied to gently machined materials than when applied to abusively machined materials.

A summary of stress corrosion response as a function of metal removal variables is shown for Ti-6Al-4V in Figure 9 and for AISI 4340 in Figure 10. The bar graphs in Figure 9 show the average tensile ductility exhibited by sheet type tensile specimens both as-machined and after a prestrained exposure while coated with salt. The data for the exposed samples show that all of the tensile ductilities generally range between 2 and 5%. No trend is indicated. The tensile ductility of the as-machined samples, however, shows a trend which may be significant. In particular, milling Conditions 12, 16 and 18 all produced relatively low tensile ductility in the as-machined samples. These conditions would be classed as abusive; they are all of the peripheral cutting type and were accomplished dry with dull tools. This observation is an outcome of the stress corrosion study, but has no relation to stress corrosion sensitivity. It is an indication, however, that in the case of abusive peripheral milling, the tensile ductility of titanium may be significantly reduced.

Figure 10 summarizes stress corrosion results obtained on AISI 4340. Scatter in the data makes it unrealistic to draw firm conclusions from the limited number of samples tested. In most cases, the behavior of each group exhibited a very broad range of life, as indicated by the small open circles. The average lives as indicated by the large closed circles show two interesting trends. Abusively ground surfaces are consistently poor with regard to stress corrosion susceptibility. All of these groups exhibited low average lives of around 200 hours. Shot peening at Level 1 produced a marked improvement in average life when applied to surfaces finished by gentle grinding and abusive grinding. Level 2 shot peening which differed from Level 1 only by a higher hardness of shot (Table XI) in contrast produced a slight decrease in test life on abusively ground samples. It should again be emphasized that the number of tests was small and that even a general trend should not be drawn based on this small group of test specimens. Wide variations in the behavior of the electropolished specimens, particularly in the unpeened condition, suggest that a refinement in this testing technique should be accomplished before additional screening tests are run.

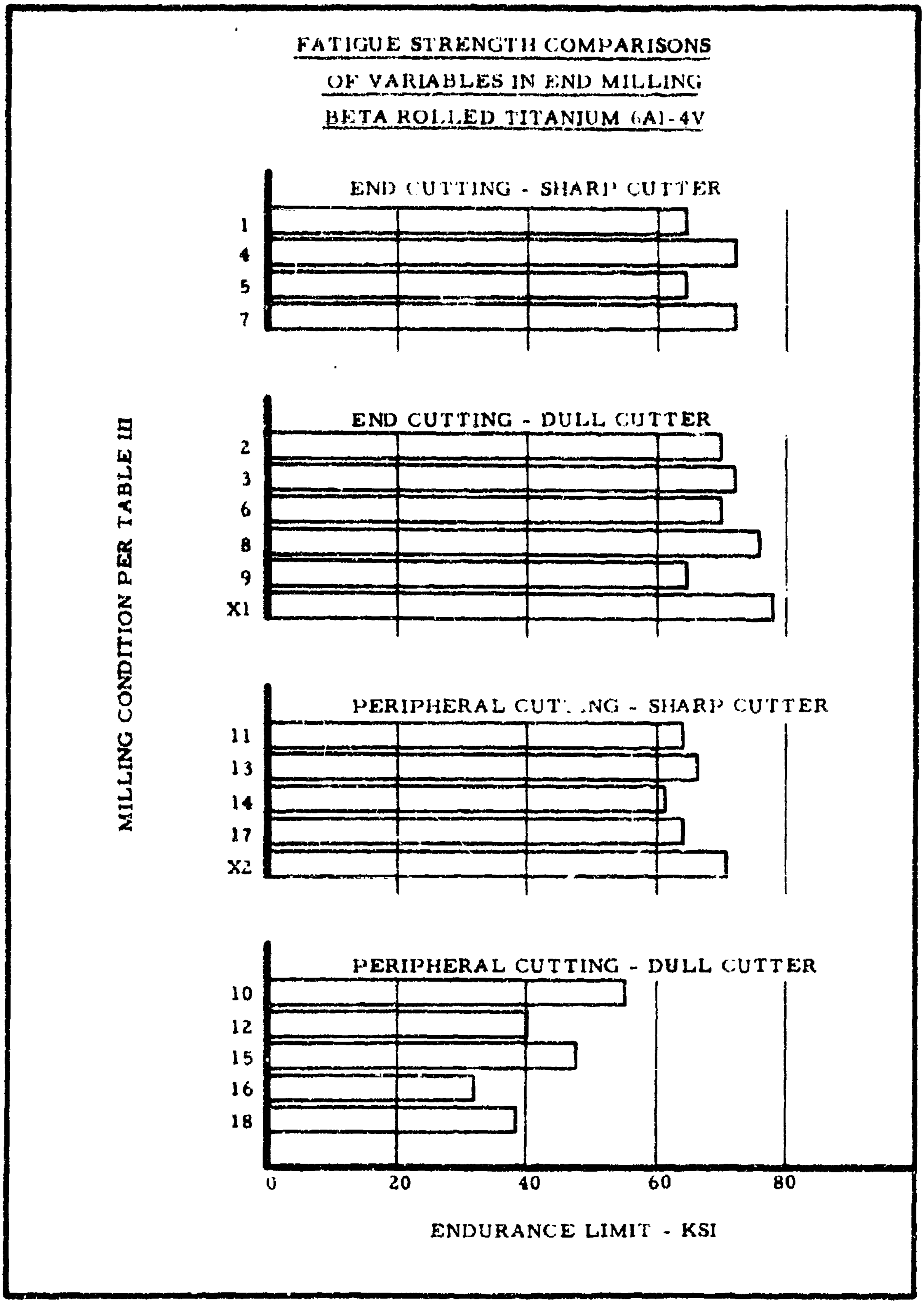
Detailed metallography, residual stress, fatigue and stress corrosion data are presented in the following sections.

FATIGUE STRENGTH COMPARISONS OF VARIABLES IN GRINDING



*SP = Shot Peen; () No. in Parentheses = Shot Peening Level

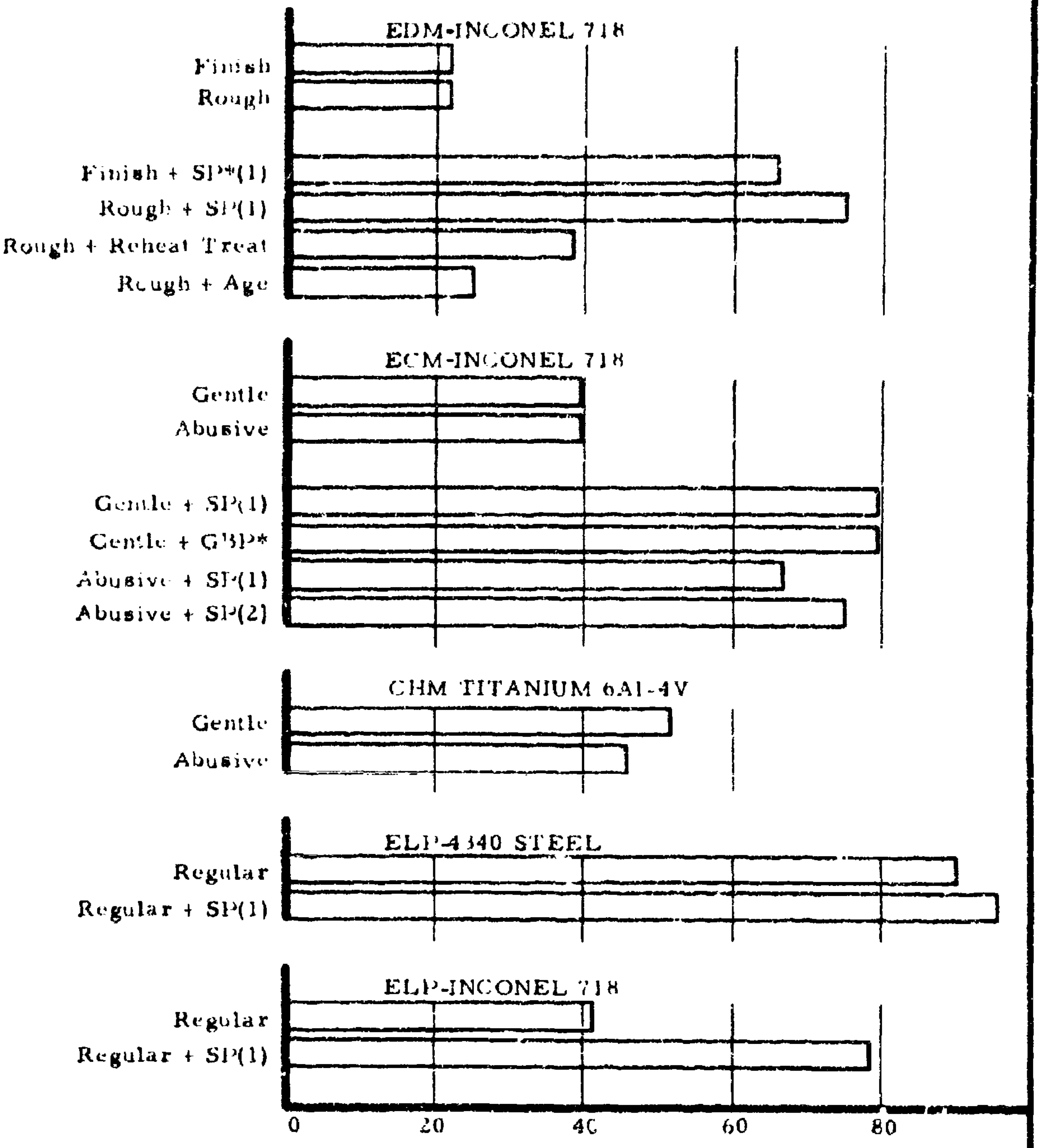
Figure 6



FATIGUE STRENGTH COMPARISONS
OF VARIABLES IN END MILLING
BETA ROLLED TITANIUM 6Al-4V
END CUTTING - SHARP CUTTER
1
4
5
7
END CUTTING - DULL CUTTER
2
3
6
8
9
X1
PERIPHERAL CUTTING - SHARP CUTTER
11
13
14
17
X2
PERIPHERAL CUTTING - DULL CUTTER
10
12
15
16
18
0
20
40
60
80
ENDURANCE LIMIT - KSI
MILLING CONDITION PER TABLE III

Figure 7

FATIGUE STRENGTH COMPARISONS OF VARIABLES IN NON CONVENTIONAL MACHINING PROCESSES



*GBP = Glass Bead Peen
SP = Shot Peen; ( ) No. in Parentheses Shot Peening Level

Figure 8

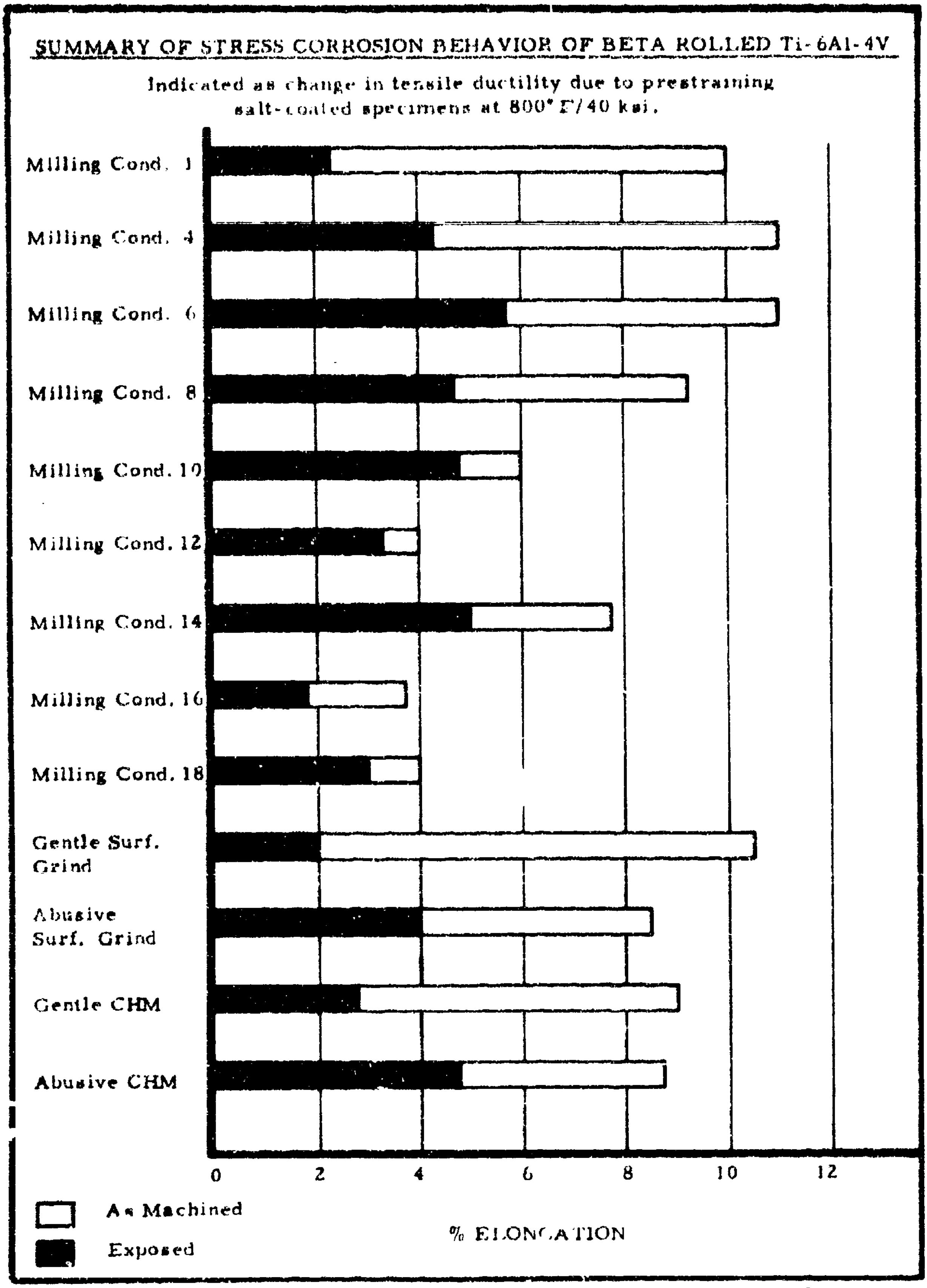
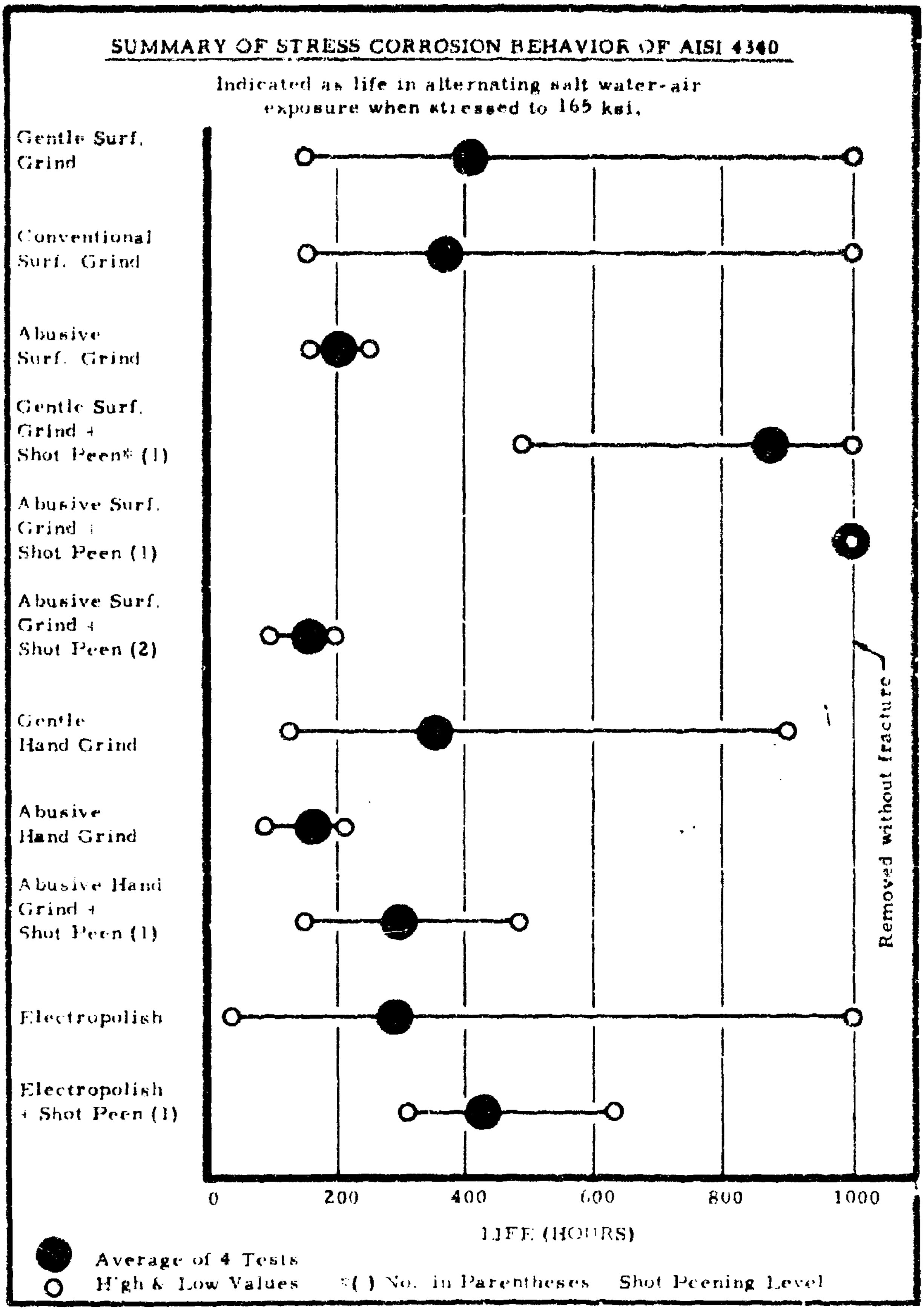

SUMMARY OF STRESS CORROSION BEHAVIOR OF BETA ROLLED Ti-6Al-4V
Indicated as change in tensile ductility due to prestraining salt-coated specimens at 800° F/40 ksi.
Milling Cond. 1
Milling Cond. 4
Milling Cond. 6
Milling Cond. 8
Milling Cond. 10
Milling Cond. 12
Milling Cond. 14
Milling Cond. 16
Milling Cond. 18
Gentle Surf. Grind
Abusive Surf. Grind
Gentle CHM
Abusive CHM
0
2
4
6
8
10
12
As Machined
Exposed
% ELONGATION

Figure 9



SUMMARY OF STRESS CORROSION BEHAVIOR OF AISI 4340
Indicated as life in alternating salt water-air exposure when stressed to 165 ksi.
Gentle Surf. Grind
Conventional Surf. Grind
Abusive Surf. Grind
Gentle Surf. Grind + Shot Peen* (1)
Abusive Surf. Grind + Shot Peen (1)
Abusive Surf. Grind + Shot Peen (2)
Gentle Hand Grind
Abusive Hand Grind
Abusive Hand Grind + Shot Peen (1)
Electropolish
Electropolish + Shot Peen (1)
Removed without fracture
0
200
400
600
800
1000
LIFE (HOURS)
Average of 4 Tests
High & Low Values
*( ) No. in Parentheses Shot Peening Level

Figure 10

6.1 Summary of Results for Titanium 6Al-4V

Metallography

A metallographic review of all of the surface conditions studied for the titanium alloy is presented in Figures 11 through 19. Surfaces exhibited by titanium produced by surface grinding under gentle, conventional, and abusive conditions are shown in Figure 11. Notice in the case of abusive and conventional surface grinding that a degree of plastic deformation or distortion is visible at the surface. Notice also that the microhardness of the extreme surface layer is lower than the base condition, indicating very shallow softening of a few points Rockwell C. This hardness drop is probably due to overaging of the titanium as a result of highly localized surface heating during grinding. The gently ground sample does not exhibit this surface softening. It is likewise free of visible plastic deformation. The hand ground samples as shown in Figure 12 both exhibit small amounts of plastic deformation. They also show evidence of surface softening and similar, relatively rough surface finishes.

Microstructures showing cross sections of surfaces cut by each of 18 different sets of end milling parameters are shown in Figures 13, 14, and 15. Milling conditions 1 through 9 (Figures 13 and 14) illustrate surface conditions produced by end cutting. Milling conditions 10 through 18 (Figures 14 and 15) were produced by peripheral cutting. The specific parameters used for each of these conditions are summarized in Table III.

Various degrees of plastic deformation at the surface can be seen in these photomicrographs. In general, the larger degree of plastic deformation is associated with dull tooling. In reviewing cutting conditions shown in Table III, dull tooling was used under those conditions for which the nominal wearland was indicated as .018 to .020 in. In contrast, a so-called sharp tooling condition was employed where the wearland was specified as .003 in. maximum.

Detailed microhardness studies were run on sections of surfaces produced by all 18 of these milling conditions. No significant or consistent microhardness variation, however, was found to exist for any of the 18 conditions. Since no microhardness variations were observed, it was felt unnecessary to present this information in graphical form.

Cross sections of holes drilled in Ti-6Al-4V are shown in Figure 16. The gently drilled sample shows a minor degree of disturbance at

6.1 Summary of Results for Titanium 6Al-4V (continued)

Metallography (continued)

the surface, although no visible surface hardness change could be detected. The abusively drilled sample, however, shows evidence of extreme surface distortion and heating. The entire area of the sample shown in the photomicrograph has been affected by surface heating as can be readily seen by comparing the two microstructures. Likewise, several layers of highly deformed metal can be seen at and parallel to the surface of the abusively drilled sample. A net hardness increase was observed for this sample, probably associated with the high degree of plastic deformation at the surface.

Photomicrographs of the cross sections of titanium surfaces cut by EDM, ECM, and CHM are shown in Figures 17, 18, and 19. The EDM of titanium (Figure 17) shows the typical recast layer which is most pronounced as a result of cutting under roughing conditions. The relatively high heat input associated with roughing conditions generally causes deeper recast layers as a result of EDM. In this sample, evidence of surface hardening, up to .002 in. deep, is also observed. This phenomenon is also associated with high localized surface heating during abusive EDM.

ECM (Figure 18) typically produces no discernable microstructure or hardness change. The abusive mode, however, causes a marked surface roughening. CHM (Figure 19) also results in no micro-structure distortion but a marked surface roughening under abusive conditions. The CHM surfaces also exhibit surface softening. This latter condition has been observed on many alloys as a result of CHM processing. (See Section 7.3 of this report.)

Residual Stress

A summary of the residual stress data developed on titanium is presented in Figures 20 through 28. Figures 20 and 21 show residual stress distribution resulting from surface grinding and hand grinding, respectively. In all situations, the surface stress is tensile. The level of the tensile stress, however, is approximately 40 ksi in the case of the gently ground samples and approximately 80 ksi in the case of the abusively ground samples. Notice also the greater depth to which the tensile stress field penetrates the surface when abusive grinding is involved, particularly due to surface grinding.

6.1 Summary of Results for Titanium 6Al-4V (continued)

Residual Stress (continued)

The residual stress distribution associated with the 18 different conditions of the statistical program run on titanium is summarized in Figures 22 through 27. In these figures, the residual stress curves are grouped three to a chart. Each set of three curves represents the same cutting speed and feed. Variations within each group are the cutting fluid, wearland, and depth of cut as summarized in Table III.

In reviewing these curves, a consistent trend may be found for the end milling-end cutting conditions, 1 through 9. In the end cutting operation, the use of a sharp cutter, specified as having .003 in. maximum wearland, results in moderate peak tensile stresses at or near the surface of the specimen. End cutting with dull tooling consistently results in peak compressive stresses near the surface. The peripheral cutting conditions, however, are not consistent in this respect.

Residual stress produced in the surface of beta rolled Ti-6Al-4V by CHM under both abusive and gentle conditions is shown in Figure 28. It is significant to note that the peak stress of 40 ksi in tension was found under both of these CHM conditions. It is also significant that this level of residual stress exists as a result of the CHM operation in that nominally CHM has been thought of as a stress-free procedure which results in so-called neutral or zero stress surfaces.

Fatigue

The fatigue behavior of beta rolled Ti-6Al-4V due to variations in grinding and chemical milling are shown in Figure 29. Most significant here is the extreme depression in fatigue strength (from 62 to 13 ksi) caused by an abusive grinding operation. It is interesting to note that gentle hand grinding exhibits an endurance limit of 57 ksi, close to the level associated with gentle surface grinding. The abusive hand grinding depressed the endurance strength to 30 ksi. While this was not as extreme as the depression to 13 ksi associated with abusive surface grinding, it is very logical that the hand held grinding, even though abusive, would be less severe than abusive grinding as imposed under conditions in a rigid machine tool.

6.1 Summary of Results for Titanium 6Al-4V (continued)

Fatigue (continued)

Also indicated in Figure 29 are fatigue curves associated with gentle and abusive CHM. Note that the endurance limits, 51 and 45 ksi, respectively, are quite close together. Notice that this situation exists in spite of a very large difference in surface finish between the gentle and abusive CHM samples, 20 and 165 microinches AA, respectively.

Ten fatigue tests were run on each of 18 sets of milling variables for execution of a statistically designed experiment to evaluate the interplay of these variables. Two additional sets of data were also run for control purposes. A summary of the statistical evaluation of these data is contained in Section 3.4 of this report. Details of the entire statistical procedure are presented in Appendix II-4. This statistical discussion presents endurance limits which were calculated statistically and separately reports standard deviations associated with these endurance limits. The presentation of the fatigue data resulting from tests on these milled samples and summarized in Figures 30 and 31 of this report is based on a conventional plot of the test data In doing so, the fatigue data shown in these figures were determined using the same method as was used for all the other fatigue data presented in this report.

Figure 30 summarizes the fatigue strengths associated with the end milling-end cutting conditions. In comparison with gentle grinding, note that all of the fatigue strengths associated with end cutting fall above the level exhibited by grinding. It is interesting to note that the milling conditions which tend to be "gentle" (i.e., involving a sharp cutter) produce a minimum increase in fatigue strength. For example, the gentle conditions 1 and 5 have endurance limits of approximately 64 ksi. On the other hand, the conditions tending to be abusive, such as 8 and X1, tend to show a more significant increase in fatigue strength to the range of 75 to 77 ksi. Strain hardening associated with the plastic deformation produced by duller tooling may account for this increase in fatigue strength, although a significant increase in surface hardness could not be detected by microhardness measurements.

The fatigue behavior associated with end milling-peripheral cutting is shown in Figure 31. In this case, the gentle peripheral cutting conditions, such as 11, 13, 17 and X2, show relatively high fatigue strengths in the range of 64 to 70 ksi. They essentially are equal to the endurance limit range exhibited by samples finished by gentle end cutting. This fatigue strength range is slightly above the endurance

6.1 Summary of Results for Titanium 6Al-4V (continued)

Fatigue (continued)

limit of 62 ksi associated with gentle grinding. Quite in contrast to behavior exhibited by end cutting, however, the abusive (dull tool) peripheral cutting conditions caused very substantial depressions in fatigue strength. Conditions 16 and 18 showed endurance limits in the range of 32 to 38 ksi.

In comparing end cutting with peripheral cutting, it may be seen that, in end cutting, abusive conditions tend to elevate the fatigue strength. On the other hand, in peripheral cutting, abusive conditions cause a rather pronounced depression in the fatigue strength. Both end cutting and peripheral cutting done under gentle conditions using sharp tooling have approximately the same fatigue characteristics as samples finished by gentle grinding. The reason for the inversion in behavior between abusive end cutting and abusive peripheral cutting has not been determined.

Stress Corrosion

The stress corrosion effects on Ti-6Al-4V were evaluated by studying changes in tensile ductility caused by prestraining salt coated specimens for 100 hours at 800°F/40 ksi. This procedure had been previously developed as suitable for measuring the relative stress corrosion sensitivity of this material. By previously developed standards, a material in a particular condition was considered to be sensitive if the samples tested after the prestraining exposure exhibited a pronounced loss in ductility. Typically, a pronounced loss would be indicated as an elongation of 1 or 2% as compared to 10-12% prior to exposure.

As may be seen in Figure 32, the performance of individual specimens varied widely. A review of the data indicates that no particular conclusions can be drawn with regard to the effects of the salt exposure.

One definite trend is indicated by the data, however. Note that milling conditions 12, 16 and 18 exhibit particularly low tensile ductility (average 4%) in the as-machined condition. These three milling conditions happen to represent abusive peripheral cutting. All three were accomplished dry and with dull tools. While not related to stress corrosion behavior, it is significant to note that an abusive cutting operation of this type can cause a significant drop in tensile

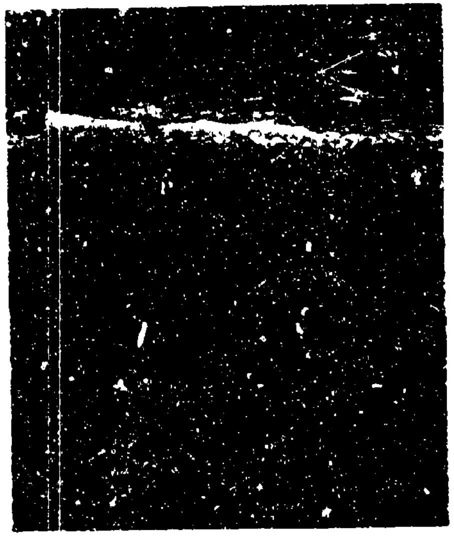
6.1 Summary of Results for Titanium 6Al-4V (continued)

Stress Corrosion (continued)

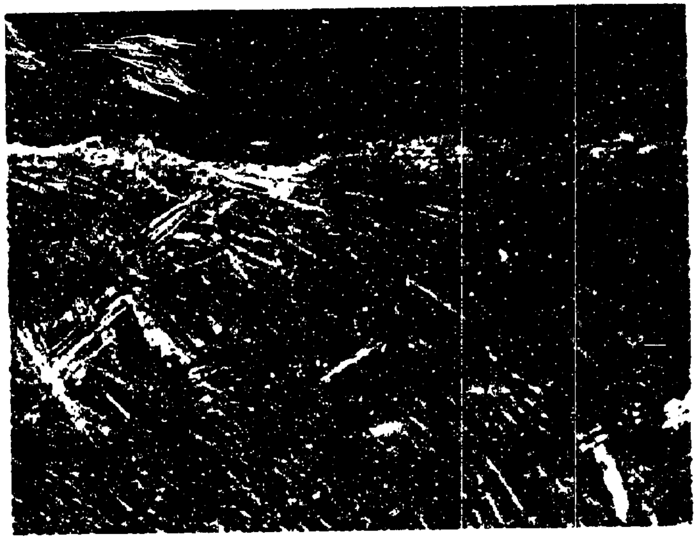
ductility of as-machined titanium. The same three conditions also exhibited the lowest fatigue values obtained for this alloy as shown in Figure 31.

A description of the stress corrosion testing procedure is contained in Appendix II-5. All of the resulting test data on Ti-6Al-4V is summarized in Table XVI.

(a) Gentle Conditions



(b) Conventional Conditions

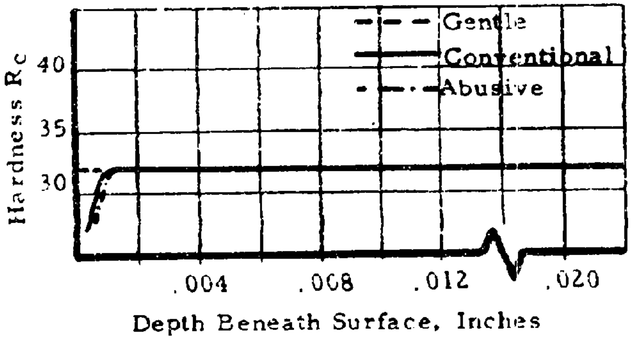


(c) Abusive Conditions

Gentle grinding produced no visible microstructure hardness, although some degree of surface roughness is evident. Conventional and abusive grinding shows evidence of plastic deformation at the surface plus some tendency toward tearing. Both conventional and abusive grinding produced surface softening due to localized surface heating. Gentle grinding did not show this effect.

Surface Finish: 35AA | Surface Finish: 45AA | Surface Finish: 65AA

1000X



SURFACE CHARACTERISTICS OF
TITANIUM 6Al-4V (Beta Rolled, 32 R_c)
PRODUCED BY GRINDING

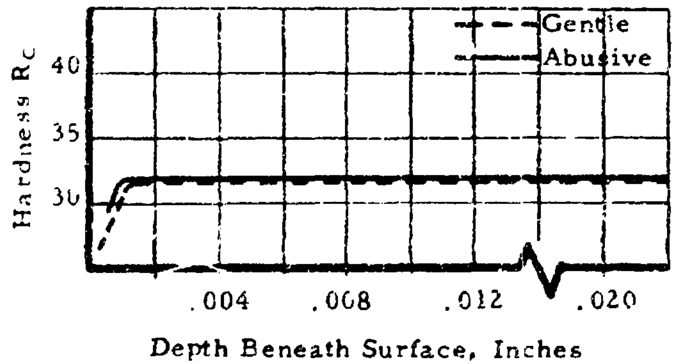
Figure 11

(a) Gentle Conditions - No visible or measurable surface distortion, but relatively rough surface.
Surface Finish: 80AA

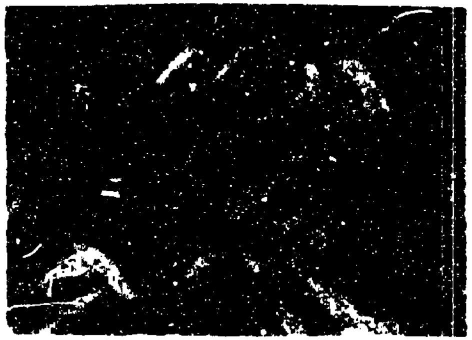
1000X

(b) Abusive Conditions - Similar in appearance and hardness variation to surface produced by gentle hand grinding.
Surface Finish: 80AA

1000X

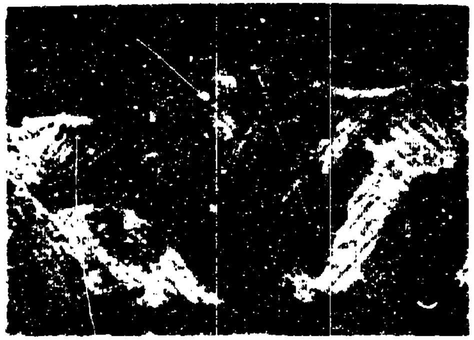


SURFACE CHARACTERISTICS OF
TITANIUM 6Al-4V (Beta Rolled, 32 R_c)
PRODUCED BY HAND GRINDING



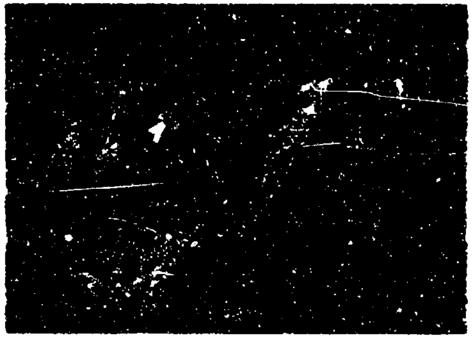
End Cutting - Condition 1
Surface Finish: 74AA

End Cutting - Condition 2
Surface Finish: 53AA

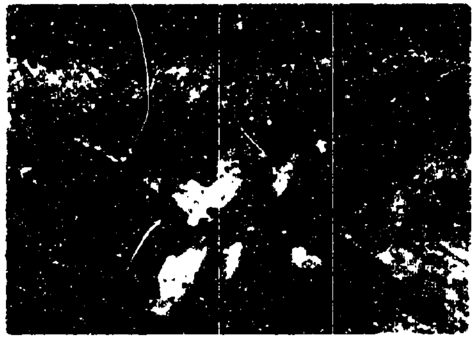


End Cutting - Condition 3
Surface Finish: 82AA

End Cutting - Condition 4
Surface Finish: 57AA



End Cutting - Condition 5
Surface Finish: 67AA



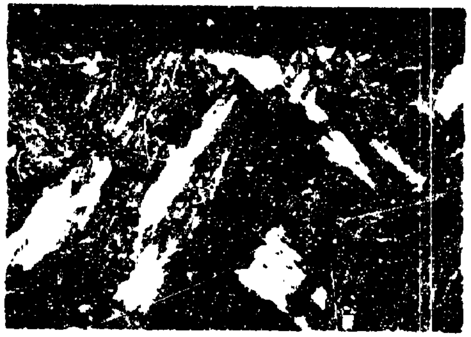
End Cutting - Condition 6
Surface Finish: 42AA

SURFACE MICROSTRUCTURES OF TITANIUM 6Al-4V (Beta Rolled, 32 R_c)
PRODUCED BY A VARIETY OF END MILLING CONDITIONS*

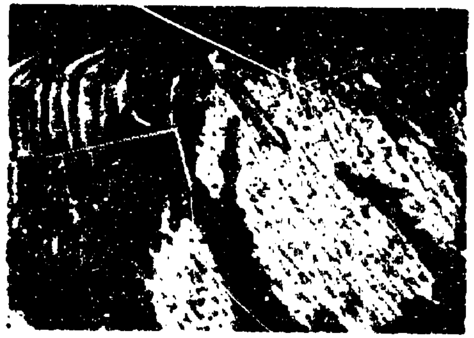
1000X

* See Table III for summary of conditions

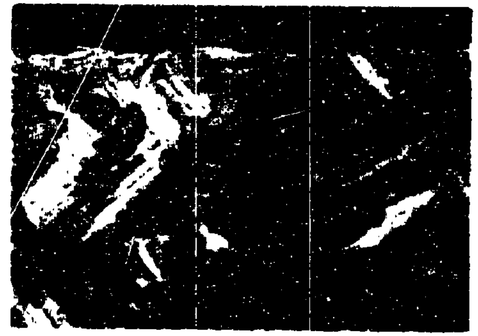
Figure 13



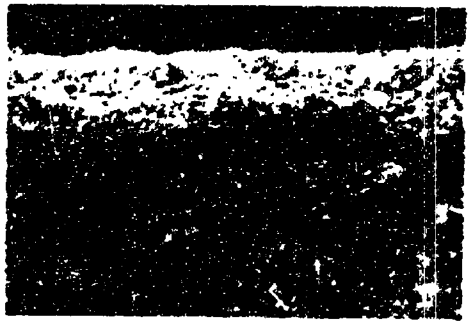
End Cutting - Condition 7
Surface Finish: 66AA



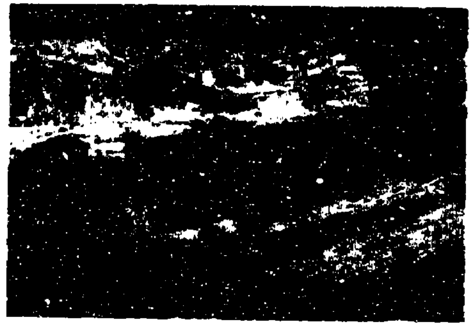
End Cutting - Condition 8
Surface Finish: 87AA



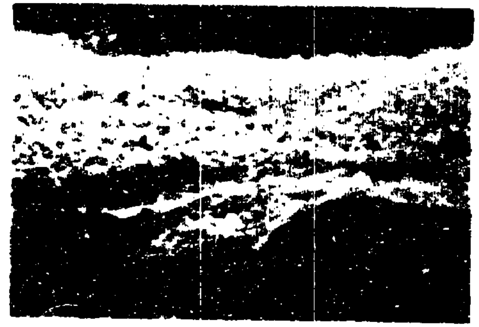
End Cutting - Condition 9
Surface Finish: 56AA



Peripheral Cutting - Condition 10
Surface Finish: 35AA



Peripheral Cutting - Condition 11
Surface Finish: 22AA



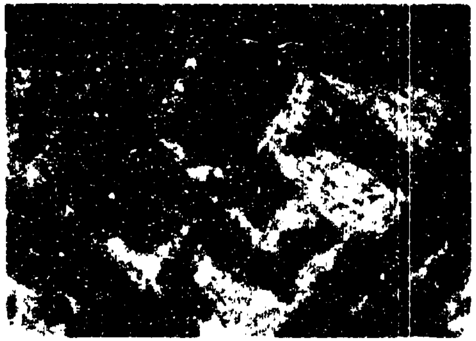
Peripheral Cutting - Condition 12
Surface Finish: 43AA

SURFACE MICROSTRUCTURES OF TITANIUM 6Al-4V (Beta Rolled, 32 R_c)
PRODUCED BY A VARIETY OF END MILLING CONDITIONS*

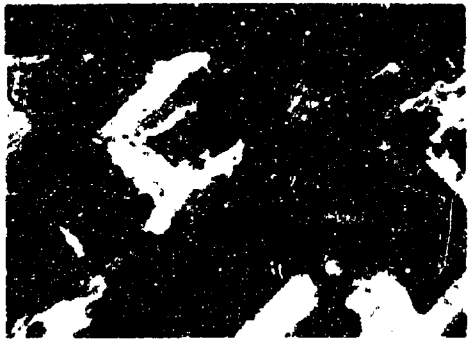
1000X

* See Table III for summary of conditions

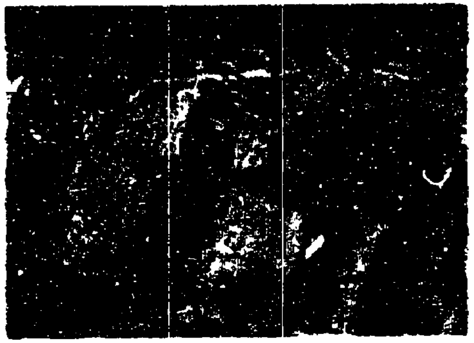
Figure 14



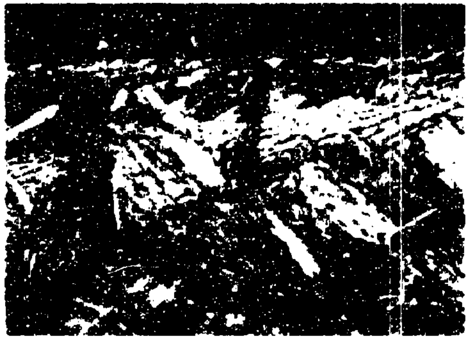
Peripheral Cutting - Condition 13
Surface Finish: 41AA



Peripheral Cutting - Condition 14
Surface Finish: 40AA



Peripheral Cutting - Condition 15
Surface Finish: 45AA



Peripheral Cutting - Condition 16
Surface Finish: 59AA

Peripheral Cutting - Condition 17
Surface Finish: 41AA

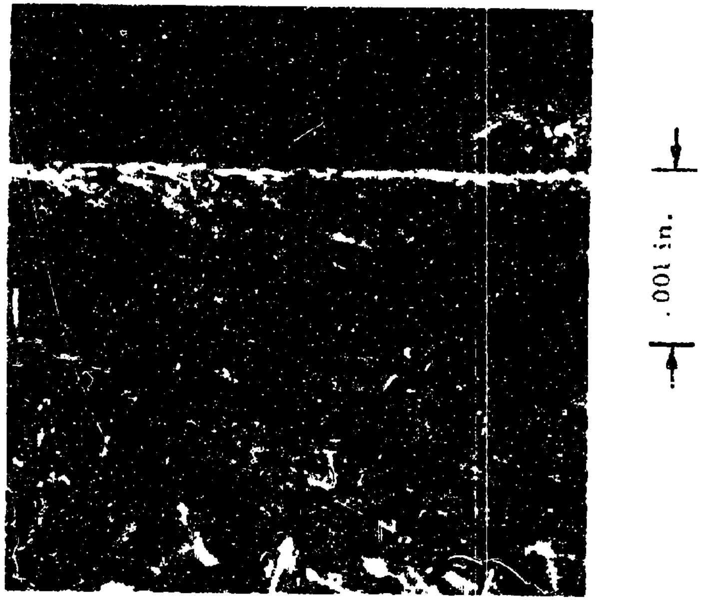
Peripheral Cutting - Condition 18
Surface Finish: 63AA

SURFACE MICROSTRUCTURES OF TITANIUM 6Al-4V (Beta Rolled, 32 R_c)
PRODUCED BY A VARIETY OF END MILLING CONDITIONS*

1000X

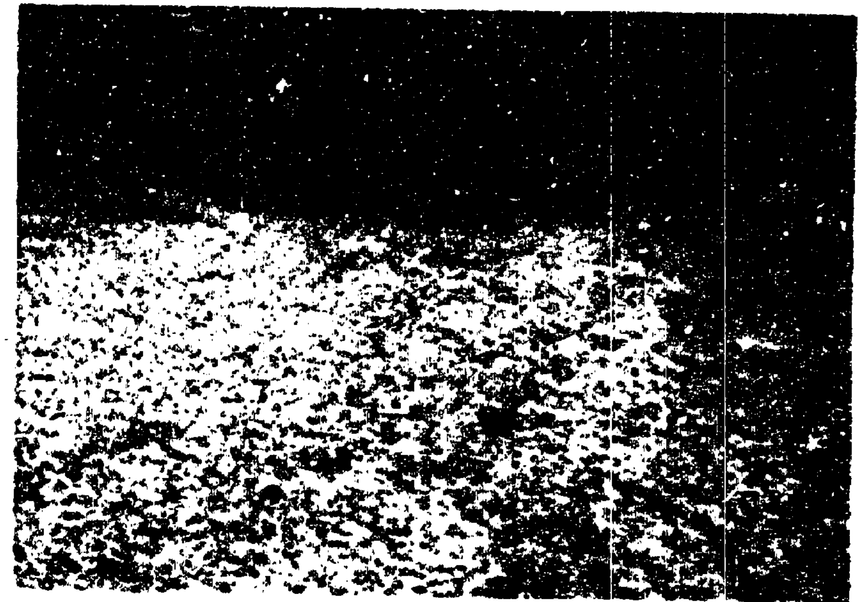
* See Table III for summary of conditions

Figure 15



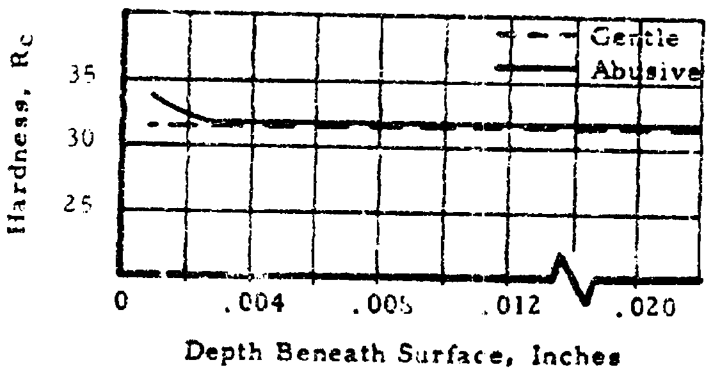
(a) Gentle Conditions - Minor visible surface distortion, but without measurable hardness change.

1000X



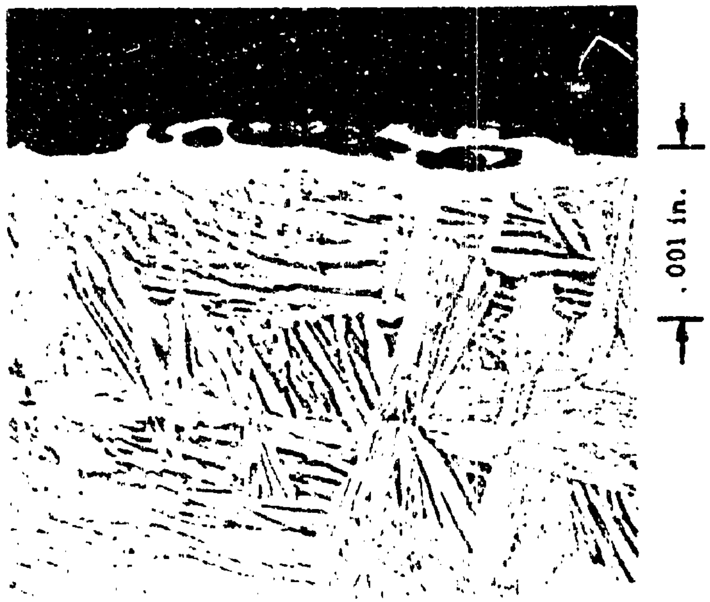
(b) Abusive Conditions - Extreme surface distortion and evidence of heating. Heat effected structure existed to depth of .004".

1000X



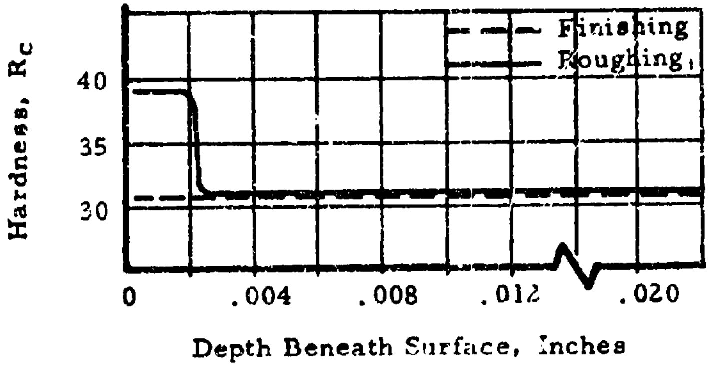
SURFACE CHARACTERISTICS OF
TITANIUM 6Al-4V (Beta Rolled, 32 R_c)
PRODUCED BY DRILLING

Figure 16



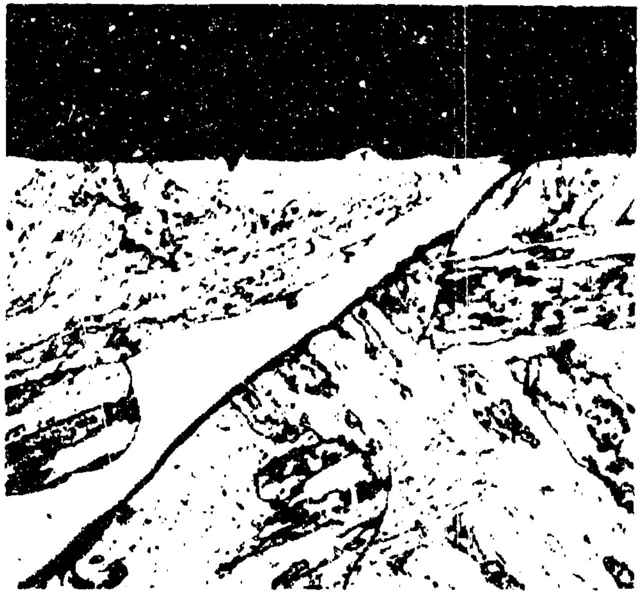
(a) Finishing Conditions - A slight recast layer is evident but without measurable hardness change.
Surface Finish: 90 AA 1000X

(b) Roughing Conditions - Slight recast layer plus hardness increase approximately .002" deep due to localized surface heating.
Surface Finish: 180 AA 1000X



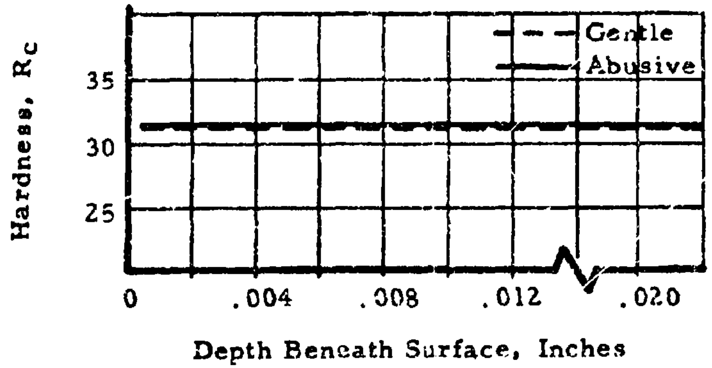
SURFACE CHARACTERISTICS OF
TITANIUM 6Al-4V (Beta Rolled, 32 R_c)
PRODUCED BY EDM

Figure 17



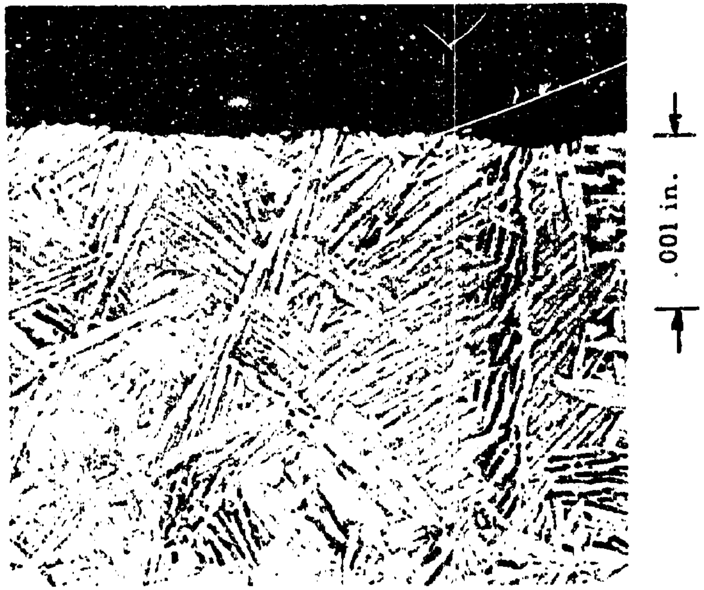
(a) Gentle Conditions - Slight surface irregularity but without other measurable effects.
Surface Finish: 18 AA 1000X

(b) Abusive Conditions - Significant surface roughness but without measurable hardness change.
Surface Finish: 205 AA 1000X



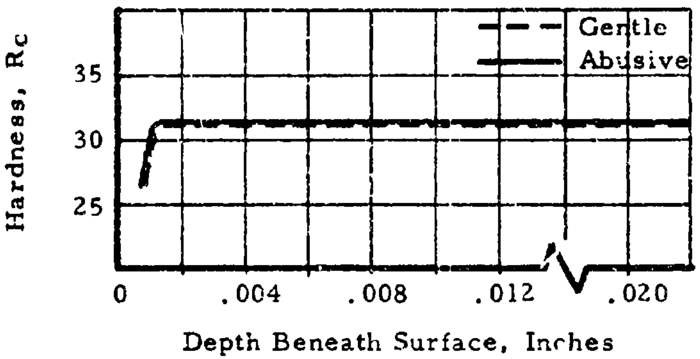
SURFACE CHARACTERISTICS OF
TITANIUM 6Al-4V (Beta Rolled, 32 R_c)
PRODUCED BY ECM

Figure 18



(a) Gentle Conditions - No visible surface distortion but with hardness loss approximating 5 points R_c.
Surface Finish: 20 AA 1000X

(b) Abusive Conditions - Significant surface roughening also exhibiting hardness loss of 5 points R_c.
Surface Finish: 165 AA 1000X



SURFACE CHARACTERISTICS OF
TITANIUM 6Al-4V (Beta Rolled, 32 R_c)
PRODUCED BY CHM

Figure 19

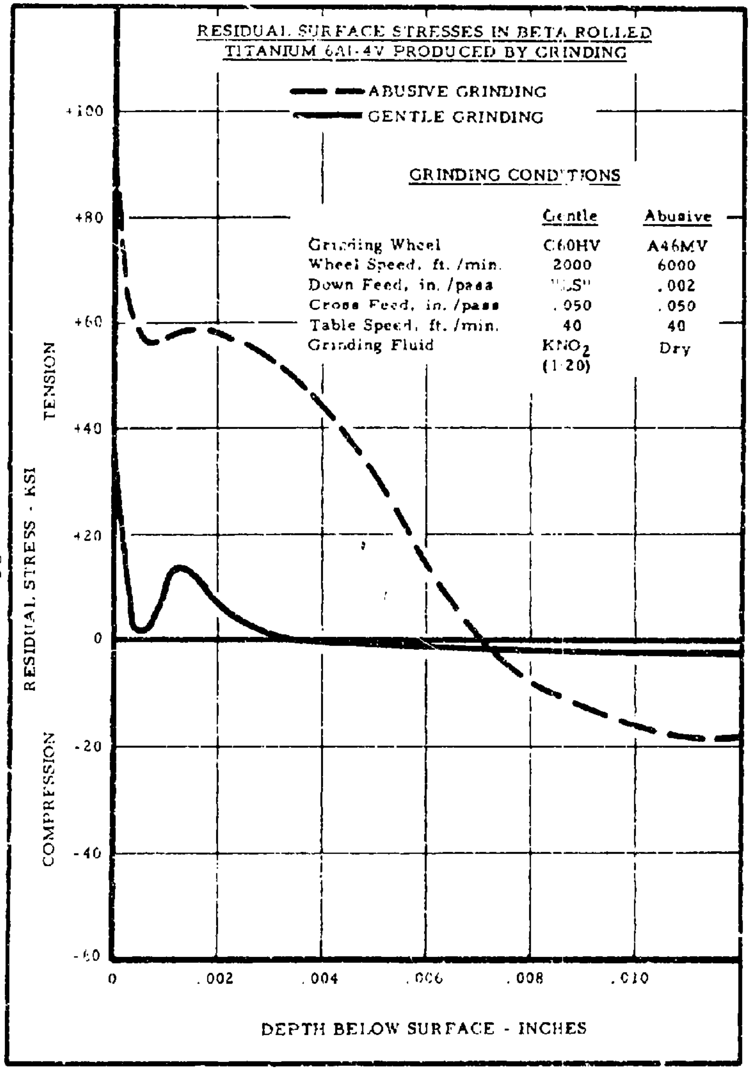


Figure 20

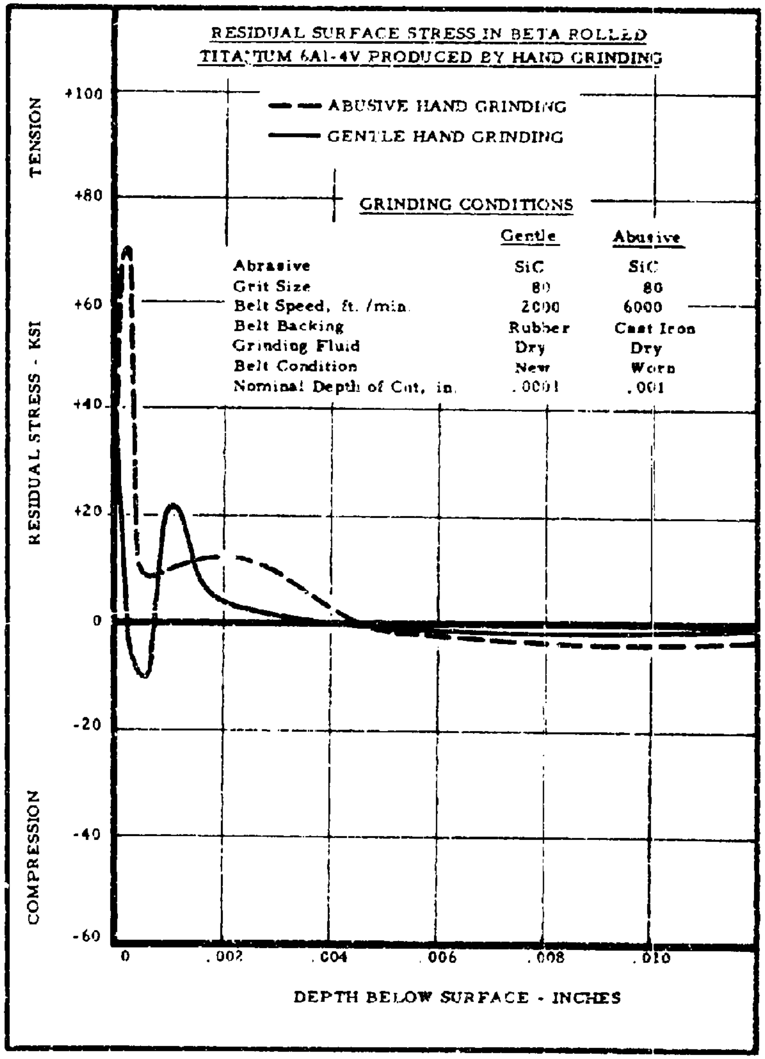
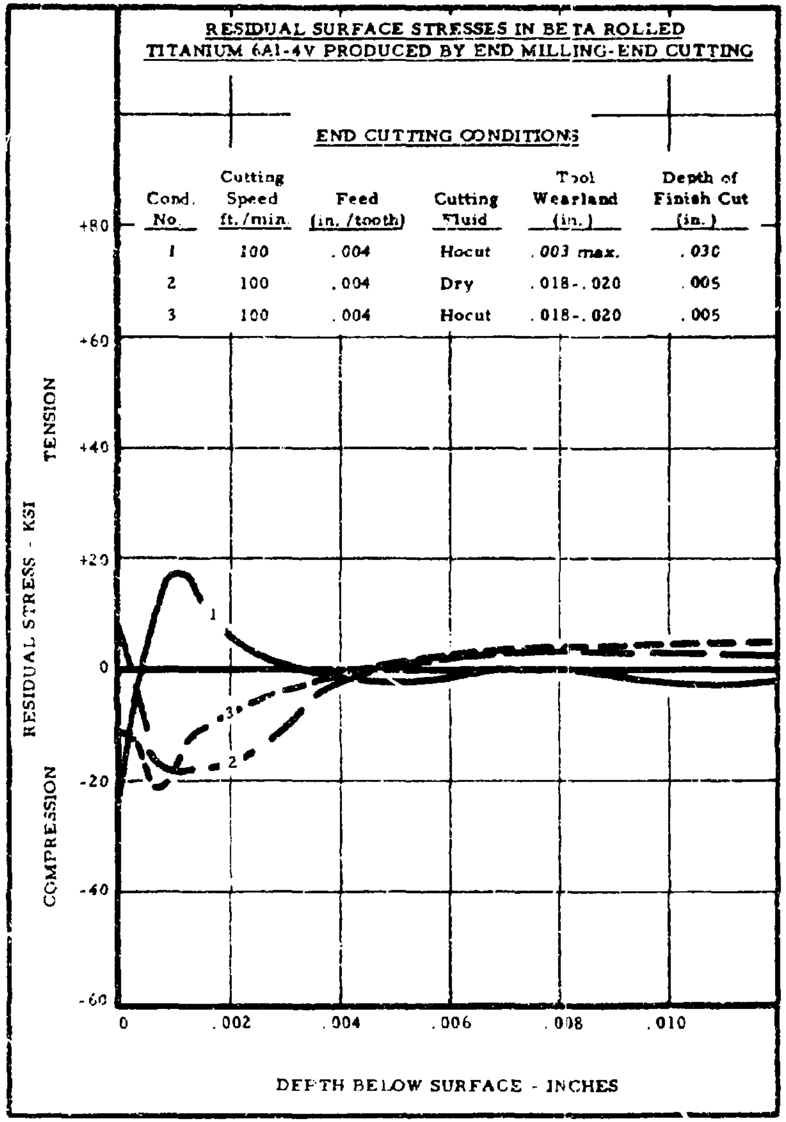
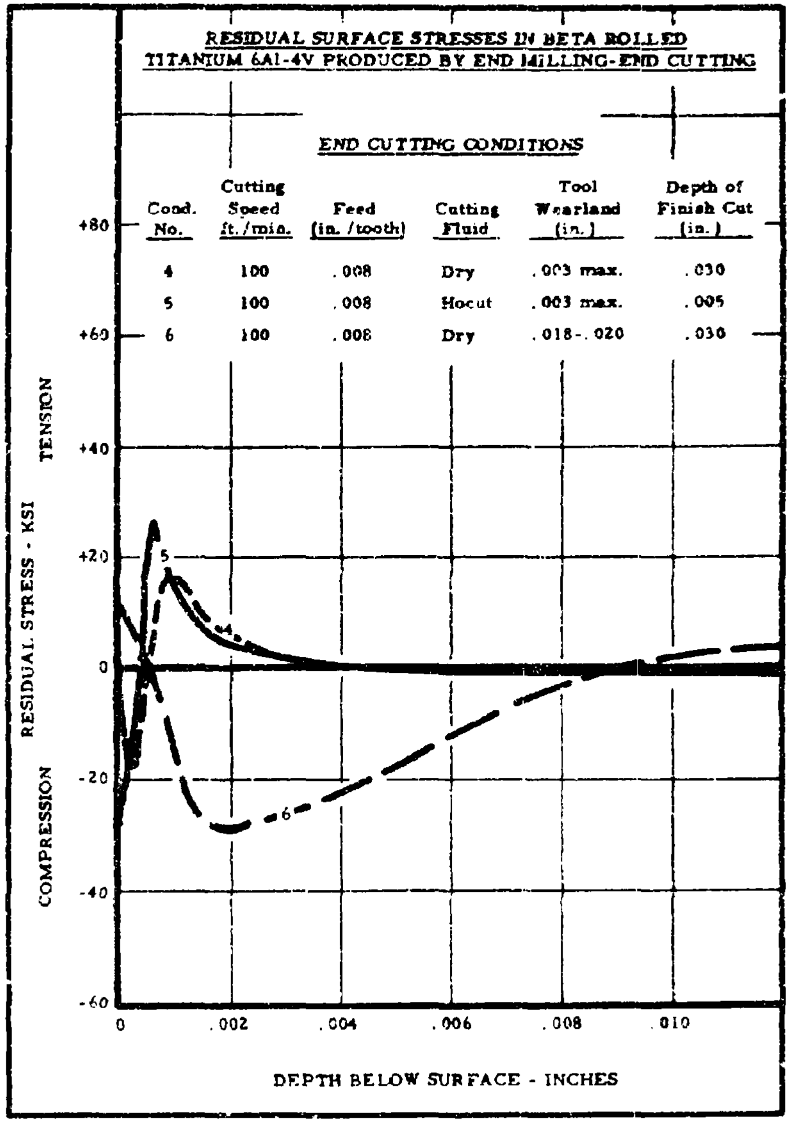


Figure 21



Cond. No.	Cutting Speed ft./min.	Feed (in./tooth)	Cutting Fluid	Tool Wearland (in.)	Depth of Finish Cut (in.)
1	100	.004	Hocut	.003 max.	.030
2	100	.004	Dry	.018-.020	.005
3	100	.004	Hocut	.018-.020	.005

Figure 22



Cond. No.	Cutting Speed ft./min.	Feed (in./tooth)	Cutting Fluid	Tool Wearland (in.)	Depth of Finish Cut (in.)
4	100	.008	Dry	.003 max.	.030
5	100	.008	Hocut	.003 max.	.005
6	100	.008	Dry	.018-.020	.030

Figure 23

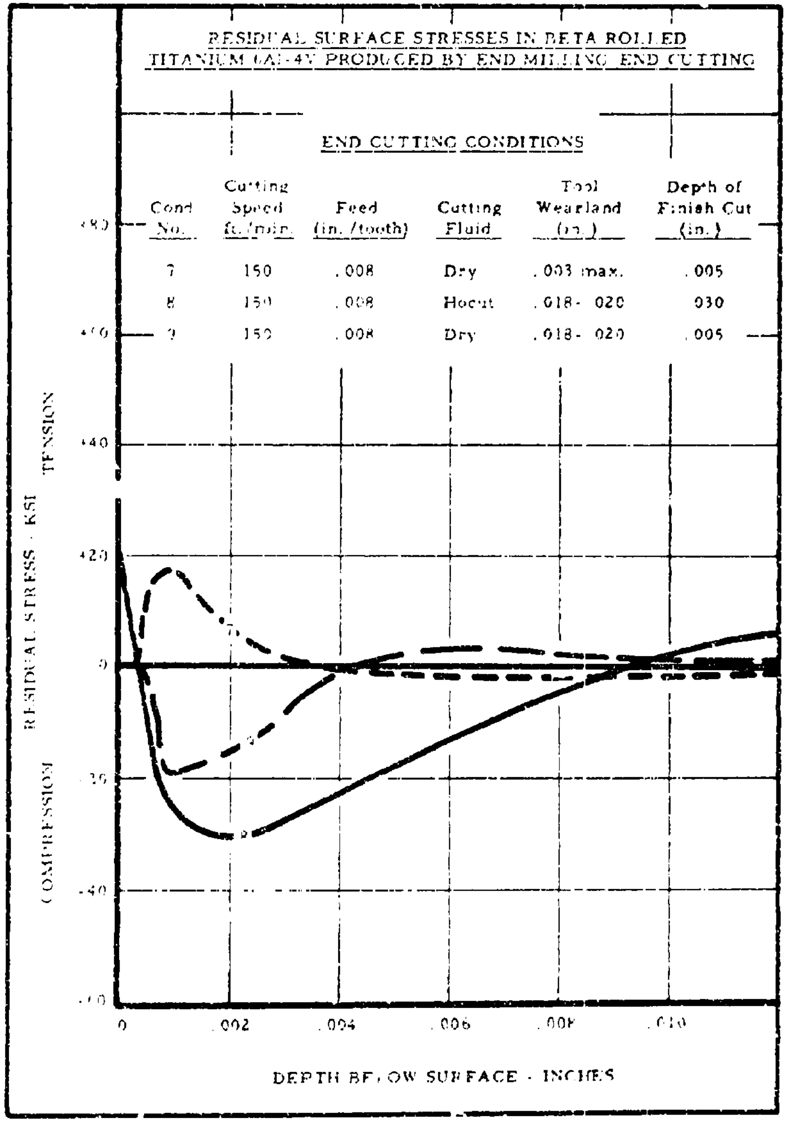


Figure 24

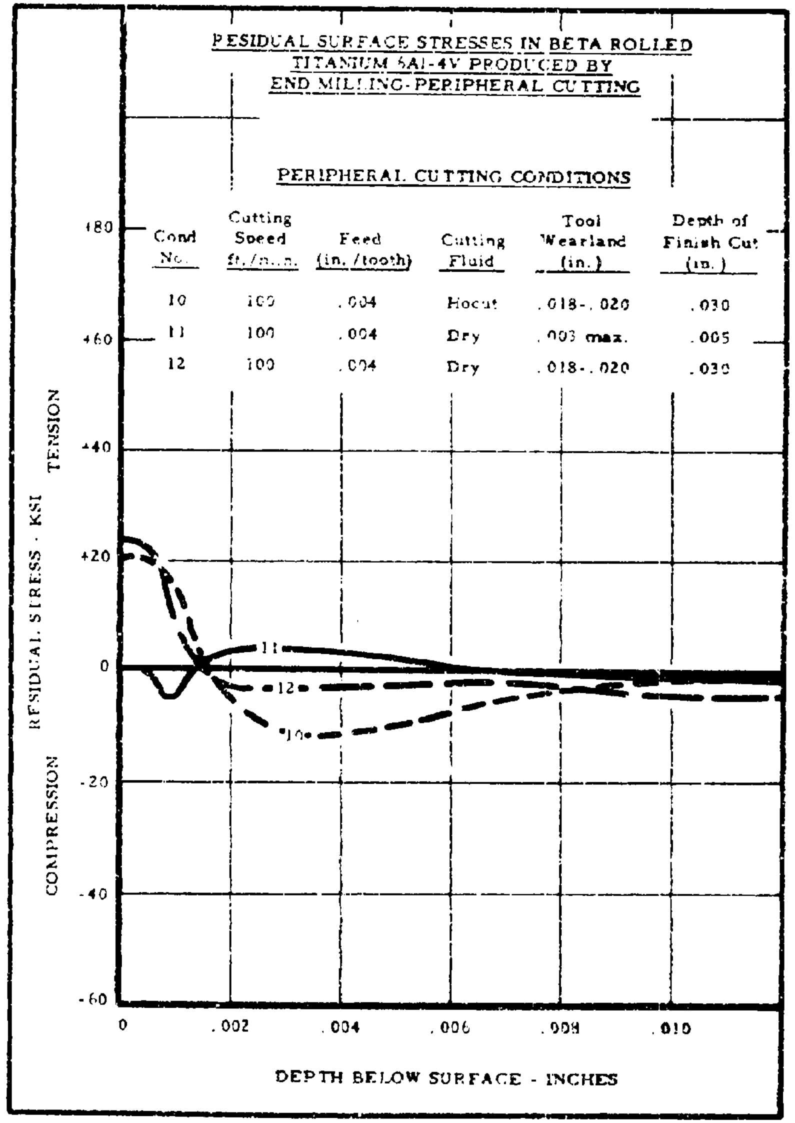


Figure 25

RESIDUAL SURFACE STRESSES IN BETA ROLLED TITANIUM 6Al-4V PRODUCED BY END MILLING-PERIPHERAL CUTTING

PERIPHERAL CUTTING CONDITIONS

Cond. No.	Cutting Speed ft./min.	Feed (in./tooth)	Cutting Fluid	Tool Wearland (in.)	Depth of Finish Cut (in.)
13	100	.008	Hocut	.003 max.	.005
14	100	.008	Dry	.003 max.	.030
15	100	.008	Hocut	.018-.020	.005

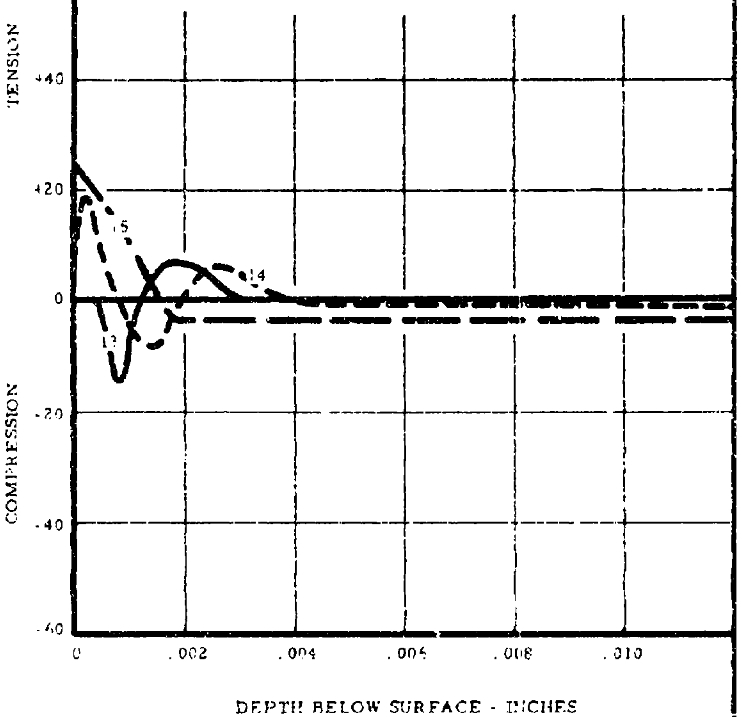


Figure 26

RESIDUAL SURFACE STRESSES IN BETA ROLLED TITANIUM 6Al-4V PRODUCED BY END MILLING-PERIPHERAL CUTTING

PERIPHERAL CUTTING CONDITIONS

Cond. No.	Cutting Speed ft./min.	Feed (in./tooth)	Cutting Fluid	Tool Wearland (in.)	Depth of Finish Cut (in.)
16	150	.008	Dry	.018-.020	.030
17	150	.008	Hocut	.003 max.	.005
18	150	.008	Hocut	.018-.020	.030

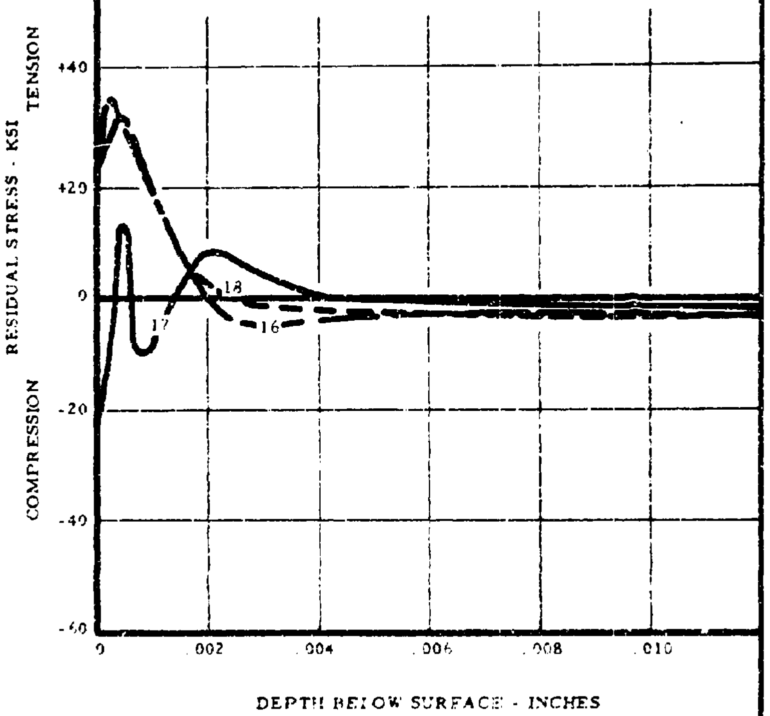


Figure 27

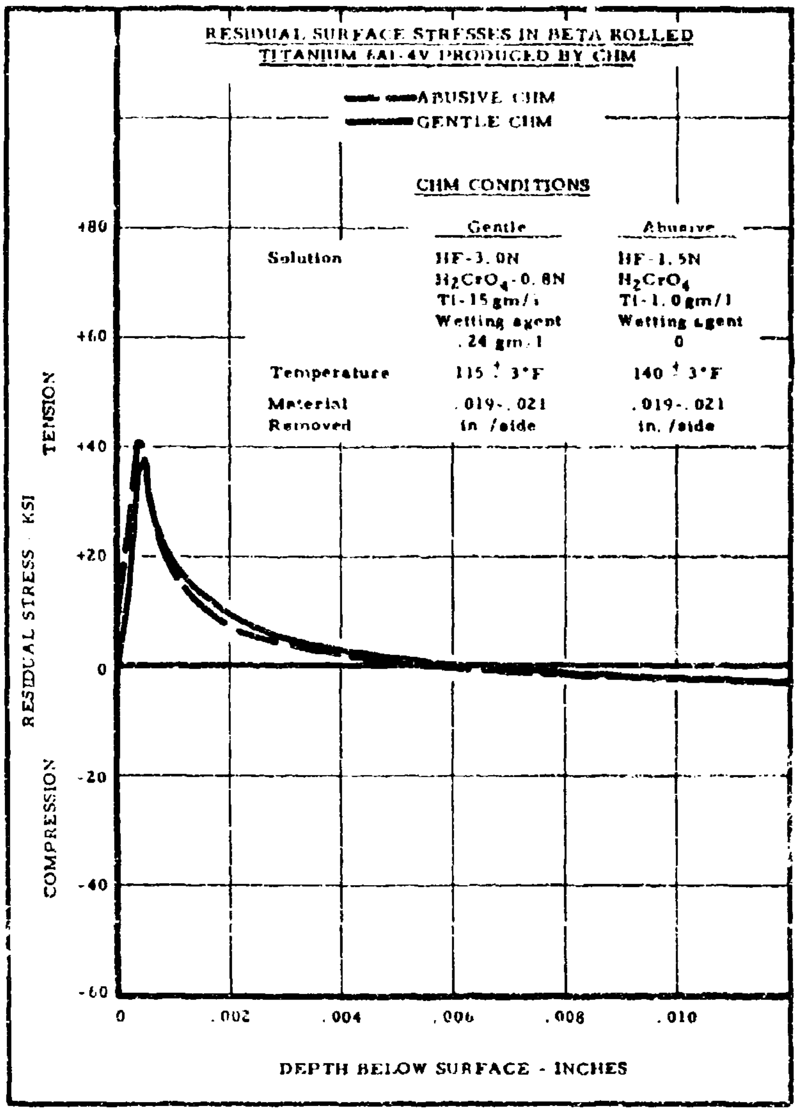
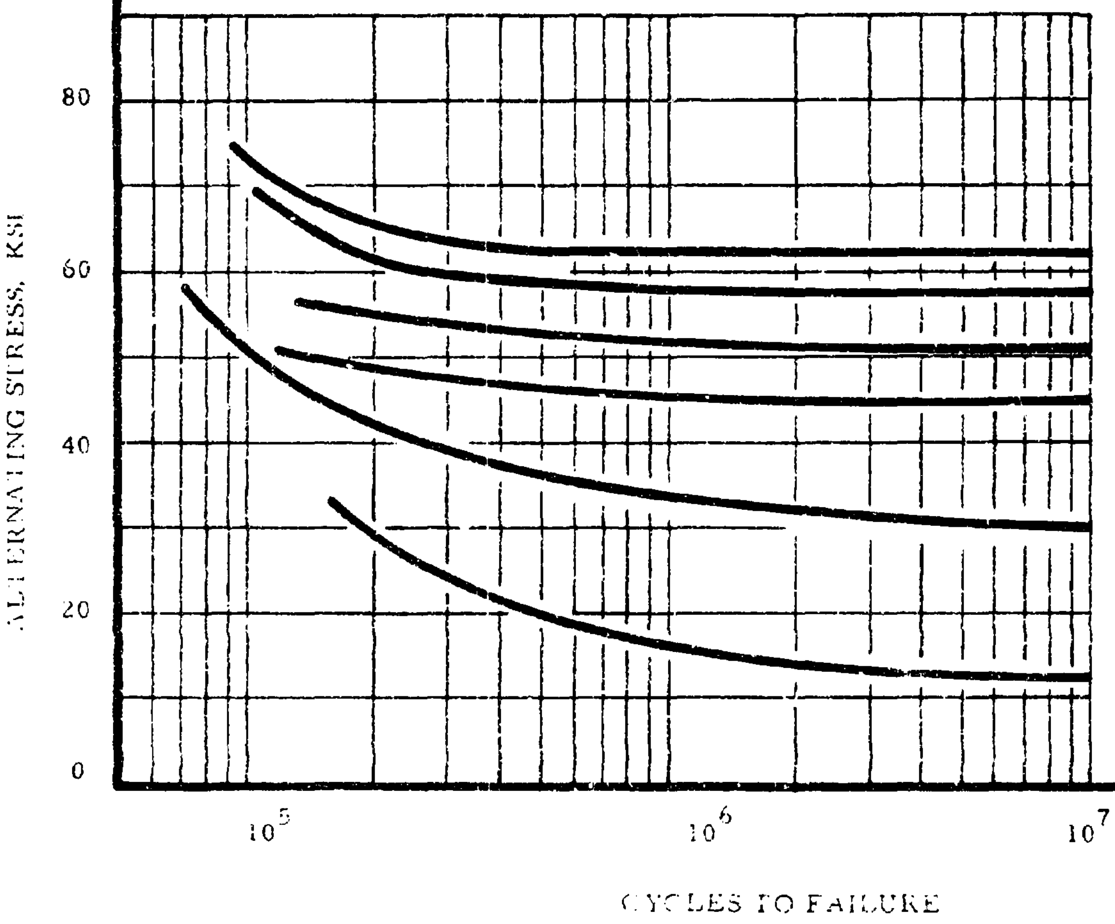

RESIDUAL SURFACE STRESSES IN BETA ROLLED TITANIUM 6Al-4V PRODUCED BY CHM
ABUSIVE CHM
GENTLE CHM
CHM CONDITIONS
Gentle
Abusive
Solution
HF-3.0N
H2CrO4-0.8N
Ti-15 gm/l
Wetting agent .24 gm/l
HF-1.5N
H2CrO4
Ti-1.0 gm/l
Wetting agent 0
Temperature
115 ± 3°F
140 ± 3°F
Material Removed
.019-.021 in./side
.019-.021 in./side
+80
+60
+40
+20
0
-20
-40
-60
TENSION
COMPRESSION
RESIDUAL STRESS - KSI
0
.002
.004
.006
.008
.010
DEPTH BELOW SURFACE - INCHES

Figure 26

FATIGUE CHARACTERISTICS OF BETA ROLLED TITANIUM 6Al-4V

METAL REMOVAL CONDITIONS: SURFACE GRINDING, HAND GRINDING, CHM
MODE: CANTILEVER BENDING, ZERO MEAN STRESS
TEMPERATURE: 75°F

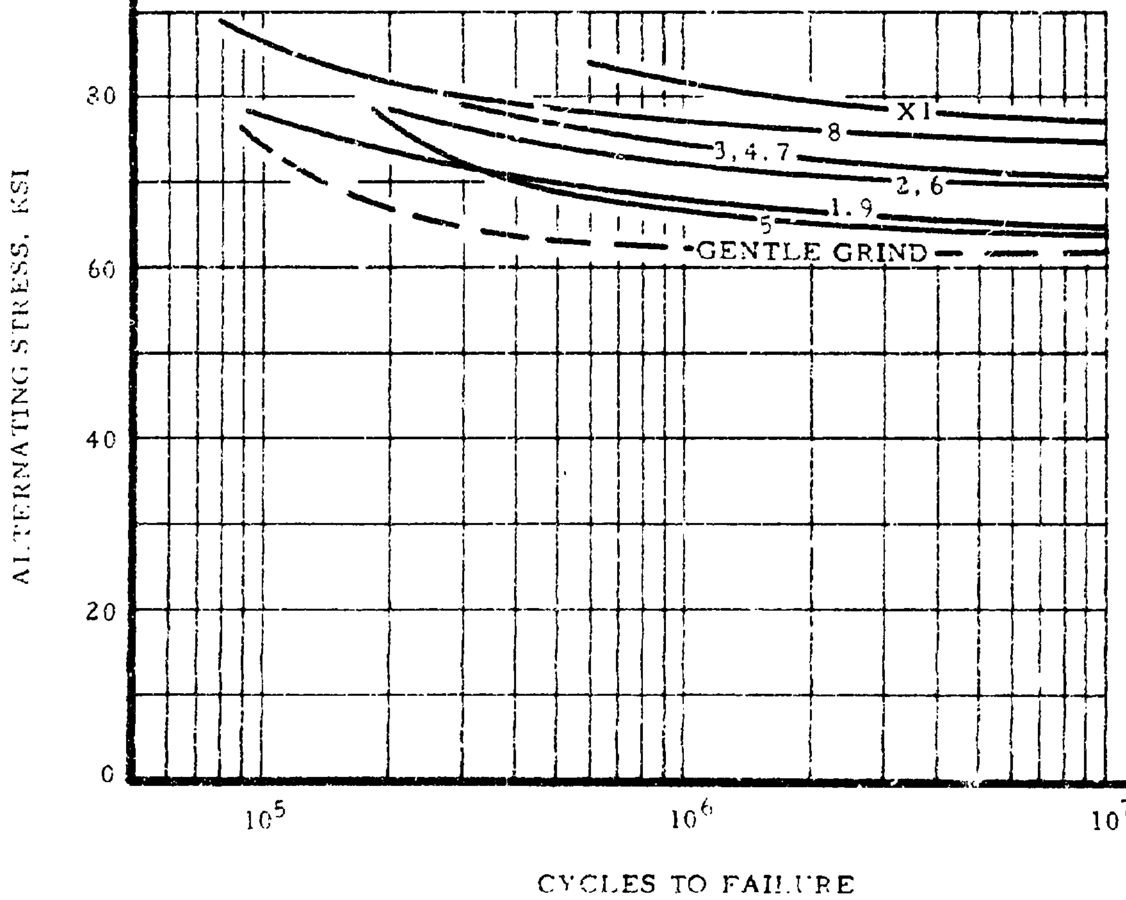


CONDITION	ENDUR. LIMIT KSI	SURF. FINISH AA
GENTLE SURFACE GRIND	62	35
GENTLE HAND GRIND	57	80
GENTLE CHM	51	20
ABUSIVE CHM	45	105
ABUSIVE HAND GRIND	30	80
ABUSIVE SURFACE GRIND	13	65

Figure 29

FATIGUE CHARACTERISTICS OF BETA ROLLED TITANIUM 6Al-4V

METAL REMOVAL CONDITIONS: END MILLING - END CUTTING
MODE: CANTILEVER BENDING, ZERO MEAN STRESS
TEMPERATURE: 75°F

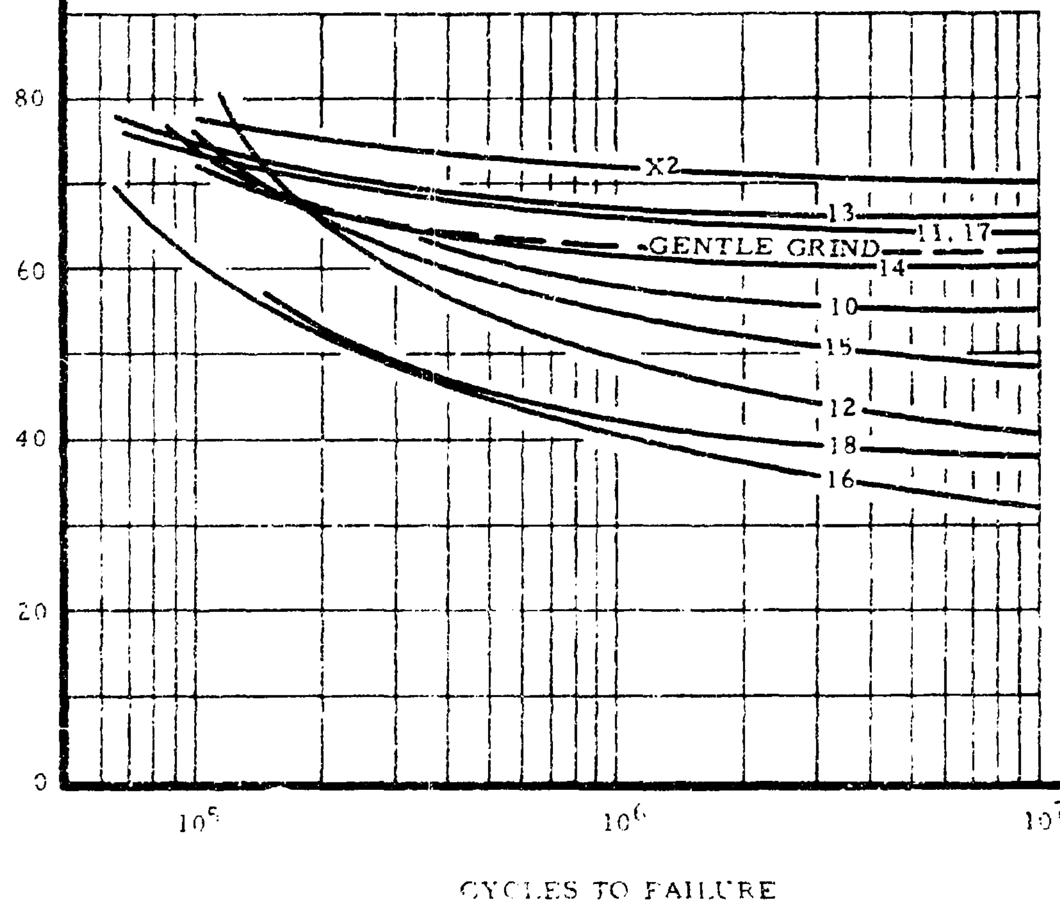


MILLING CONDITION	ENDUR. LIMIT KSI	SURF. FINISH AA
1	64	74
2	70	53
3	72	82
4	72	57
5	64	67
6	70	42
7	72	66
8	75	87
9	64	56
X1	77	84
GENTLE SURFACE GRIND	62	35

Figure 30

FATIGUE CHARACTERISTICS OF BETA ROLLED TITANIUM 6Al-4V

METAL REMOVAL CONDITIONS: END MILLING - PERIPHERAL CUTTING
MODE: CANTILEVER BENDING, ZERO MEAN STRESS
TEMPERATURE: 75°F



MILLING CONDITION	ENDUR. LIMIT KSI	SURF. FINISH AA
10	55	35
11	64	22
12	40	43
13	[illegible]	41
14	61	40
15	47	45
16	32	[illegible]
17	64	41
18	38	[illegible]
X2	70	17
GENTLE SURFACE GRIND	62	35

Figure 51

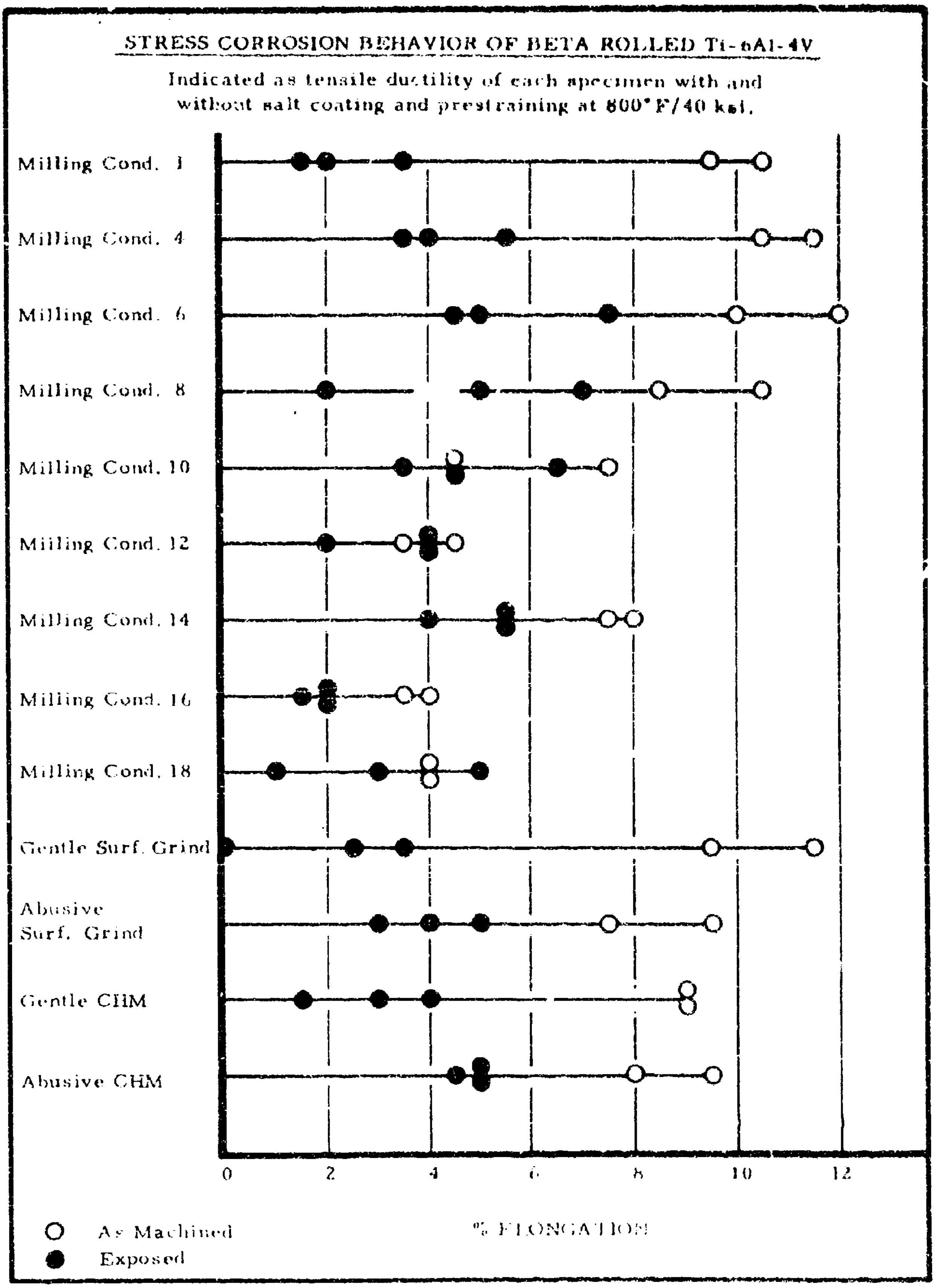

STRESS CORROSION BEHAVIOR OF BETA ROLLED Ti-6Al-4V
Indicated as tensile ductility of each specimen with and without salt coating and prestraining at 800°F/40 ksi.
Milling Cond. 1
Milling Cond. 4
Milling Cond. 6
Milling Cond. 8
Milling Cond. 10
Milling Cond. 12
Milling Cond. 14
Milling Cond. 16
Milling Cond. 18
Gentle Surf. Grind
Abusive Surf. Grind
Gentle CHM
Abusive CHM
0
2
4
6
8
10
12
% ELONGATION
As Machined
Exposed

Figure 32

6.2 Summary of Results for AISI 4340

Metallography

The metallography of machined surfaces of AISI 4340 is probably typical of that of most ferrous alloys other than the austenitic steels. Expected metallographic changes, however, are different from those of the nonferrous materials because of the martensite reaction which occurs in steel. If a steel, typified by 4340, is heated to a temperature roughly in the range of 1500 to 1700°F, the solid state microstructure immediately changes from a mixture of ferrite or pearlite plus iron carbide, which had been present in some proportions, to austenite. As soon as the heat source is removed, the temperature drops rapidly, usually resulting in a transformation of this austenite into a hard brittle phase known as martensite. If such heating is applied to a steel previously in the martensitic state, the austenite-martensite cycle is simply repeated.

The austenite-martensite reaction can be made to occur within an extremely short time cycle. Metal cutting operations which produce high localized heating only for very short periods of time will cause the reaction to occur.

If localized surface heating is applied to an annealed steel and if the temperature is high enough to produce austenite, brittle untempered martensite will be formed on the surface upon cooling. The area immediately adjacent to the layer or patches of martensite formed in this way will be essentially unaffected. If, on the other hand, localized surface heating is applied to a steel which had previously been in the martensitic condition, a different situation will occur. The layer or patches of martensite will form if the surface temperature is high enough to produce austenite at the peak temperature. The adjacent parts of the microstructure, however, will now be somewhat softer than they were in their original condition. This is because the localized surface heating at that particular point, while insufficient to form austenite which would revert to hard primary martensite, was sufficient to produce a further tempering or softening of the martensite in the original workpiece. Therefore, localized heating applied to martensitic steel most frequently results in surface patches of hard martensite followed by a layer of overtempered or softened martensite immediately beneath it. In machining these materials, it is of course possible to produce localized heating which is not quite sufficient to produce austenite at the maximum temperature. In this case, overtempering of the

6.2 Summary of Results for AISI 4340 (continued)

Metallography (continued)

previous existing martensite can and does frequently occur. If localized heating is great enough to form primary martensite, adjacent layers of overtempered softened martensite will almost always by found if the material were originally in the martensitic condition. Overtempered martensite by itself, however, can be produced without the presence of rehardened primary martensite.

The metallographic studies made of 4340 in conjunction with this program are summarized in Figures 33 through 43. Figure 33 shows cross sections of surfaces produced by gentle, conventional, and abusive surface grinding. Notice that gentle grinding produced no visible surface alterations. Abusive grinding produces a layer of primary untempered martensite, approximately .001 in. deep. This can be determined both visually from measuring the light etching band at the surface of the structure shown in Figure 33(c) and also from an analysis of the microhardness data presented. The presence and depth of overtempered and softened zone of martensite immediately beneath this layer can also be verified from the microhardness data provided in Figure 33. In the case of conventional grinding, small discontinuous surface patches of untempered martensite were observed. One such patch is shown in Figure 33(b). The microhardness data provided indicate a slight surface softening associated with conventional grinding. This may be attributed directly to a slight overtempering of the surface during the grinding process. The small patches of untempered martensite (light etching) were not large enough, however, to be detected by the microhardness measuring equipment.

Photomicrographs of surfaces produced by hand grinding are shown in Figure 34. These show evidence of the rough surface finish produced by the particular hand grinding conditions used. Neither the microstructures nor the microhardness data, however, show evidence of either overtempering of the surface or of untempered martensite formation.

Surface conditions produced by end milling are shown in Figures 35 and 36. End cutting under gentle conditions produced what appears to be a low distortion surface both with respect to microstructure and microhardness variation. Abusive end cutting resulted in a relatively rough surface which contained a slight trace of plastic deformation. Any effects were very shallow, however, as evidenced

6.2 Summary of Results for AISI 4340 (continued)

Metallography (continued)

by viewing both the microstructure and noting that no change in hardness could be measured. Peripheral milling, on the other hand, produced extensive plastic deformation under abusive conditions. Work hardening to the extent of six points Rockwell C, for a total affected depth of approximately .004 in., was measured. Both the microstructure shown in Figure 36(b) and the pattern of hardness change suggest that this particular alteration is a result of excessive plastic deformation and strain hardening rather than the martensite hardening reaction more commonly found on ferrous alloys.

Cross sections of holes drilled under gentle and abusive conditions in 4340 are shown in Figure 37. Gentle drilling, featuring a sharp drill with adequate cooling, produced a surface with no visible distortion. Abusive drilling, involving the use of dull tooling and inadequate cooling, produced very severe surface distortion. The entire area of microstructure shown in Figure 37(b), though only at 100X, is essentially all rehardened or primary martensite. The extent of this surface damage may also be seen from the microhardness data, indicating a band of martensite .016 in. deep and a total affected zone of .030 in. Note again the typical hardened zone of untempered martensite on the surface and underlying zone of overtempered martensite which lies .022 to .030 in. beneath the surface.

Of the various nonconventional metal removal processes, electrical discharge machining (EDM) produces high localized surface heating and, in turn, may be expected to produce the usual untempered/overtempered martensite reaction associated with conventional metal removal processes which also produce a high surface heating. In addition, the EDM process produces a molten surface layer during operation which results in a layer of recast metal being deposited on most materials. As may be seen in Figure 38, this recast layer is evident under both finishing and roughing conditions. The layer tends, however, to be somewhat deeper under roughing conditions, which involve higher current densities and presumably higher surface temperatures. Microhardness data indicate that a thin layer of untempered martensite and overtempered martensite is present in the structure.

The ECM operation, in contrast, produces little or no surface heating as indicated in Figure 39. There is no particular

6.2 Summary of Results for AISI 4340 (continued)

Metallography (continued)

evidence of a surface phase change on 4340 from either gentle or abusive ECM conditions. Note, however, the slight surface pitting indicated on the sample cut under gentle ECM conditions. Notice also that the abusive condition resulted simply in surface roughening and possibly more extensive pitting.

The effects of gentle and abusive CHM are shown in Figure 40. As would be expected for this process, no microhardness changes were observed. Notice that the effect of the abusive condition appeared insignificant, other than to produce a slight roughening of the surface. The microstructure characteristic of an electropolished surface is shown in Figure 41. No alterations or hardness changes are evident.

The effects of shot peening on various surfaces of 4340 are shown in Figures 42 and 43. Figure 42 shows the effect of Level 1 shot peening on electrolytic polishing plus gentle surface grinding and abusive hand grinding. Prior to peening, all three of these surfaces contained no detectable untempered martensite, although a thin layer of overtempered martensite may have been present, particularly in the case of the abusive hand grinding. The shot peening process caused no apparent change in the surface microstructures. A slight softening at the surface was detected in all three of these samples. This is in contrast to the absence of any microhardness change exhibited by these surfaces in the as-machined condition. While not definitely established, this slight softening might be attributable to strain relaxation which has been reported as a result of peening materials heat treated to the relatively high hardness level of 50 R_C.

Figure 43 illustrates the effect of shot peening at Level 1 versus Level 2 on abusively ground 4340. The photomicrographs show slightly different amounts of untempered martensite as evidenced by the depth of white layer. The difference between these, however, may be attributed to differences in the samples as ground and is not related to the difference in shot peening. Neither photomicrograph shows any evidence of the effect of shot peening, even though the shot used in the Level 2 peening was somewhat harder than the shot used for Level 1 peening, other conditions being the same. Again, it is further presumed that the shot peening had no effect on microhardness

6.2 Summary of Results for AISI 4340 (continued)

Metallography (continued)

since the microhardness curves produced by both of the samples are essentially the same. Differences between them may be attributed to differences that would be expected from one sample to the next. The effects of shot peening, therefore, as evidenced by change in fatigue strength, must be attributed to factors other than microstructure and microhardness change.

Residual Stress

Residual stress data obtained on 4340 are summarized in Figures 44 through 47. The residual stress distribution associated with gentle, conventional, and abusive grinding is shown in Figure 44. Note that gentle grinding produces compressive surface stresses of relatively low magnitude. The gentle grinding procedure used was very similar to the so-called low stress grinding procedure which was developed by Metcut several years ago. As in this particular case, stresses normally associated with low stress grinding are both compressive and low in magnitude. In contrast, stress distribution associated with conventional and abusive grinding tends to be tensile and of relatively high magnitude. Here again, the type of stress distribution associated with abusive grinding as shown in Figure 44 is typical for most of the alloys with which experience has been developed.

The effect of shot peening as a post treatment or possibly corrective process when applied to ground 4340 is shown in Figure 45. Notice that the stress distribution patterns are very similar whether the workpiece was previously ground by gentle or abusive means. This suggests that the shot peening operation is reasonably effective in masking over the prior surface condition. Notice also that compressive stresses equal to the yield strength of the material are possible with shot peening.

Residual stresses associated with hand grinding are shown in Figure 46. The stress distribution associated with hand grinding is similar to that exhibited by gentle surface grinding. The stress distribution associated with abusive hand grinding, however, shows predominantly compressive stresses. This is in contrast to previous experience with abusive grinding practice.

Residual stress distribution attributable to electropolishing is shown in Figure 47. As had been anticipated, ELP resulted in an essentially stress-free surface condition.

6.2 Summary of Results for AISI 4340 (continued)

Fatigue

Fatigue data developed under this contract are summarized in Figures 48 and 49. Figure 48 contains standard S/N curves for surface grinding, hand grinding, and electropolishing. Figure 49 summarizes similar data for all metal removal combinations which were subsequently shot peened.

Perhaps most significant among the characteristics of grinding and ELP is the fatigue strength depression associated with conventional and abusive grinding. As may be seen in Figure 48, conventional grinding exhibited an endurance limit of 70 ksi and abusive grinding exhibited an endurance limit of 62 ksi in comparison with an endurance limit of 102 ksi which is associated with gentle grinding. Notice also that the surface finish for all three of these processes fell within the range of 36 to 50 microinches AA. This indicates that surface finish is probably not a significant factor in determination of surface integrity.

Data for both abusive and gentle hand grinding are also shown in Figure 48. Abusive hand grinding exhibits an endurance limit of 98 ksi in comparison to that of 94 ksi associated with gentle hand grinding. This is the only instance in this surface integrity investigation in which an abusive grinding operation yielded a higher endurance limit than its gentle counterpart. It was also noted previously that the predominant residual stress associated with abusive hand grinding is compressive, which is also contrary to other experience with abusive grinding procedures. The reason for this particular behavior is not understood. It must be recognized, however, that the data available are based on a very limited number of samples. Perspective can also be gained by comparing the various endurance limits to the 90 ksi level exhibited by ELP. ELP generally is considered as a metal removal method which produces a stress-free surface. This was essentially borne out by the residual stress data, Figure 47.

Figure 49 shows the effect of shot peening applied as a post-processing operation to these metal removal processes. A review of the data indicates that shot peening is effective in elevating the fatigue strength of all of the materials. In general, the peening processes do not increase the endurance limit above the level of 102 ksi which is the baseline established by the gentle surface grinding process. There are two exceptions. One is the application of shot peening to gentle

6.2 Summary of Results for AISI 4340 (continued)

Fatigue (continued)

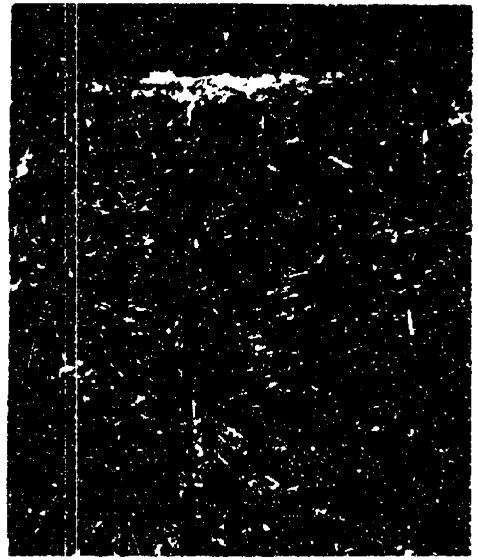
grinding itself. In this instance, the endurance limit is raised from 102 to 112 ksi. Another exception is the elevation of the endurance limit in abusive hand grinding from 98 to 118 ksi shot peening. It would appear that the particular combination of strain hardening caused by the abusive grinding and enhanced by peening is an effective combination for elevation of fatigue strength. Insufficient sampling is available, however, to comment on whether this is a real and repeatable phenomenon or a product of isolated circumstances.

Stress Corrosion

Stress corrosion data obtained on 4340 are summarized in Figure 50. Data here is indicated as the life exhibited by each specimen when prestrained and exposed to an alternating salt water - air environment. A great deal of scatter is immediately evidenced. As indicated in Figure 50, most of the samples either failed after a relatively short exposure in the range of 100-300 hours, or were removed without failure after exposure at 1000 hours. The general trends which can be drawn from these data are summarized in the average life plots shown in Figure 10 and as discussed in Section 6. The same inference can be drawn from Figure 50 although in this figure greater appreciation for the degree of scatter can be gained. Shot peening at Level 1 indicates a trend toward being effective at decreasing stress corrosion sensitivity. Note the large percentage of shot peened samples which were removed after 1000 hours exposure without failure. Abusive grinding, on the other hand, is consistent in that all of the samples processed in this way exhibited lives of 200 hours or less. Nothing more than an indication of trends is possible, however, because of the scatter encountered. Refinements of the stress corrosion evaluation procedure should be accomplished before additional surface integrity studies are undertaken.

The procedure used for stress corrosion testing on AISI 4340 is summarized in Appendix II-5. A summary of the data obtained on each test specimen is contained in Table XVII.

(a) Gentle Conditions



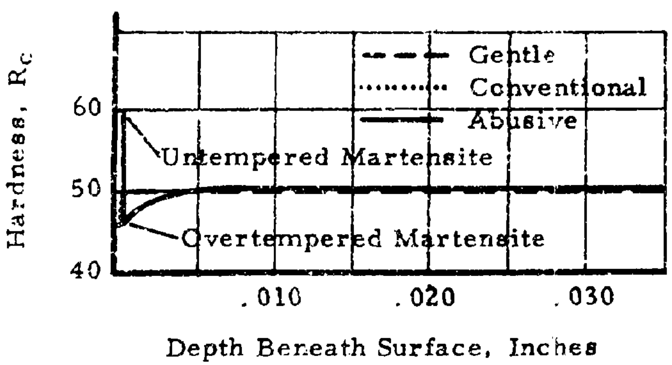
(b) Conventional Conditions

(c) Abusive Conditions

Gentle grinding produced no visible surface alterations. Conventional grinding shows evidence of spotty surface rehardening and underlying overtempering or softening. Abusive grinding produced a rehardened surface layer averaging .001" deep and an underlying overtempered zone approximately .004" deep.

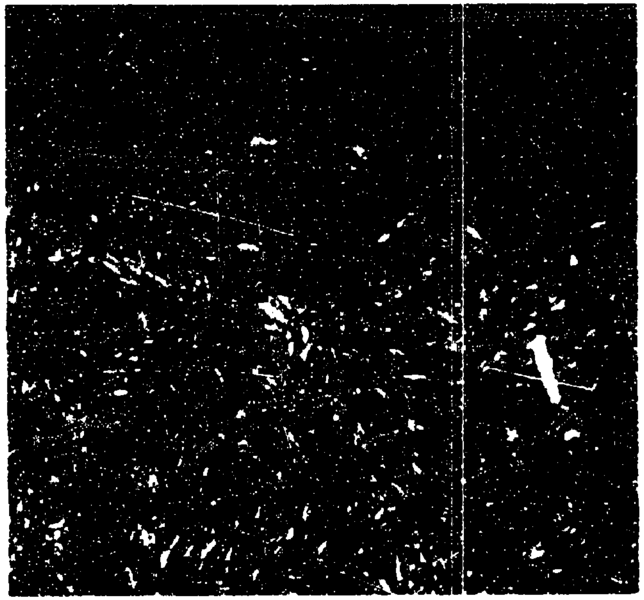
Surface Finish: 45AA — Surface Finish: 40AA — Surface Finish: 50AA

1000X



SURFACE CHARACTERISTICS OF
AISI 4340 (Quenched and Tempered, 50 R_c)
PRODUCED BY GRINDING

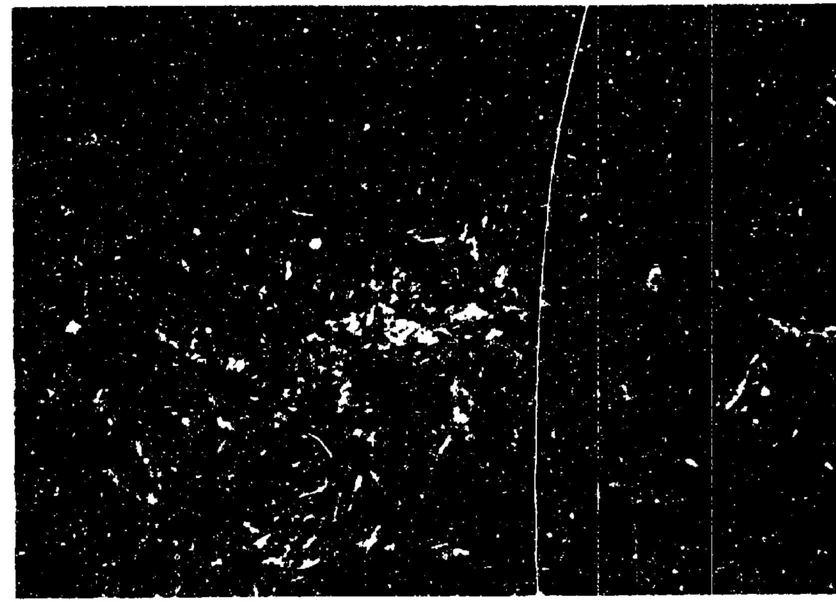
Figure 33



(a) Gentle Conditions - Roughened surface with no visible distortion, although slight evidence of tearing.

Surface Finish: 115AA

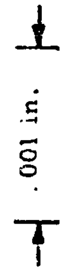
1000X

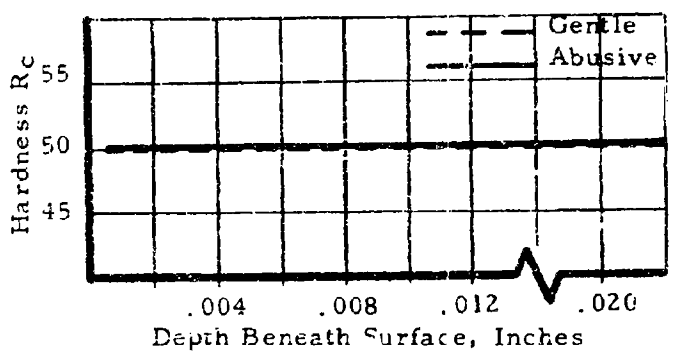


(b) Abusive Conditions - Roughened surface similar to that produced by gentle conditions, but without visible distortion or measurable microhardness change.

Surface Finish: 105AA

1000X

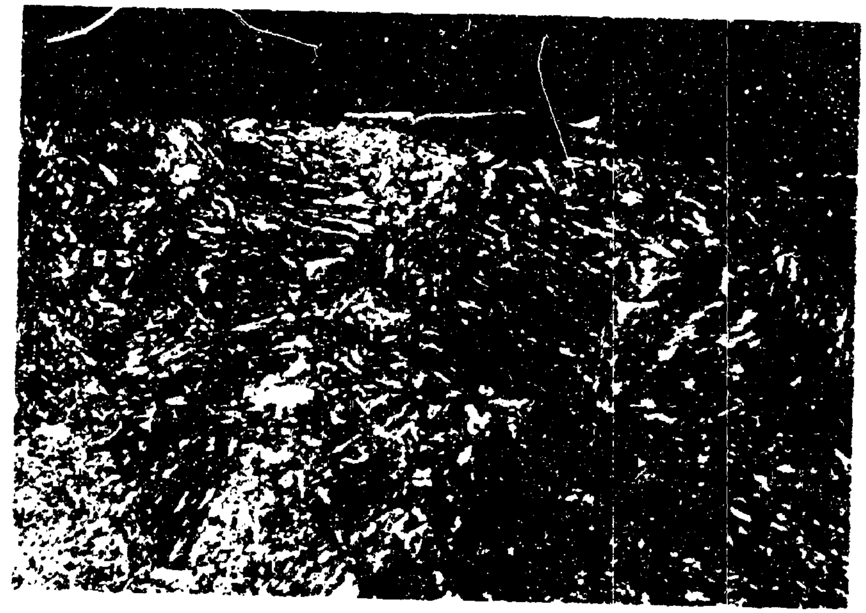




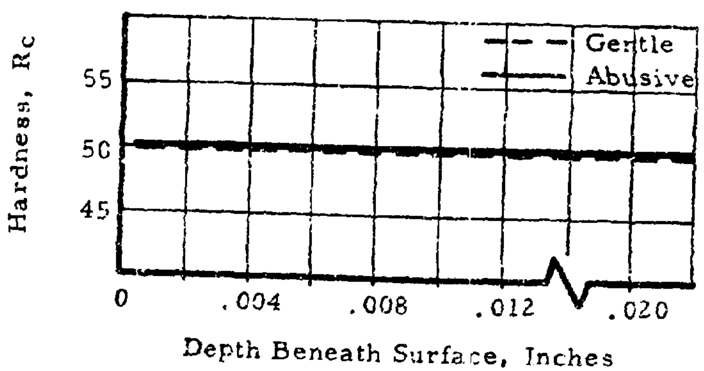
SURFACE CHARACTERISTICS OF
AISI 4340 (Quenched and Tempered, 50 R_c)
PRODUCED BY HAND GRINDING

Figure 34

(a) Gentle Conditions - No visible or measurable surface distortion.
Surface Finish: 20 AA 1000X

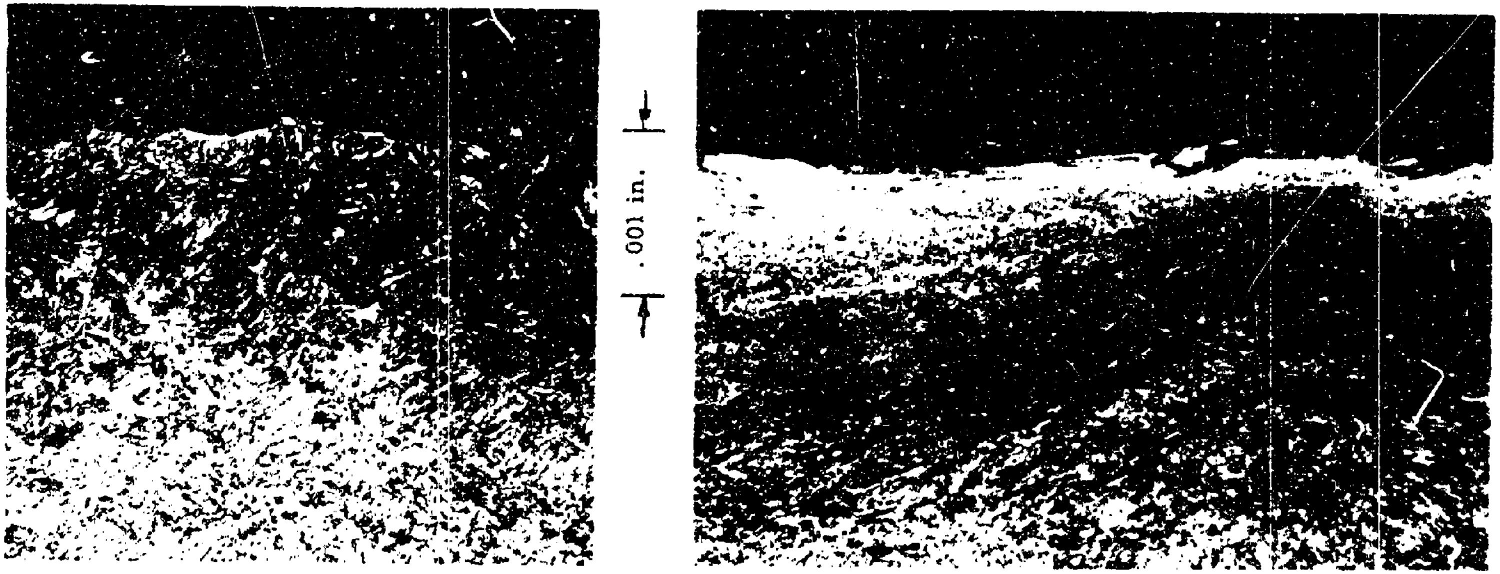


(b) Abusive Conditions - Slight trace of plastic deformation but without measurable hardness change.
Surface Finish: 190 AA 1000X



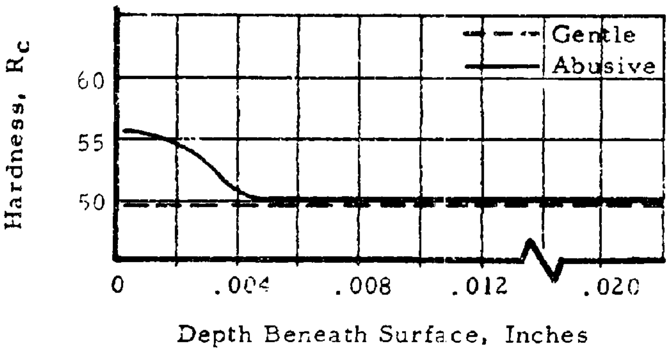
SURFACE CHARACTERISTICS OF
AISI 4340 (Quenched and Tempered, 50 R_c)
PRODUCED BY END MILLING - END CUTTING

Figure 35



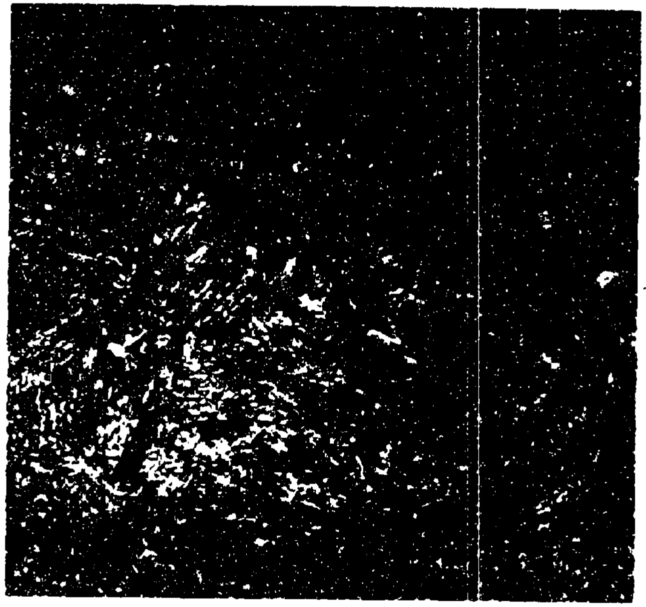
(a) Gentle Conditions - Slight surface roughening but without measurable hardness change.
Surface Finish: 85 AA 1000X

(b) Abusive Conditions - Extensive plastic deformation at surface plus partial hardening to the extent of 6 points R_c.
Surface Finish: 170 AA 1000X

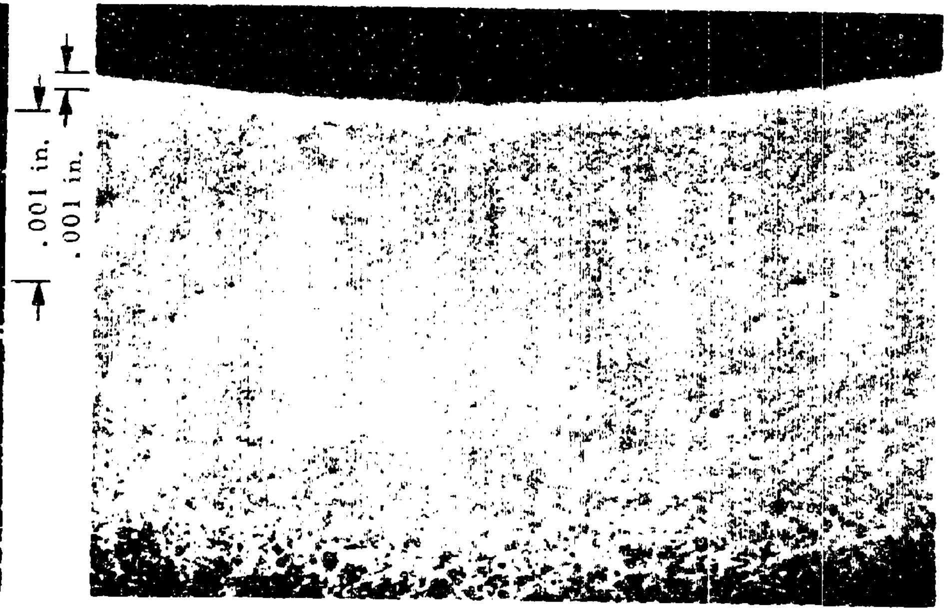


SURFACE CHARACTERISTICS OF
AISI 4340 (Quenched and Tempered, 50 R_c)
PRODUCED BY END MILLING - PERIPHERAL CUTTING

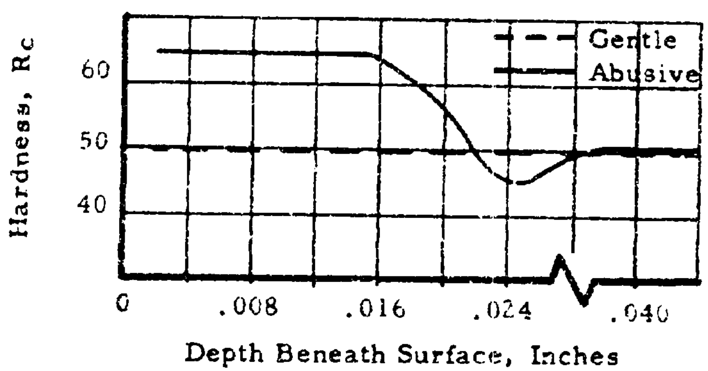
Figure 36



(a) Gentle Conditions - No visible surface distortion or microhardness change.
1000X

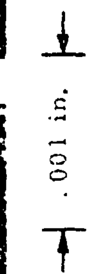


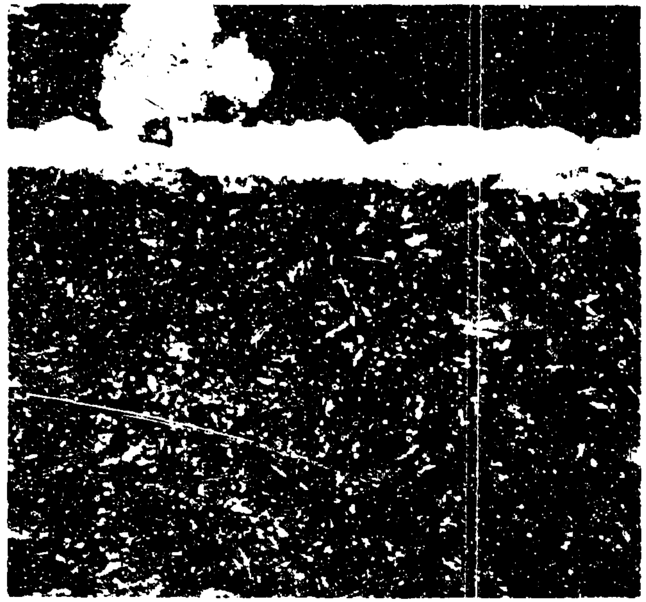
(b) Abusive Conditions - Extensive untempered martensite formation to a depth of approximately .020" plus underlying overtempered martensite layer.
100X



SURFACE CHARACTERISTICS OF
AISI 4340 (Quenched and Tempered, 50 R_c)
PRODUCED BY DRILLING

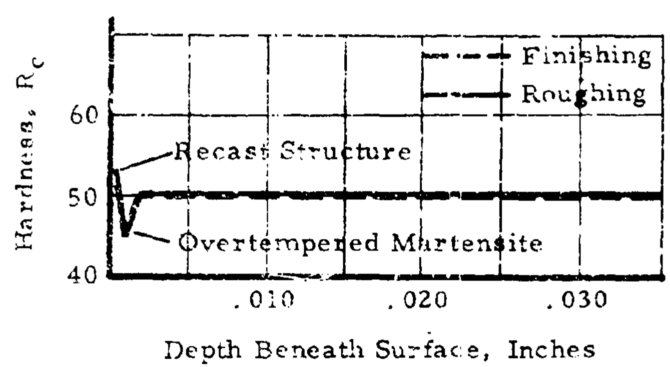
Figure 37





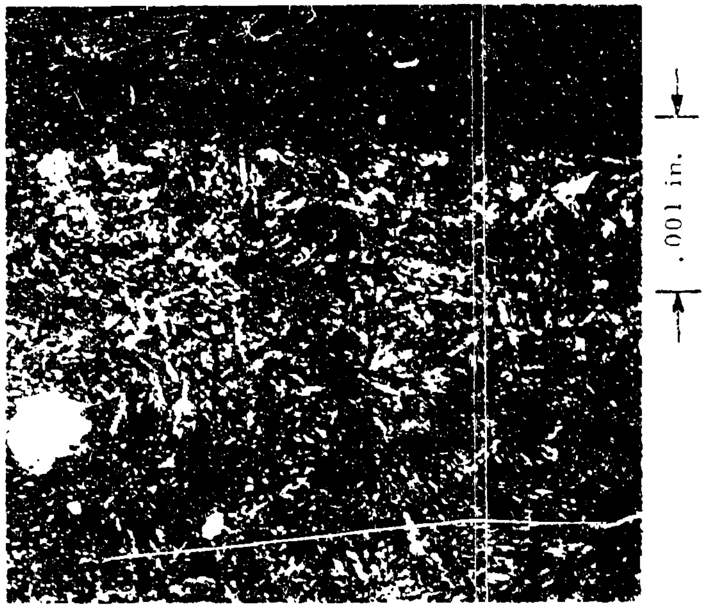
(a) Finishing Conditions - A uniform recast layer approximately .0003" deep was formed. Evidence of a very thin over-tempered layer was also observed.
Surface Finish: 55 AA 1000X

(b) Roughing Conditions - Spattered recast metal was deposited at random across the surface. Underlying layers of untempered and overtempered martensite were also produced in a total heat affected zone averaging .002" deep.
Surface Finish: 190 AA 1000X

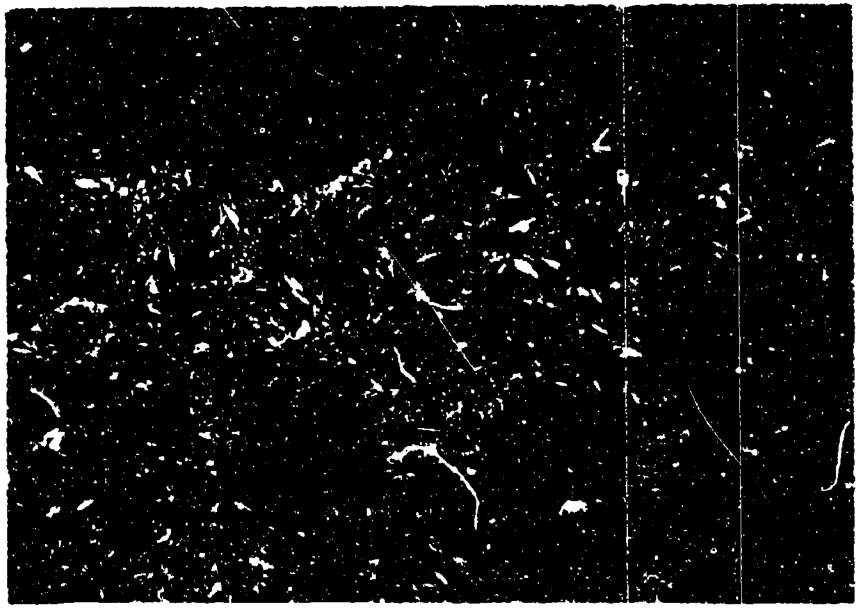


SURFACE CHARACTERISTICS OF
AISI 4340 (Quenched and Tempered, 50 R_c)
PRODUCED BY EDM

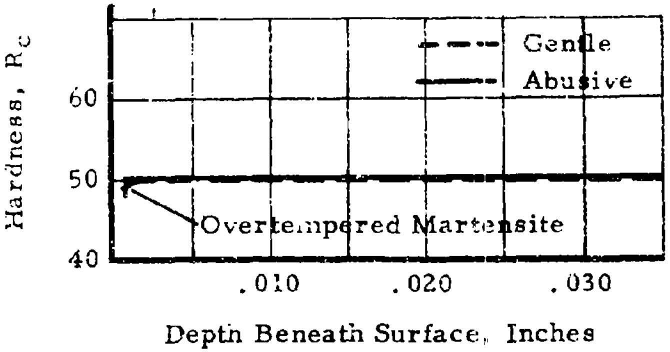
Figure 38



(a) Gentle Conditions - Very slight surface softening and some surface pitting were produced. 1000X
Surface Finish: 10AA

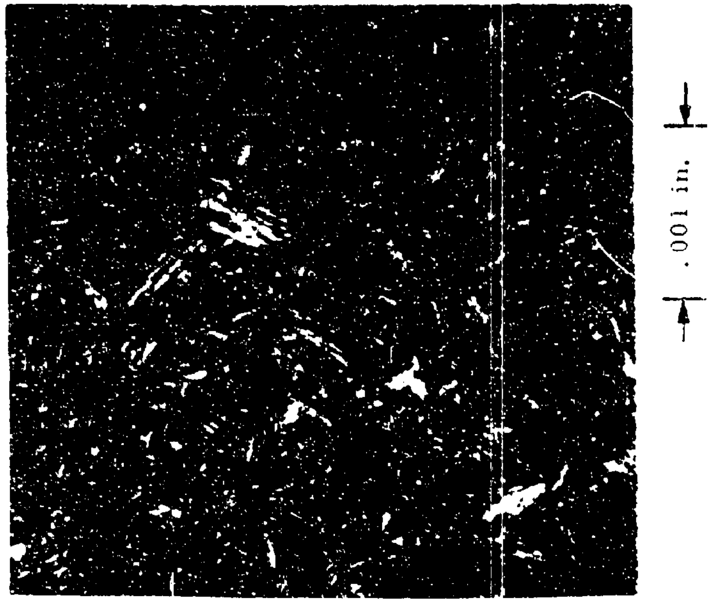


(b) Abusive Conditions - Surface softening and pitting were produced. The pitting was somewhat more extensive than under the gentle ECM conditions.
Surface Finish: 105AA 1000X

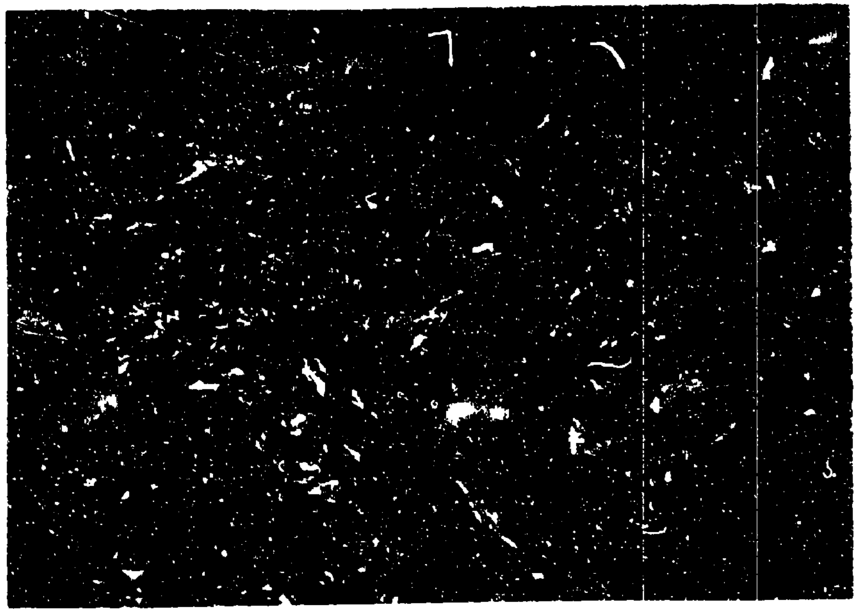


SURFACE CHARACTERISTICS OF
AISI 4340 (Quenched and Tempered, 50 R_c)
PRODUCED BY ECM

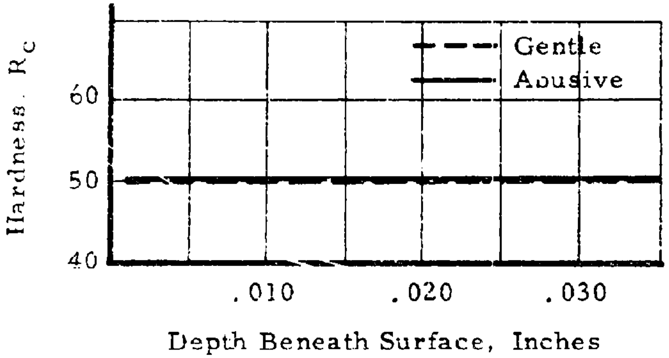
Figure 39



(a) Gentle Conditions - No visible surface alterations were produced. 1000X
Surface Finish: 37AA

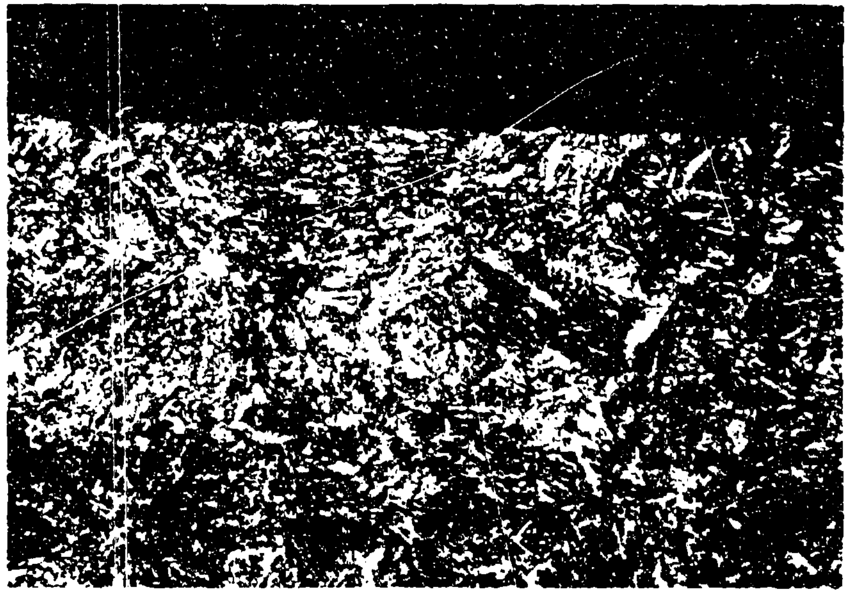


(b) Abusive Conditions - No visible surface alterations were produced other than the slight roughening of the surface as seen above. 1000X
Surface Finish: 200AA

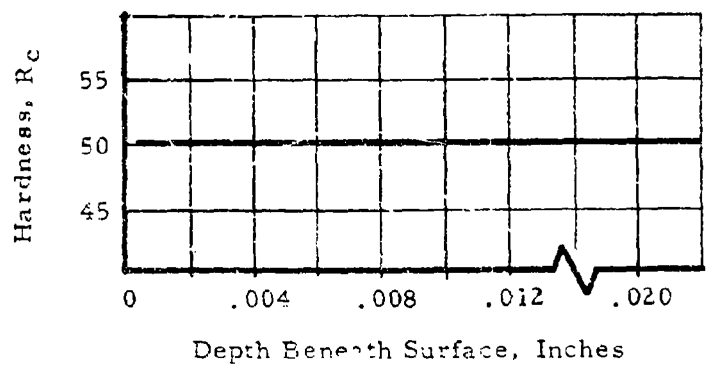


SURFACE CHARACTERISTICS OF
AISI 4340 (Quenched and Tempered, 50 R_c)
PRODUCED BY CHM

Figure 40

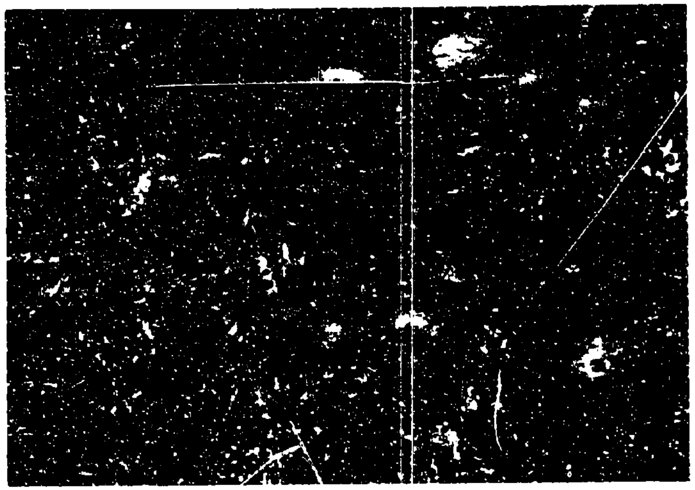


No visible or measurable surface distortion.
Surface Finish: 15 AA 1000X



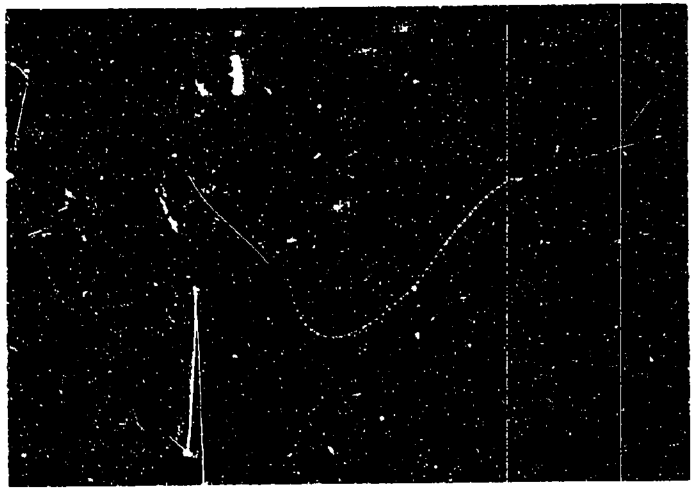
SURFACE CHARACTERISTICS OF
AISI 4340 (Quenched and Tempered, 50 R_c)
PRODUCED BY ELP

Figure 41

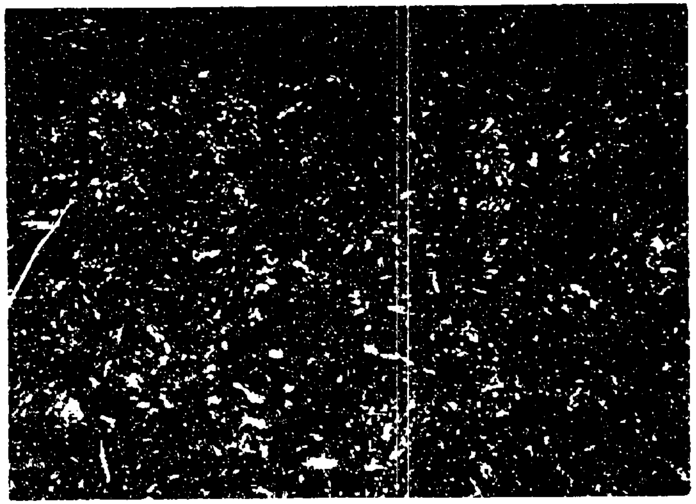


.001 in.

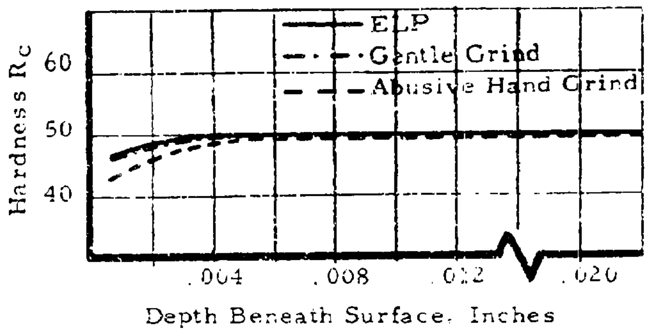
Electrolytic Polishing + Shot Peening
Surface Finish: 46AA



Abusive Hand Grind + Shot Peening
Surface Finish: 56AA

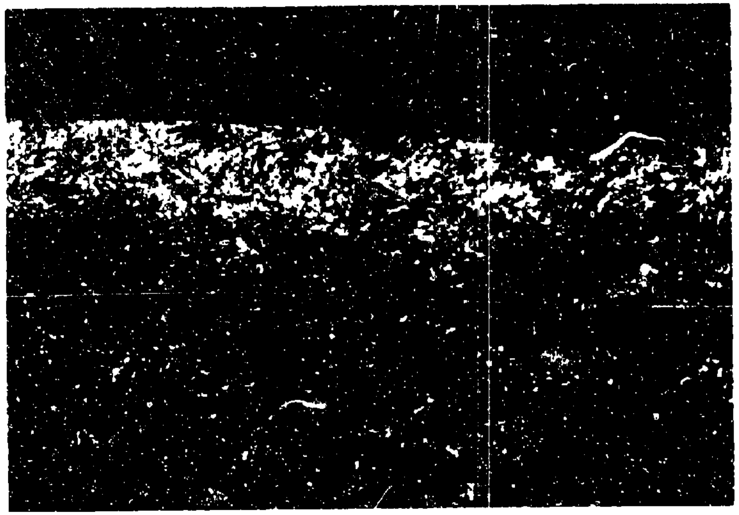


Gentle Grinding + Shot Peening
Surface Finish: 35AA



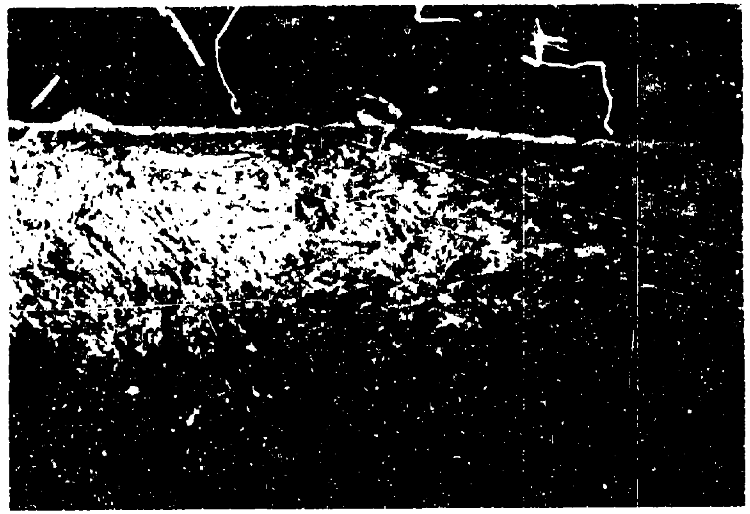
SURFACE CHARACTERISTICS OF AISI 4340 (Quenched and Tempered, 50 R_c)
PRODUCED BY A POST-PROCESSING SHOT PEENING OPERATION

Figure 42

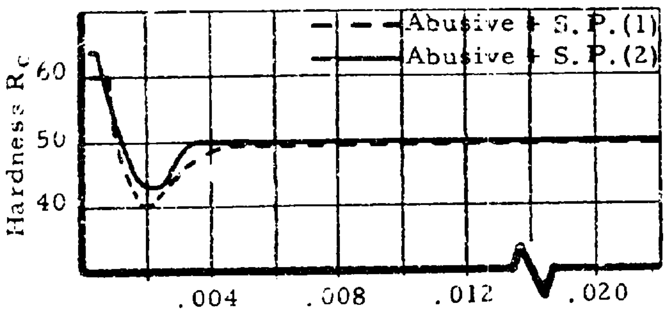


(a) Abusive Grinding Plus Shot Peening (Level 1) - Untempered martensite from abusive grinding is evident, but without visible indic...ion of shot peening effect.
Surface Finish: 40AA
1000X

.001 in.



(b) Abusive Grinding Plus Shot Peening (Level 2) Deeper layer of untempere... martensite due to variation in grinding, but no obvious difference in structure due to Level 2 shot peening conditions.
Surface Finish: 76AA
1000X



SURFACE CHARACTERISTICS OF
AISI 4340 (Quenched and Tempered, 50 R_c)
PRODUCED BY ABUSIVE GRINDING PLUS SHOT PEENING

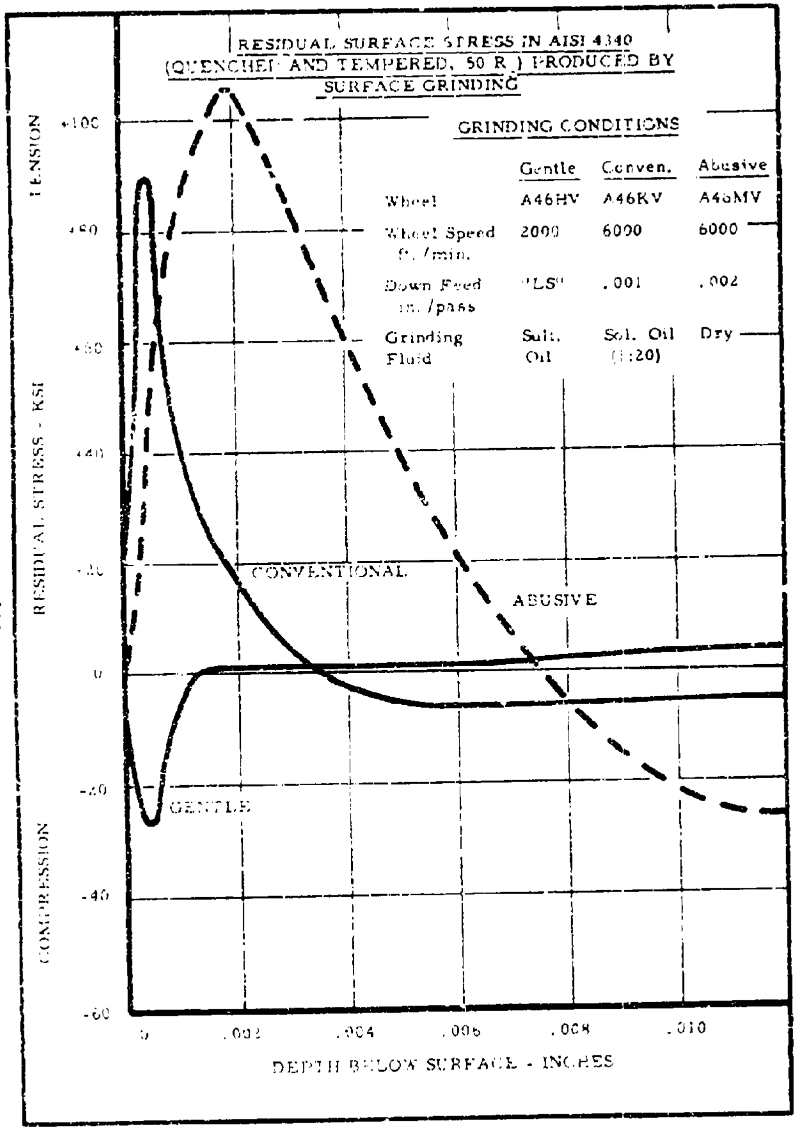


Figure 44

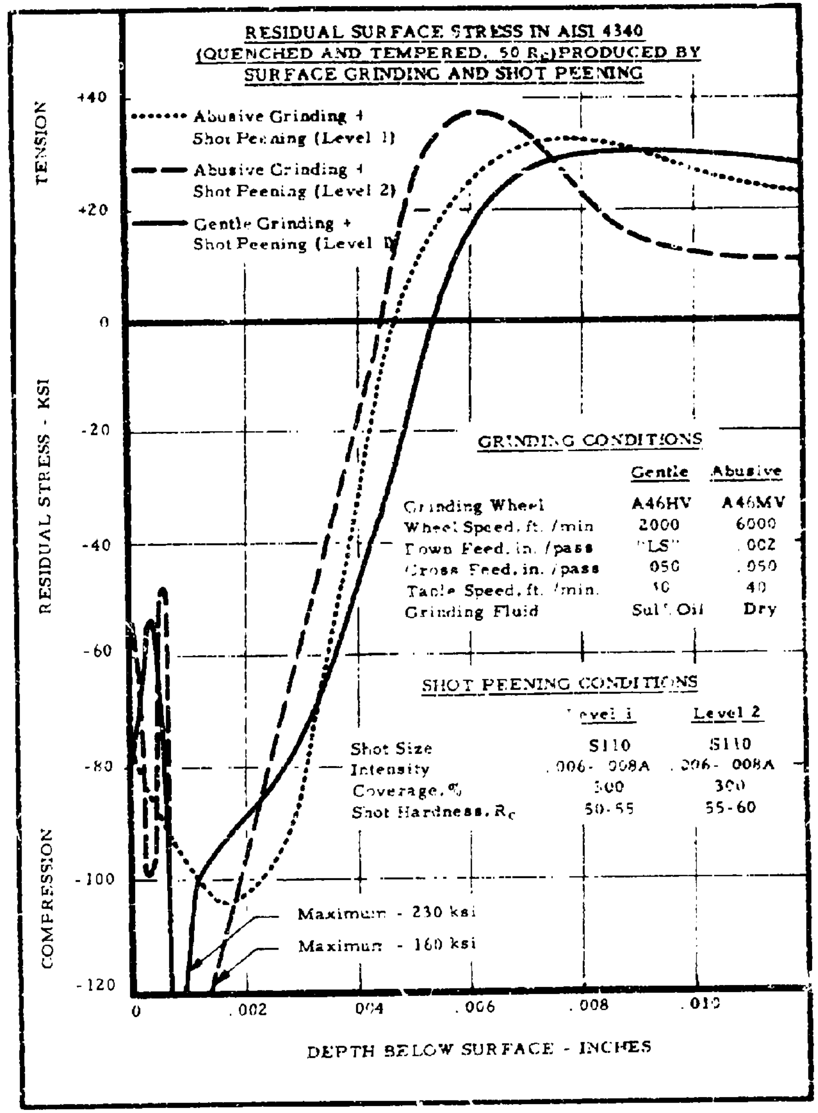


Figure 45

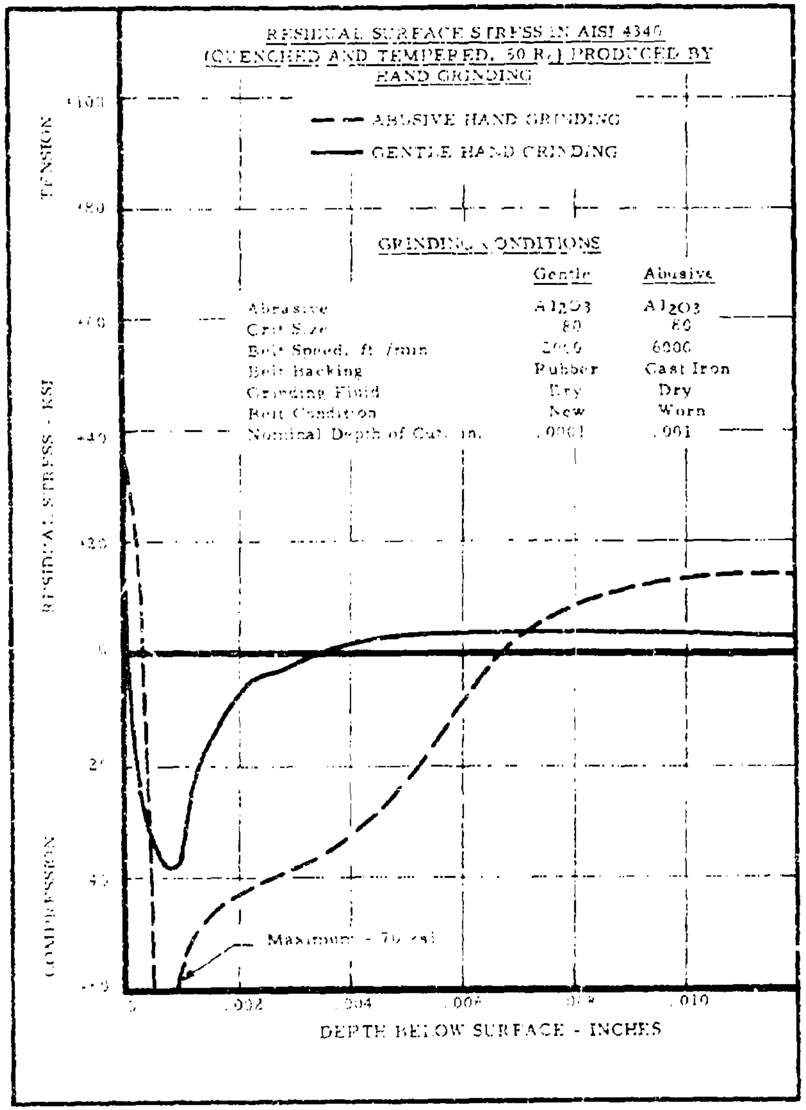


Figure 46

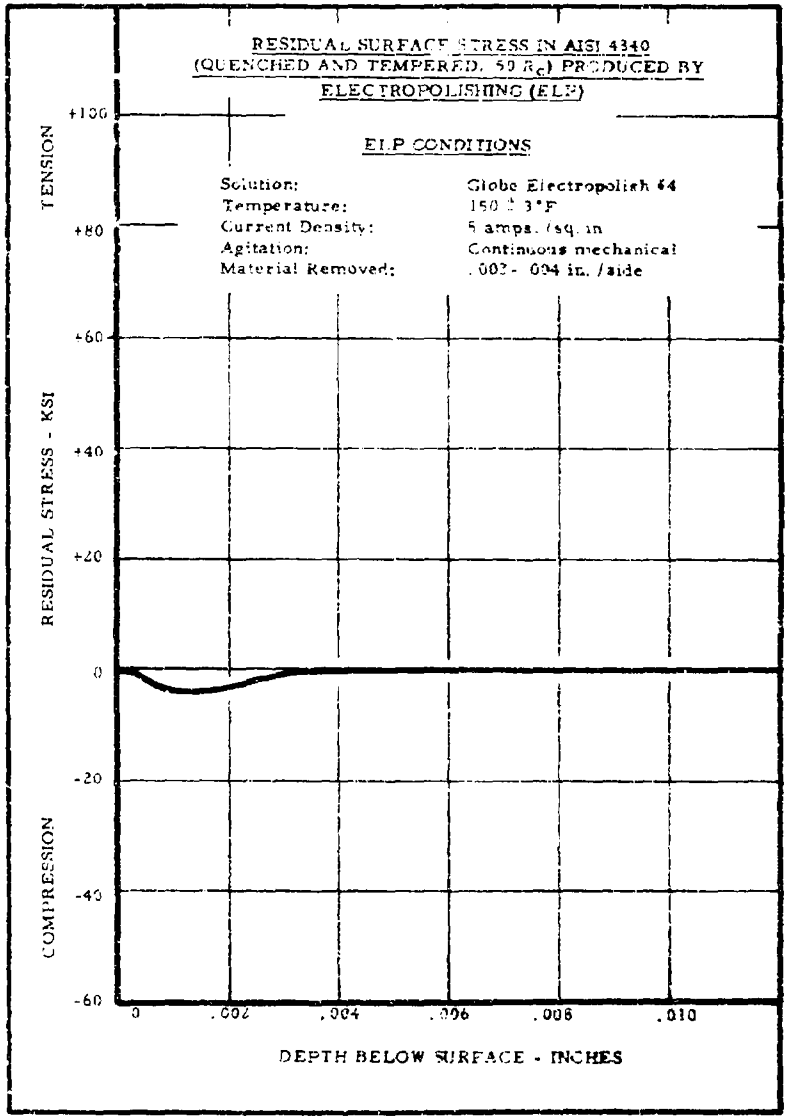
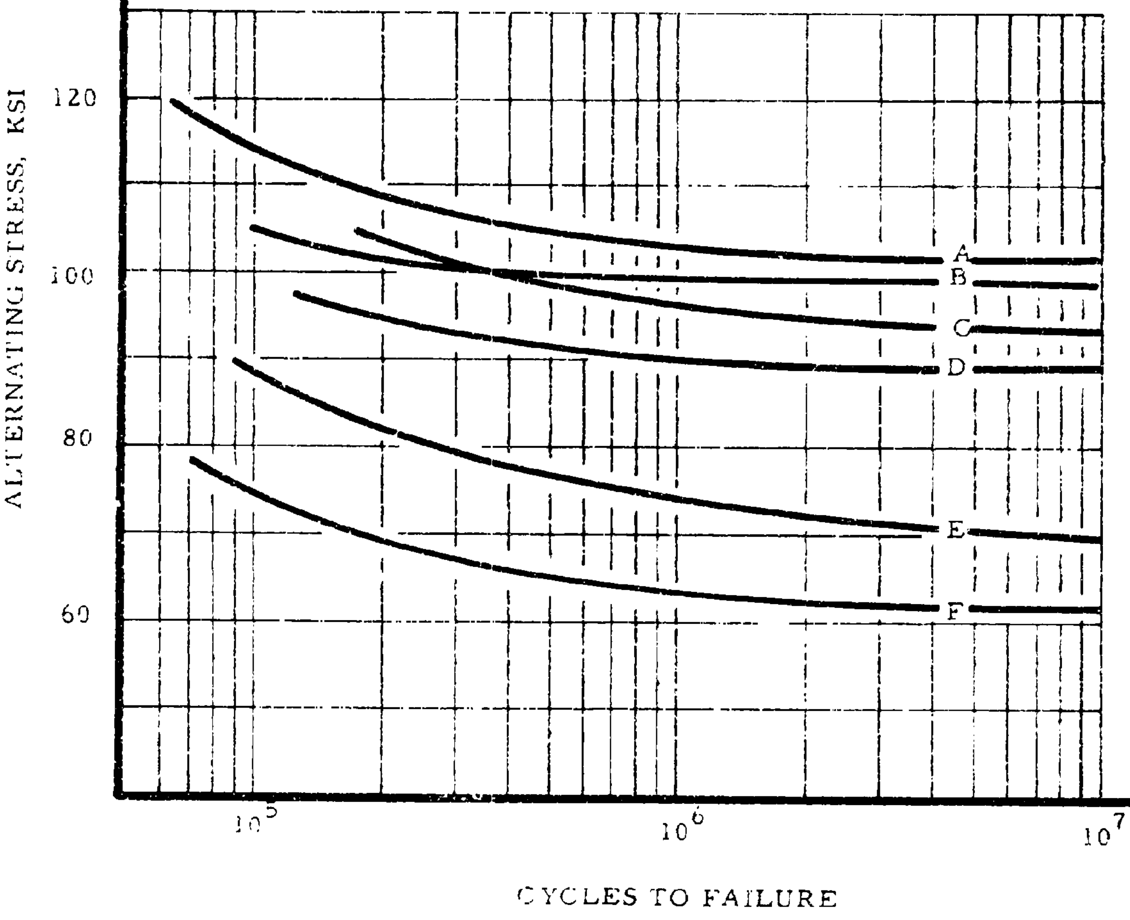


Figure 47

FATIGUE CHARACTERISTICS OF AISI 4340 (QUENCHED AND TEMPERED, 50 R)

METAL REMOVAL CONDITIONS: SURFACE GRINDING, HAND GRINDING, ELP
MODE: CANTILEVER BENDING, ZERO MEAN STRESS
TEMPERATURE: 75° F

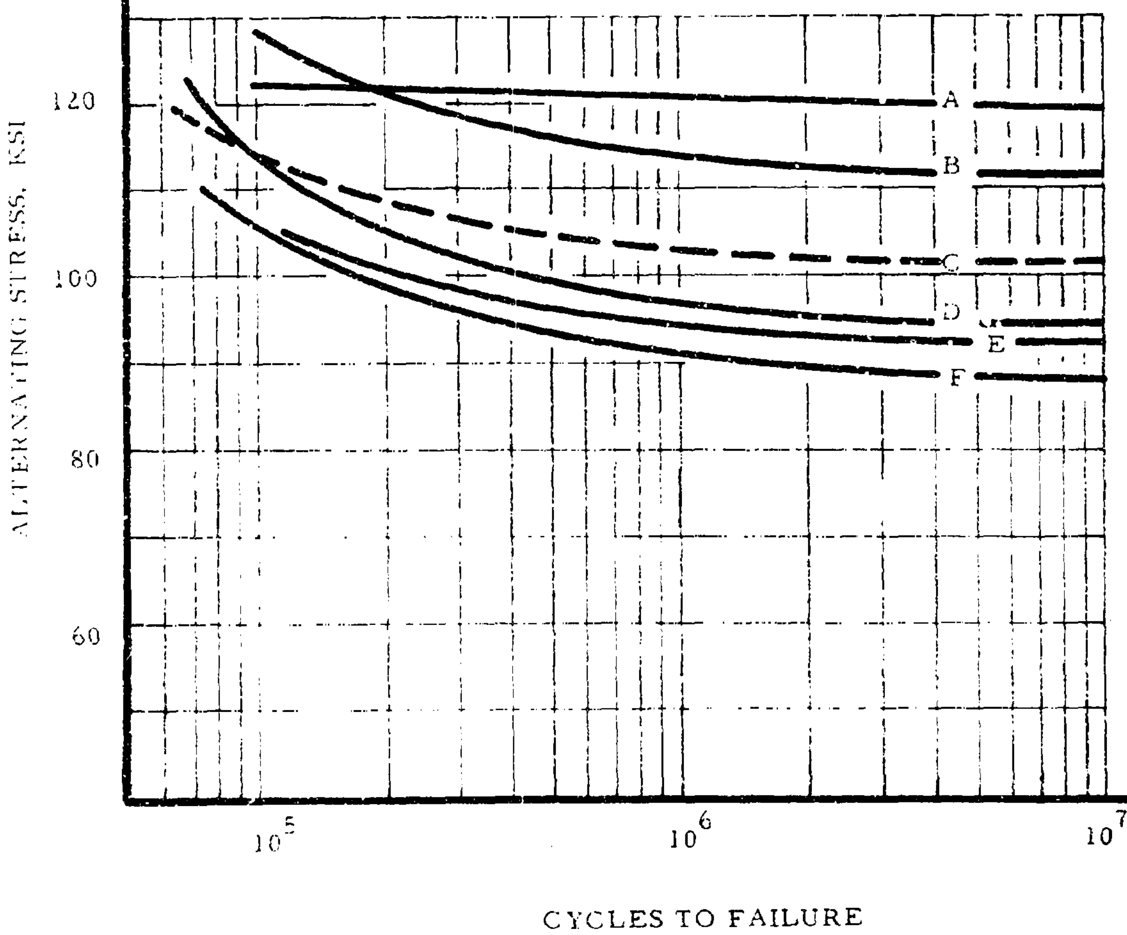


CURVE	CONDITION	ENDUR. LIMIT KSI	SURFACE FINISH AA
A	GENTLE SURFACE GRIND	102	45
B	ABUSIVE HAND GRIND	98	105
C	GENTLE HAND GRIND	94	115
D	ELP	90	15
E	CONVENTIONAL SURFACE GRIND	70	40
F	ABUSIVE SURFACE GRIND	62	50

Figure 48

FATIGUE CHARACTERISTICS OF AISI 4340 (QUENCHED AND TEMPERED, 50 R_c)

METAL REMOVAL CONDITIONS: MACHINING + SHOT PEENING
MODE: CANTILEVER BENDING, ZERO MEAN STRESS
TEMPERATURE: 75°F



CURVE	CONDITION	ENDUR. LIMIT KSI	SURFACE FINISH AA
A	ABUSIVE HAND GRIND + SP (LEVEL 1)	118	56
B	GENTLE SURFACE GRIND + SP (LEVEL 1)	112	25
C	GENTLE SURFACE GRIND	102	45
D	ELP + SP (LEVEL 1)	96	46
E	ABUSIVE SURFACE GRIND + SP (LEVEL 1)	92	40
F	ABUSIVE SURFACE GRIND + SP (LEVEL 2)	88	76

Figure 19

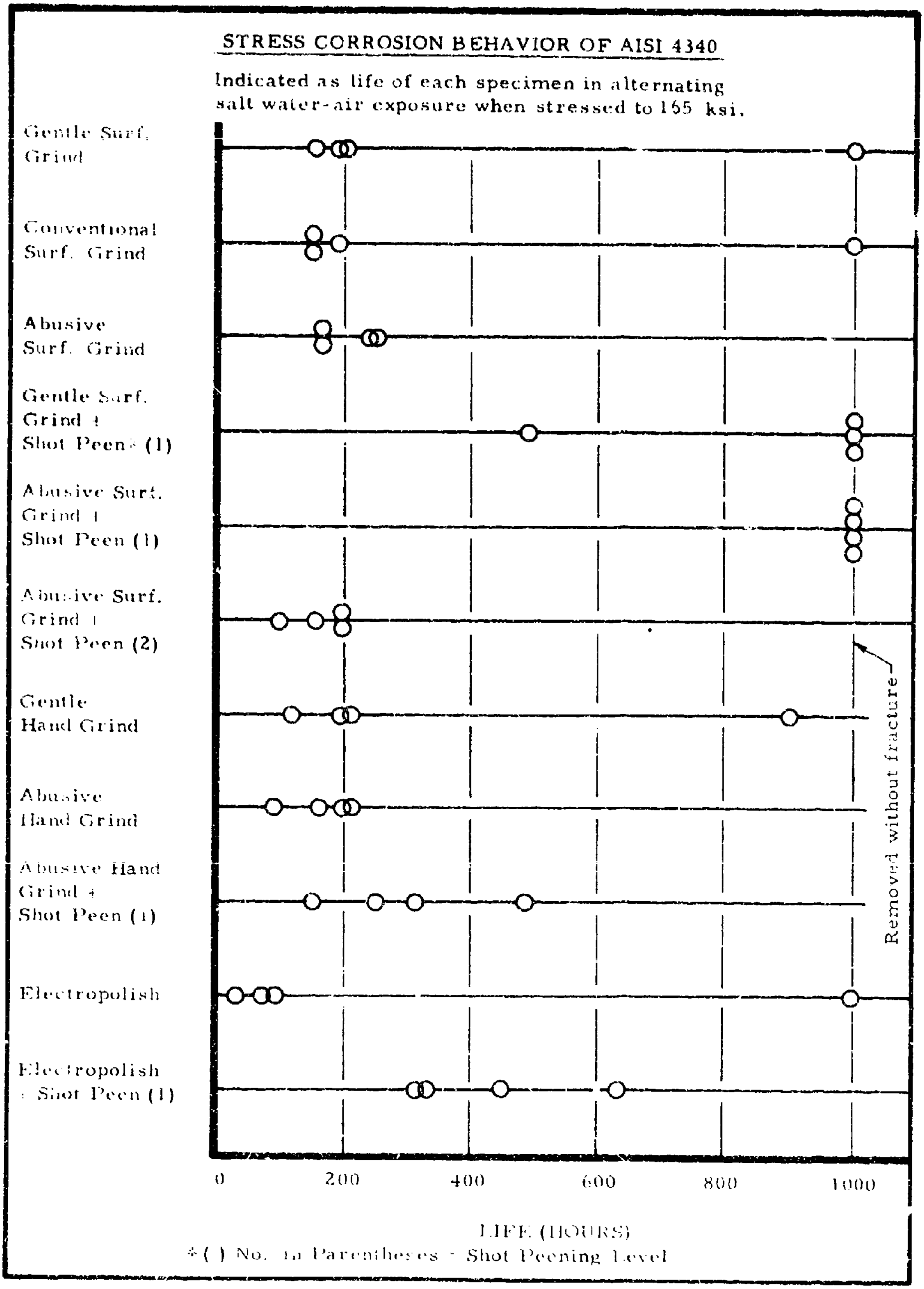

STRESS CORROSION BEHAVIOR OF AISI 4340
Indicated as life of each specimen in alternating salt water-air exposure when stressed to 165 ksi.
Gentle Surf. Grind
Conventional Surf. Grind
Abusive Surf. Grind
Gentle Surf. Grind + Shot Peen* (1)
Abusive Surf. Grind + Shot Peen (1)
Abusive Surf. Grind + Shot Peen (2)
Gentle Hand Grind
Abusive Hand Grind
Abusive Hand Grind + Shot Peen (1)
Electropolish
Electropolish + Shot Peen (1)
Removed without fracture
0
200
400
600
800
1000
LIFE (HOURS)
*( ) No. in Parentheses - Shot Peening Level

Figure 50

6.3 Summary of Results for Inconel 718

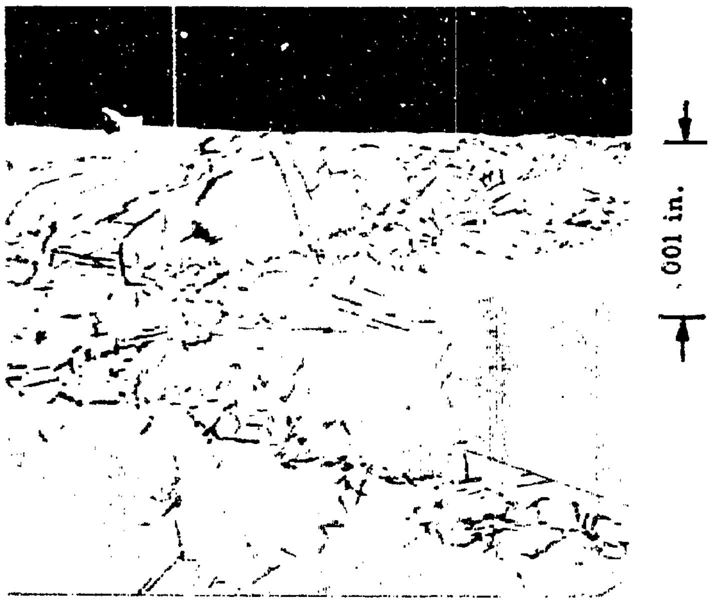
Metallography

The metallography of all of the surface conditions studied for Inconel 718 is presented in Figures 51 through 68. Surface effects exhibited by Inconel 718 were evaluated in two different heat treatment conditions. The basic heat treatment studied was the standard solutioning and aging, as described in Section 5.2, which resulted in a hardness of 44 R_c. The second study consisted of performing the metal removal operation on the material after solution treating followed by aging in vacuum. In this case, the metallographic studies including microhardness measurements were performed after solution treating only. Residual stress and fatigue studies, however, were performed on samples after the vacuum aging had been completed.

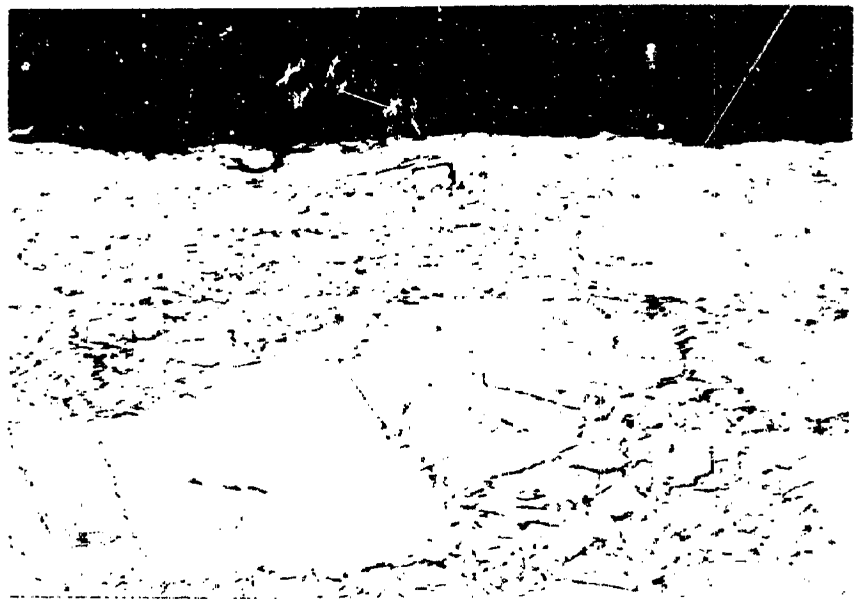
Photomicrographs of Inconel 718 produced by gentle, conventional, and abusive grinding are shown in Figure 51 for the as-solutioned material and in Figure 52 for the fully aged material. Notice the increasing surface roughness associated with an increase in grinding severity. Notice also the microhardness increase associated with conventional and abusive grinding on the solution treated material. This hardness increase is believed due to localized aging of the alloy during grinding because of localized surface heating. Notice that the depth of hardness increase is much greater in the case of abusive grinding than in the case of conventional grinding (.015 in. versus .005 in.). The gentle grinding did not produce sufficient heating to cause any measurable surface hardness increase. Microhardness variation in the fully aged material was not observed. This is shown in Figure 52. In both of these materials, microstructure changes are at a minimum, except for differences in surface roughness as noted above.

Cross sections of surfaces produced by hand grinding under both gentle and abusive conditions on fully heat treated Inconel 718 are shown in Figure 53. This procedure gave evidence of neither microstructure nor hardness change. The surface roughness, however, is somewhat greater than was observed with the surface ground samples.

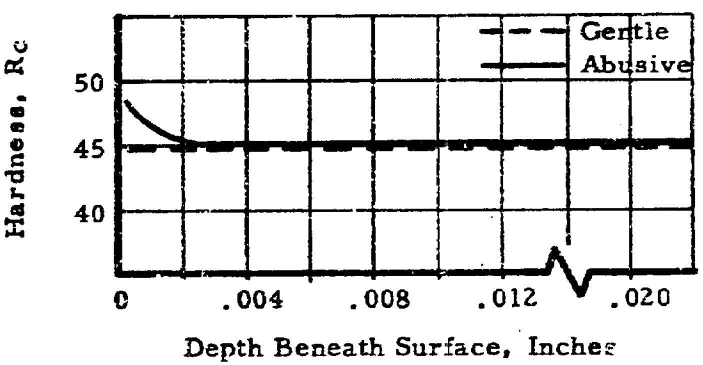
Photomicrographs of Inconel 718 produced by end milling are shown in Figures 54 and 55. The end milling-end cutting (Figure 54) shows no evidence of measurable hardness change, although a small degree of plastic deformation can be seen on the sample cut under abusive conditions. Peripheral cutting (Figure 55) produced a higher degree



(a) Gentle Conditions - No visible surface deformation.
Surface Finish: 20 AA 1000X



(b) Abusive Conditions - Slight plastic deformation and surface tearing plus microhardness increase approximately .002" deep.
Surface Finish: 65 AA 1000X



SURFACE CHARACTERISTICS OF
INCONEL 718 (Solution Treated and Aged, 44 R_c)
PRODUCED BY END MILLING - PERIPHERAL CUTTING

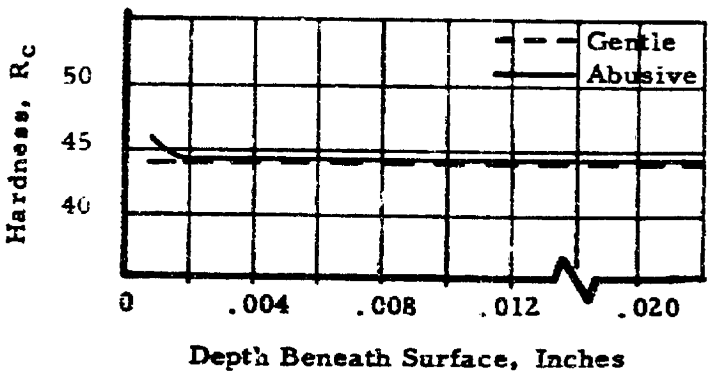
Figure 55

(a) Gentle Conditions - Thin layer of surface distortion is evident, but of insufficient depth to detect hardness change.

1000X

(b) Abusive Conditions - Surface distortion readily apparent. Microhardness increase indicates strain hardening approximately .002" deep.

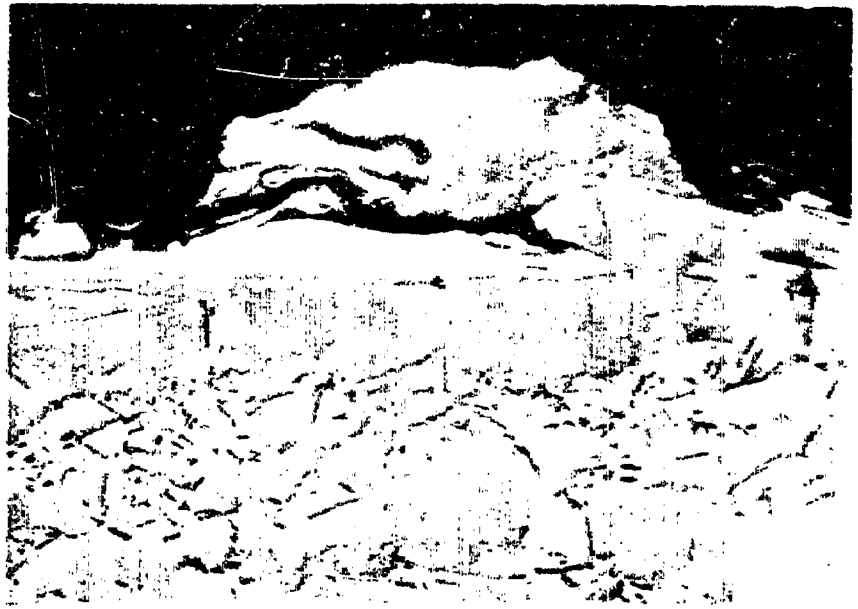
1000X



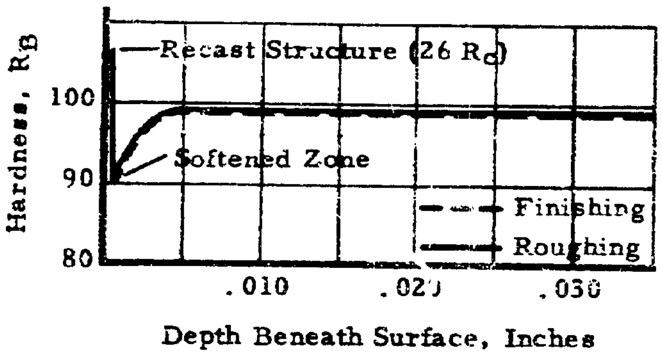
SURFACE CHARACTERISTICS OF
INCONEL 718 (Solution Treated and Aged, 44 R_c)
PRODUCED BY DRILLING

Figure 56

(a) Finishing Conditions - A thin discontinuous recast layer .0001" deep and a softened subsurface zone were produced on the surface.
Surface Finish: 65 AA 1000X

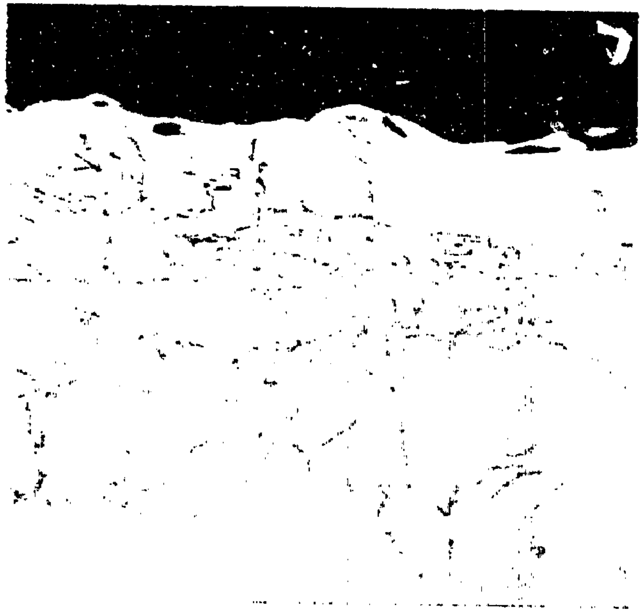


(b) Roughing Conditions - A discontinuous recast layer plus spattered recast metal was deposited at depths up to .002" across the surface. Subsurface softening for a total depth of .004" was also observed.
Surface Finish: 155 AA 1000X

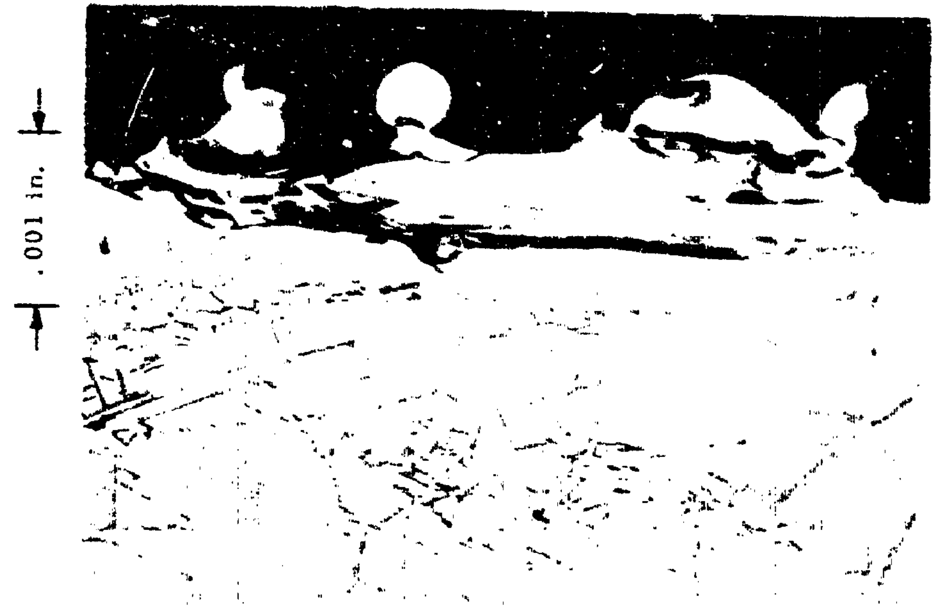


SURFACE CHARACTERISTICS OF
INCONEL 718 (Solution Treated, 98 R_B)
PRODUCED BY EDM

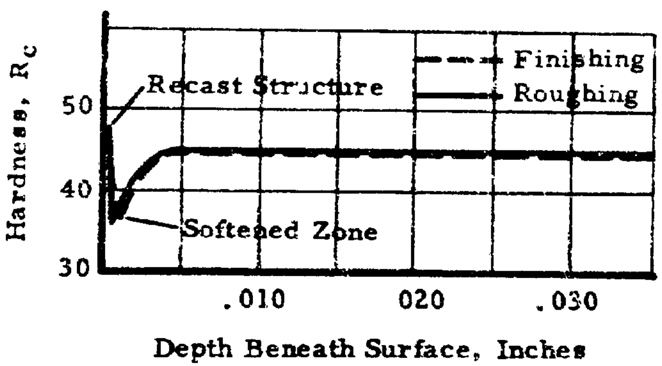
Figure 57



(a) Finishing Conditions - A thin recast layer averaging less than .0001" was produced on the surface. A softening was also produced.
Surface Finish: 60 AA 1000X



(b) Roughing Conditions - A discontinuous recast layer averaging .0015" deep was formed on the surface. Subsurface softening was evidenced for a total depth of .004".
Surface Finish: 170 AA 1000X



SURFACE CHARACTERISTICS OF
INCONEL 718 (Solution Treated and Aged, 44 R_c)
PRODUCED BY EDM

Figure 58

6.3 Summary of Results for Inconel 718 (continued)

Metallography (continued)

correcting or compensating for surface damage associated with the metal removal operation. Figure 67 shows the effects of a complete reheat treatment on Inconel 718 which had been finished by a conventional grinding operation. The microstructure resulting is essentially the same as that prior to the post heat treatment, as may be seen by comparing Figure 67 to Figure 52(b). The post heat treatment does impose a very slight surface softening which was not evident in the conventionally ground sample in the as-machined condition. This slight softening may be within the realm of experimental error in making microhardness measurements or may be due to a chemistry change at the surface which occurred during the post heat treatment, even though this was carried out in a vacuum.

Figure 68 shows surfaces of two samples originally processed by EDM under roughing conditions and then subjected to post heat treatments. Figure 68(a) was subjected to the full Inconel 718 heat treatment cycle in vacuum. The sample shown in Figure 68(b) was subjected to the aging cycle only -- 1325°F/8 hours, etc. (see Section 5.2). In comparing Figures 58(b) and 68(b), it may be concluded that the microstructure was unaffected by the aging cycle alone. In Figure 68(a), however, it may be seen that the full heat treatment cycle accomplished a partial solution as well as other alterations in the recast surface layer which had been produced by EDM. Likewise, the post heat treatment operations succeeded in eliminating the high surface hardness of the recast structure. These changes may be seen by comparing hardness data in Figure 68 with that shown in Figure 58.

Residual Stress

Residual stress data obtained on Inconel 718 are summarized in Figures 69 through 78. Plots of surface grinding under gentle, conventional, and abusive conditions are shown in Figure 69. These data are quite typical of residual stress distribution patterns associated with grinding. Gentle grinding produces a peak subsurface stress of a moderate level in compression, while abusive and conventional grinding produce surface and subsurface tensile stresses. Also typical, the abusive surface grinding causes somewhat deeper penetration of stress than does the conventional grinding.

Residual Stress (continued)

EDM under both roughing and finishing conditions causes moderately high residual tensile stress to be formed. Compared with grinding, however, the depth of these stresses is quite shallow. Likewise, the stress distributions associated with roughing and finishing EDM are very similar. These comparisons may be seen in Figure 70.

Figure 71 shows residual stress distributions measured in ECM surfaces produced under both gentle and abusive conditions. In both instances, stress-free surfaces are produced. A similar behavior is shown in Figure 72 for electropolishing. This curve also shows the effect of electropolishing prior to aging, which again gives rise to a stress-free condition.

Residual stress distribution associated with shot peening has also been determined on several different Inconel 718 surfaces. Shot peening distribution as applied to ELP is shown in Figure 72. The high level of compressive stress indicated is characteristic of the shot peening process. The effect of shot peening on stress distribution in EDM surfaces is shown in Figure 73. The effect of shot peening as well as glass bead peening on ECM surfaces is shown in Figure 74. The pattern of high residual surface and subsurface compression for all of these conditions is evident.

The distribution of residual stress in Inconel 718 which had been solution treated, machined, and then aged in vacuum is shown in Figures 75 through 77. Data are presented for grinding, EDM, and ECM, respectively. Notice that the orientation of residual stress in each case is similar to the conventionally processed counterpart, although the magnitude of stresses is greatly reduced. This may be seen for grinding by comparing Figures 75 to 69; for EDM, by comparing Figures 76 and 70; and for ECM, by comparing Figures 77 and 71. Presumably, this very substantial reduction in residual stress is due to stress relief and relaxation during the aging cycle.

Residual stresses found in surfaces which had been fully reheat treated after machining are shown in Figure 78 for conventional grinding and roughing EDM. Here again, it may be seen that the stress levels are greatly reduced by the heat treating cycle.

6.3 Summary of Results for Inconel 718 (continued)

Fatigue

Figures 79 and 80 summarize the fatigue behavior of Inconel 718 which had been fully heat treated before surface test cuts were made. Figure 79 shows fatigue strengths produced by the various metal removal processes, while Figure 80 shows the effects of shot peening and reheat treatment which are applied as post-processing operations. Figure 81 shows the fatigue strength of Inconel 718 which was machined in the solution treated condition followed by aging in vacuum after machining.

As indicated in Figure 79, the gentle grinding condition, which we consider as a baseline reference, produced an endurance limit of 60 ksi in Inconel 718. In contrast, a nominal conventional grinding caused a depression in fatigue strength to 24 ksi. Of particular interest is the fatigue behavior exhibited by EDM and ECM surfaces. Both roughing and finishing EDM yielded fatigue strengths of 22 ksi, while both gentle and abusive ECM yielded fatigue strengths of 39 ksi. It was quite significant to note here that both the gentle and abusive (or finishing and roughing) versions of these processes yield the same fatigue strength level. It is also of particular interest to note that the endurance limit produced by EDM under finishing and roughing conditions is identical, even though the surface finishes are 60 and 170 microinches AA.

Electrolytic polishing applied to Inconel 718 exhibited an endurance limit of 42 ksi. In reviewing Figure 79, the interesting points to be noted are the range of endurance limits associated with these different properties as well as the lack of difference between gentle and abusive processing under EDM and ECM. A comparison of surface finish as shown in Figure 79 with the endurance limit fails to establish any correlation between surface finish and fatigue strength. To the contrary, a careful review of the surface finish data presented suggests that such a correlation does exist.

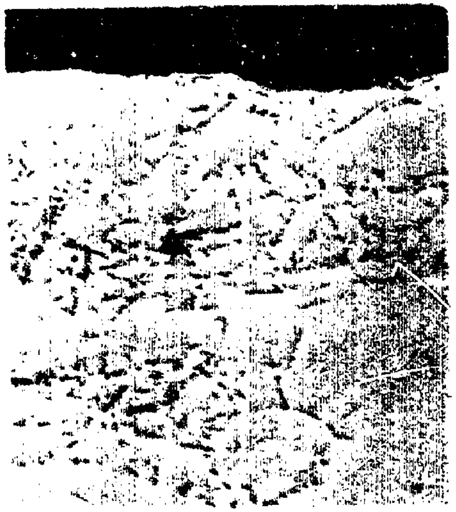
Figure 80 shoes the effect of peening and post heat treatment on several different Inconel 718 surfaces. A comparison between Figures 80 and 79 indicates that all of these post-processing treatments are effective in, to some degree, improving fatigue strength. It is obvious, however, that the peening operations are much more potent than the post heat treating operations in improving fatigue strength.

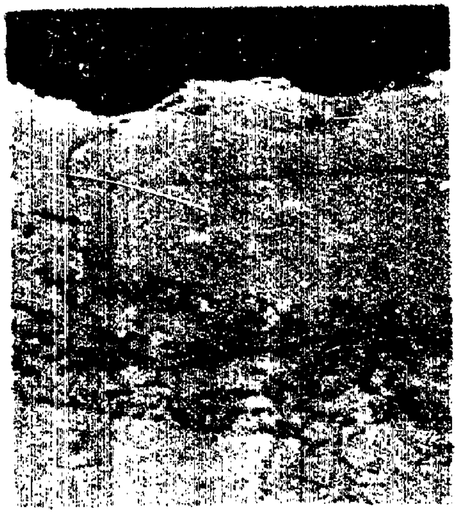
6.3 Summary of Results for Inconel 718 (continued)

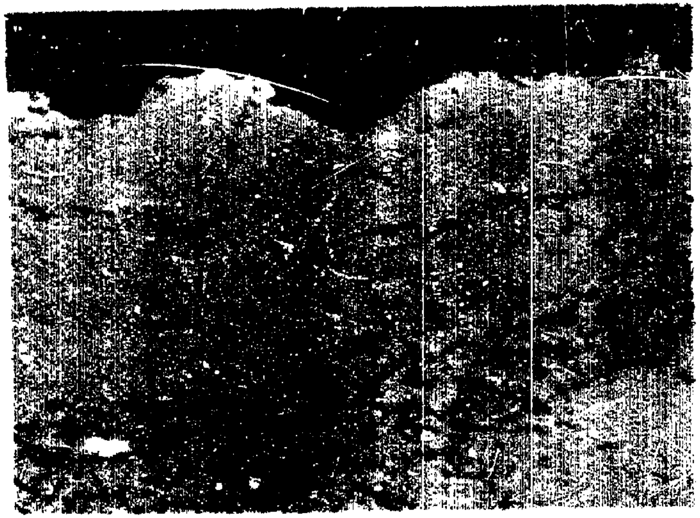
Fatigue (continued)

The fatigue strengths exhibited by Inconel 718 which was machined in the solution treated condition and subsequently aged in vacuum are shown in Figure 81. In this case, gentle grinding produced an endurance limit of 74 ksi as compared to 60 ksi following grinding in the fully heat treated condition (Figure 79). The reason for this strength level, as well as those exhibited by EDM and ECM being higher than their counterparts in Figure 77, is not understood. The difference may, however, be due to a change in surface chemistry. It is interesting to note, however, that here again both gentle and abusive ECM have the same endurance limit, 42 ksi. Likewise, finishing and roughing EDM have the same endurance limit, 29 ksi. For the EDM process, it is again particularly interesting in view of the big difference in surface finish between finishing and roughing cuts, 65 and 155 microinches AA, respectively.

ELP on Inconel 718 in the solution treated condition, followed by aging in vacuum, yielded a fatigue strength of 28 ksi. The reason for this low value in comparison to 42 ksi resulting from ELP after full heat treatment is not understood. All of the ELP samples were examined metallographically, but a condition which might explain this behavior was not observed.



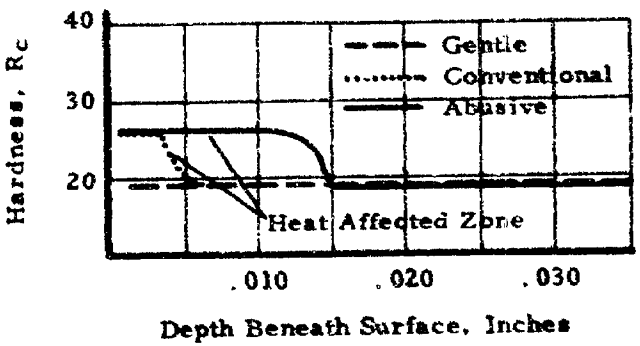




(a) Gentle Conditions (b) Conventional Conditions (c) Abusive Conditions

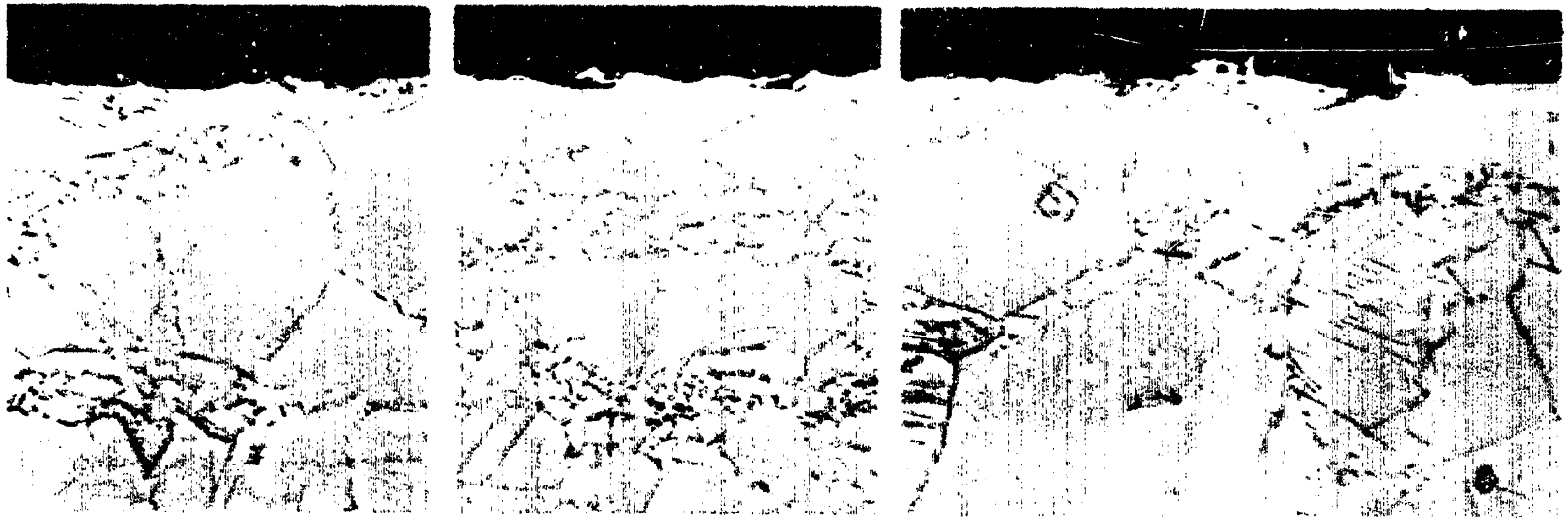
Gentle conditions produced no visible surface alteration. Conventional and abusive conditions both produced an elevation of surface hardness as noted below. The total depth affected was approximately .005" by conventional grinding and .015" by abusive grinding. The hardness increase may be due to a partial aging of this material, which was in the solution treated state.

Surface Finish: 17AA Surface Finish: 46AA Surface Finish: 86AA



SURFACE CHARACTERISTICS OF
INCONEL 718 (Solution Treated, 98 R_B)
PRODUCED BY GRINDING

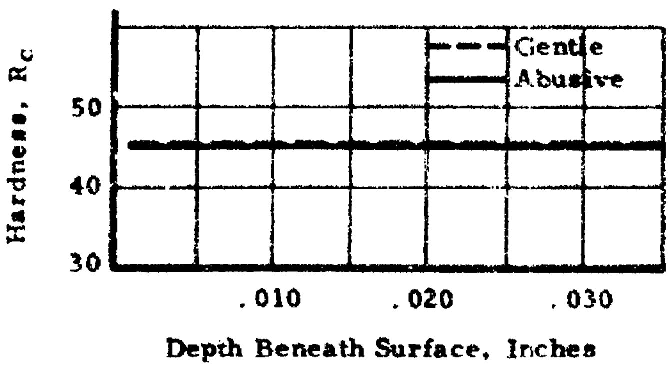
Figure 51



(a) Gentle Conditions (b) Conventional Conditions (c) Abusive Conditions

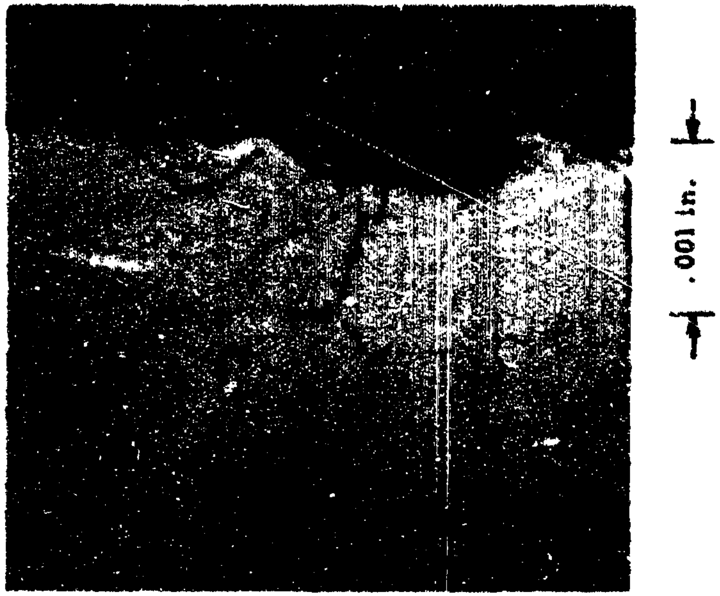
None of the various grinding procedures produced visible surface alterations as a result of the particular grinding variables employed. The absence of surface changes is judged both from microstructure and from microhardness measurement.

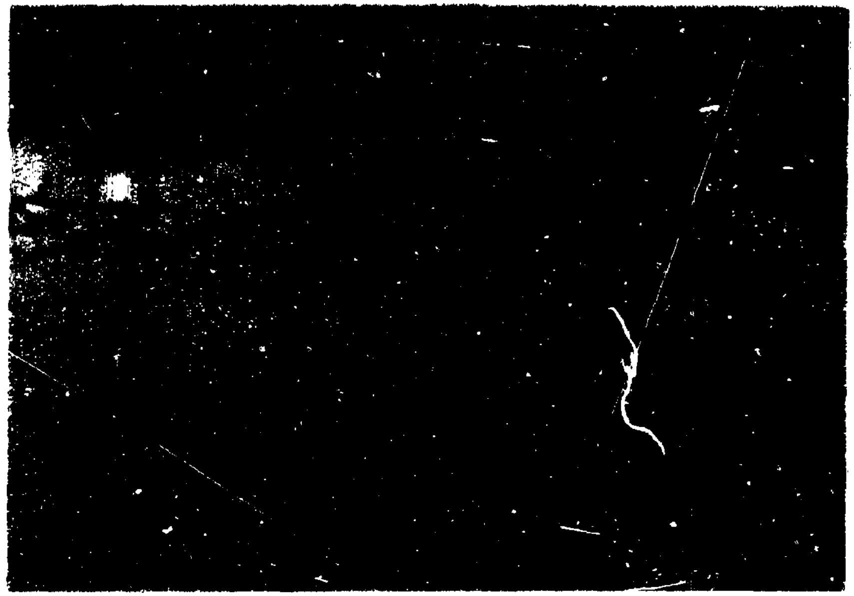
Surface Finish: 15AA Surface Finish: 22AA Surface Finish: 40AA



SURFACE CHARACTERISTICS OF
INCONEL 718 (Solution Treated and Aged, 44 R_c)
PRODUCED BY GRINDING

Figure 52



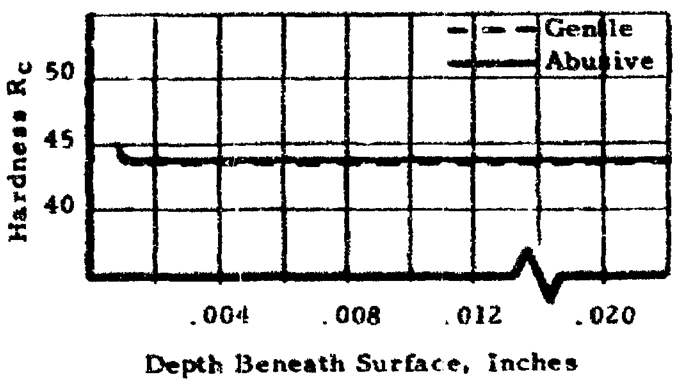


(a) Gentle Conditions - Moderate surface roughness, but without other evidence of distortion.

Surface Finish: 75AA 1000X

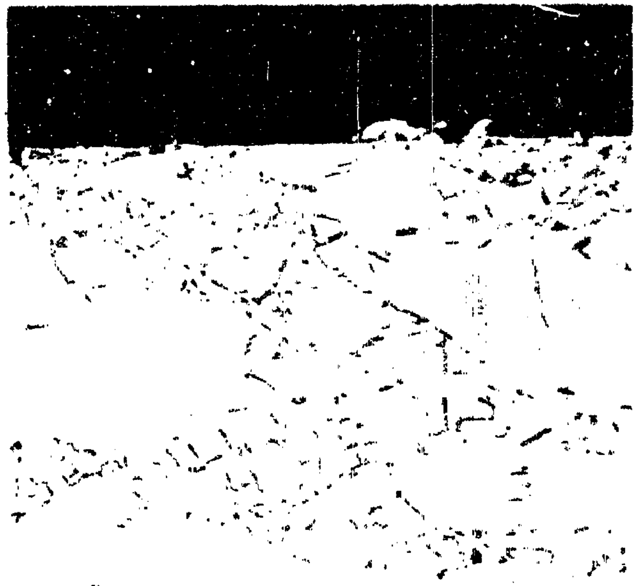
(b) Abusive Conditions - Fairly severe surface roughness with some evidence of tearing, but lacking subsurface distortion.

Surface Finish: 130AA 1000X

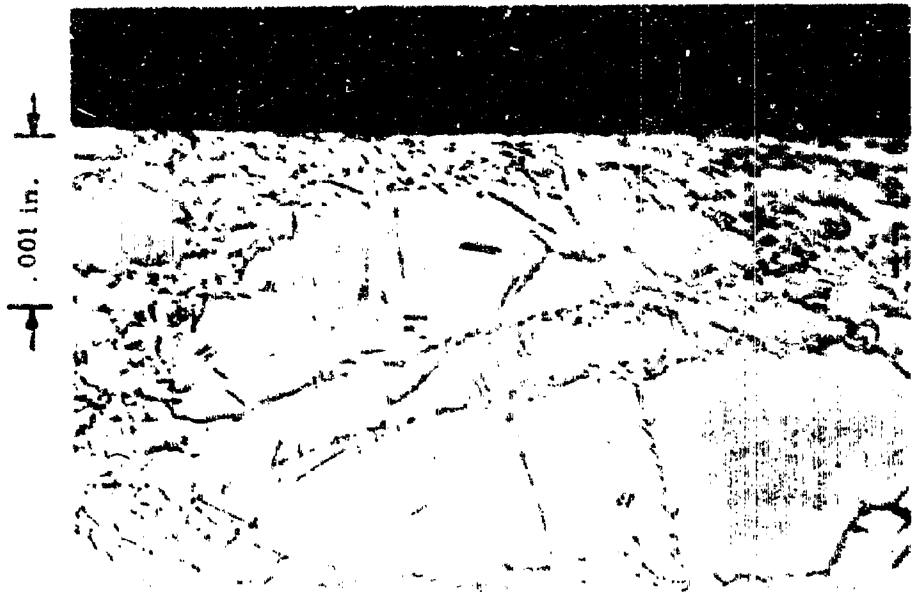


SURFACE CHARACTERISTICS OF
INCONEL 718 (Solution Treated and Aged, 44 R_c)
PRODUCED BY HAND GRINDING

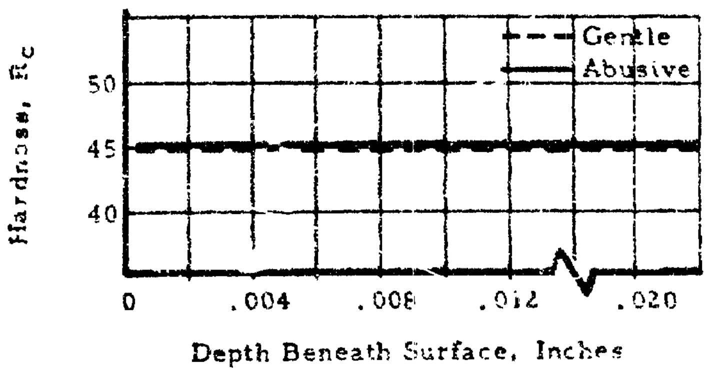
Figure 53



(a) Gentle Conditions - Slight built-up edge in isolated areas but without visible sub-surface distortion.
Surface Finish: 35 AA 1000X



(b) Abusive Conditions - Uniform layer of plastic deformation approximately .0003" deep but without measurable hardness change.
Surface Finish: 50 AA 1000X



SURFACE CHARACTERISTICS OF
INCONEL 718 (Solution Treated and Aged, 44 R_c)
PRODUCED BY END MILLING - END CUTTING

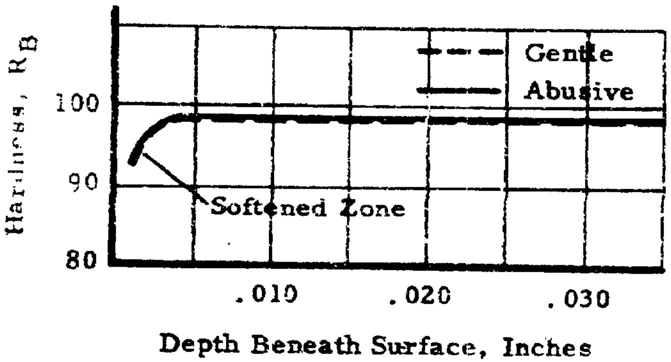
Figure 64

(a) Gentle Conditions - No visible surface alterations were produced although some surface softening was noted.

Surface Finish: 19 AA 1000X

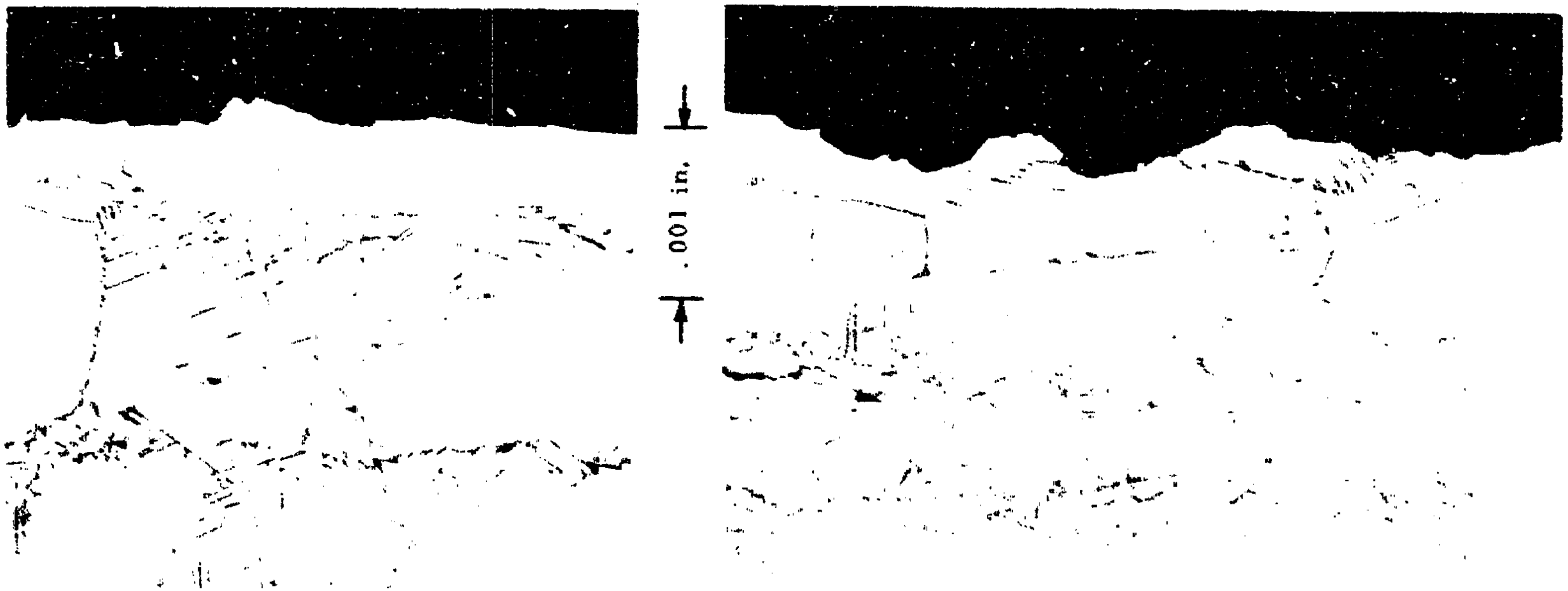
(b) Abusive Conditions - A relatively rough angular surface resulted from this procedure. Surface softening was observed by microhardness measurement.

Surface Finish: 55 AA 1000X



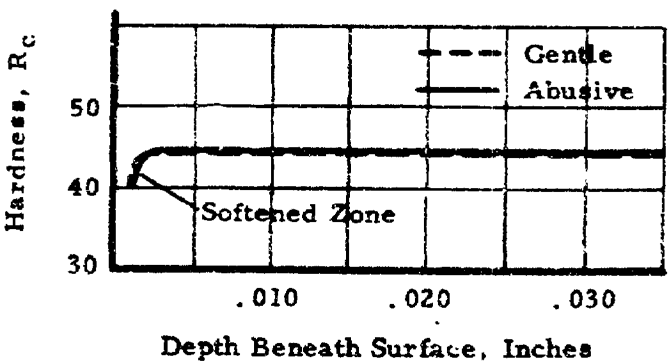
SURFACE CHARACTERISTICS OF INCONEL 718 (Solution Treated, 98 R_B) PRODUCED BY ECM

Figure 59



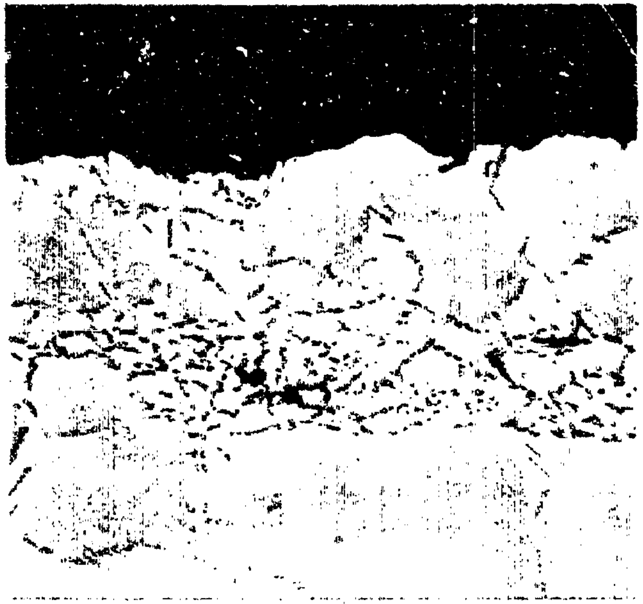
(a) Gentle Conditions - Subsurface softening plus a typical etched surface were produced.
Surface Finish: 43 AA 1000X

(b) Abusive Conditions - Subsurface softening plus an irregular surface were observed. Note the sharpness of surface irregularities as produced by ECM on this alloy.
Surface Finish: 74 AA 1000X

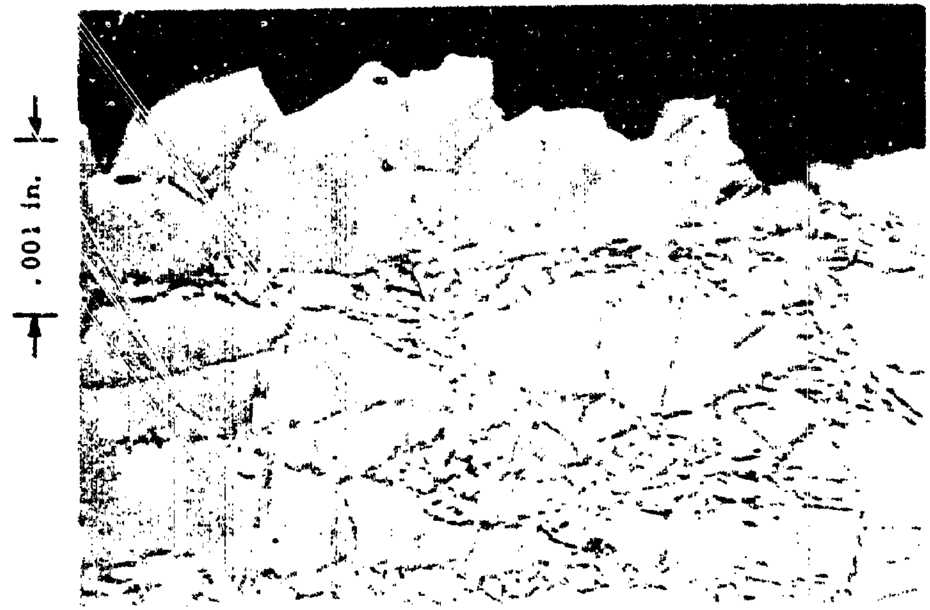


SURFACE CHARACTERISTICS OF
INCONEL 718 (Solution Treated and Aged, 44 R_c)
PRODUCED BY ECM

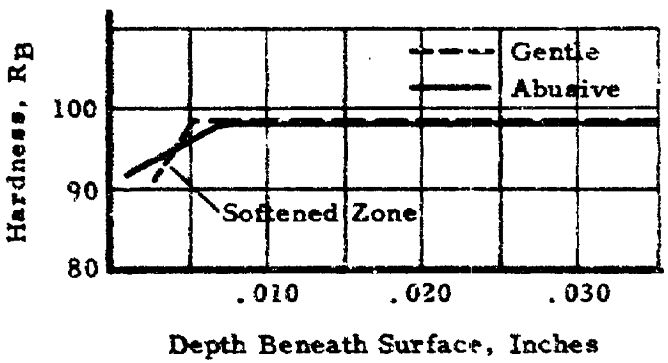
Figure 60



(a) Gentle Conditions - Subsurface softening and some evidence of intergranular penetration was produced.
Surface Finish: 125 AA 1000X

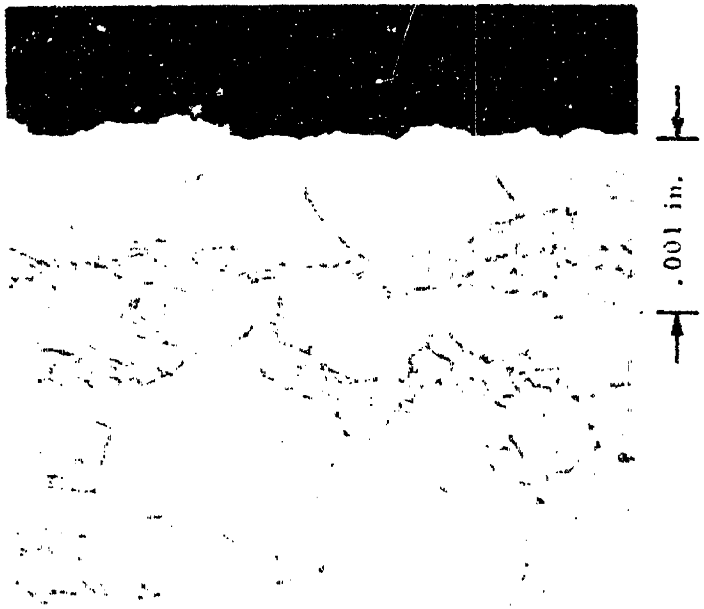


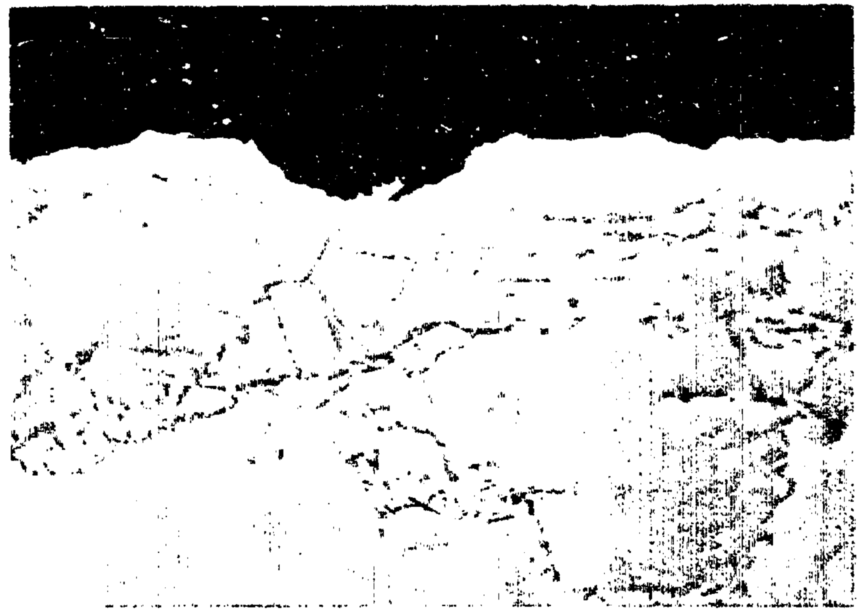
(b) Abusive Conditions - Subsurface softening, a considerable degree of surface irregularity, and evidence showing a tendency toward intergranular penetration may be seen.
Surface Finish: 180 AA 1000X



SURFACE CHARACTERISTICS OF
INCONEL 718 (Solution Treated, 98 R_B)
PRODUCED BY CHM

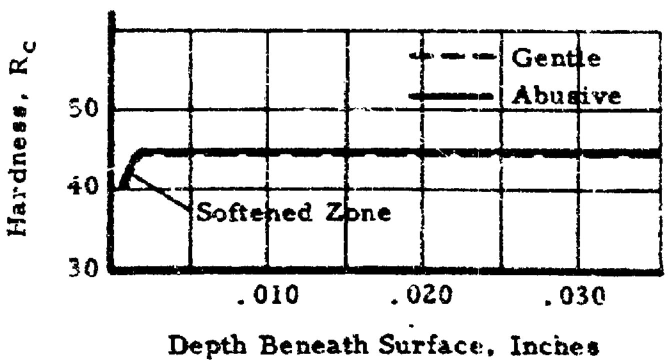
Figure 61





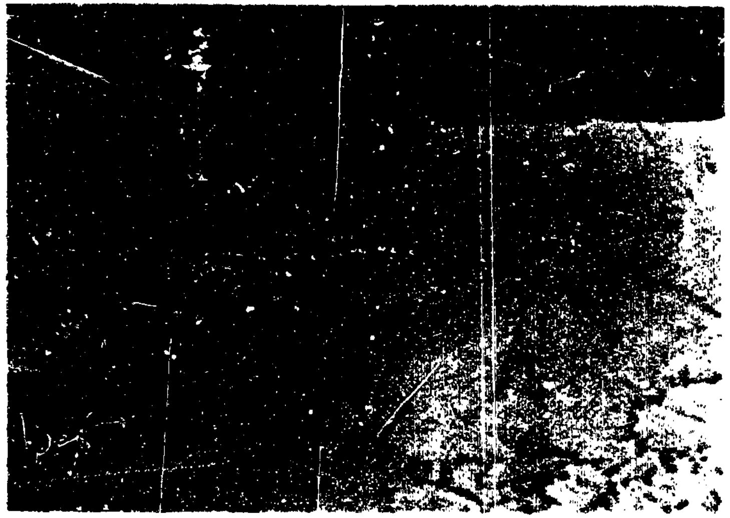
(a) Gentle Conditions - A somewhat irregular surface and slight softening at the surface were produced. 1000X
Surface Finish: 45 AA

(b) Abusive Conditions - Surface softening similar to that produced by the gentle conditions was produced. A considerably rougher surface and some tendency toward preferential attack or pitting may also be observed. 1000X
Surface Finish: 175 AA



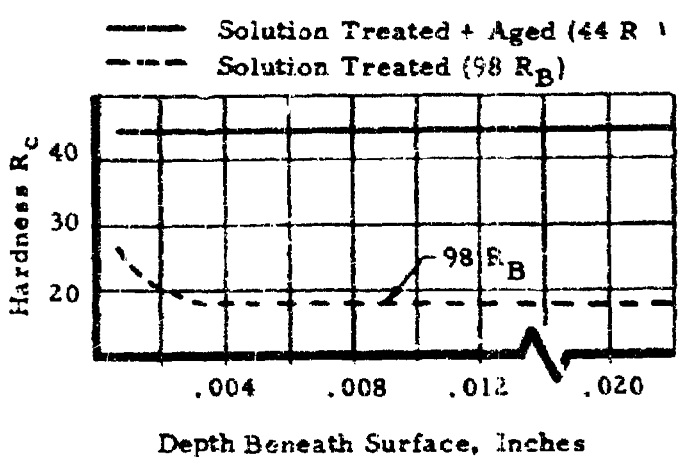
SURFACE CHARACTERISTICS OF
INCONEL 718 (Solution Treated and Aged, 44 R_c)
PRODUCED BY CHM

Figure 62



(a) Soultion Treated 98 R_B - No micro-structural alteration with significant surface hardness buildup as noted below.
Surface Finish: 15AA   1000X

(b) Solution Treated and Aged, 44 R_c - No visible surface distortion except for small random irregularities as shown above.
Surface Finish: 15AA   1000X



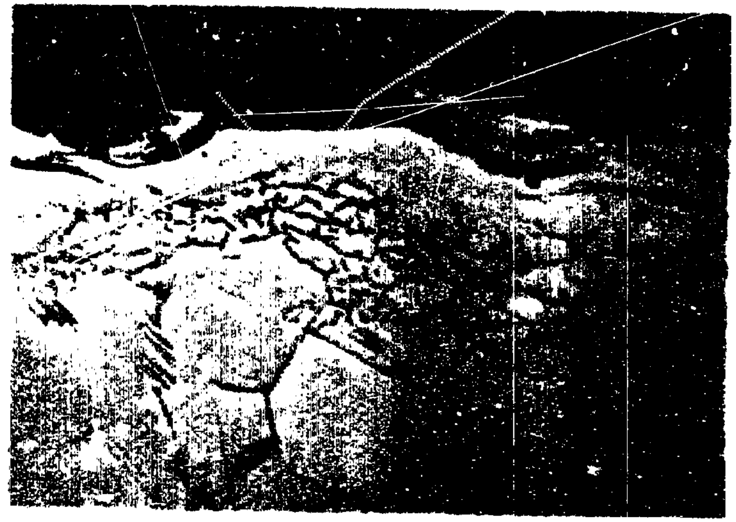
SURFACE CHARACTERISTICS OF
INCONEL 718 (Solution Treated and Aged, 44 R_c)
PRODUCED BY ELP

Figure 65

(a) Finishing EDM Plus Shot Peening (Level 1) - Recast surface layer due to EDM plus evidence of subsurface strain hardening due to peening may be seen.
Surface Finish: 43AA

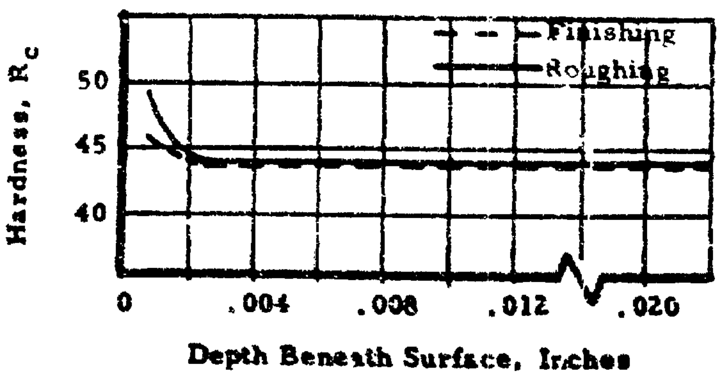
1000X

.001 in.



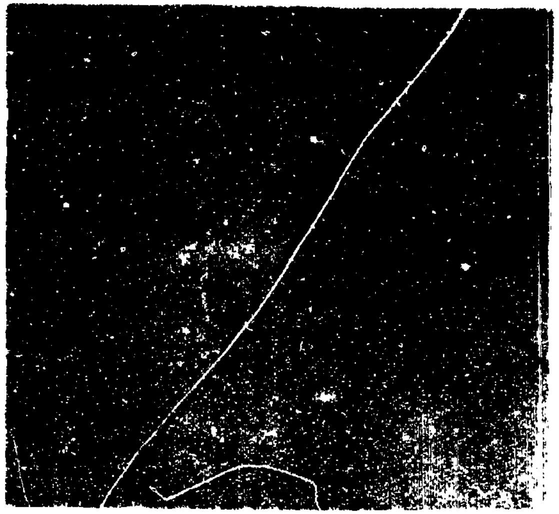
(b) Roughing EDM Plus Shot Peening (Level 1) Similar to finishing conditions, but with evidence of heavier, more discontinuous recast EDM layer.
Surface Finish: 125AA

1000X



SURFACE CHARACTERISTICS OF
INCONEL 718 (Solution Treated and Aged, 44 R_c)
PRODUCED BY EDM PLUS SHOT PEENING

Figure 64



(a) Gentle ECM Plus Shot Peening (Level I)

(b) Gentle ECM Plus Glass Bead Peen

(c) ELP Plus Shot Peening (Level I)

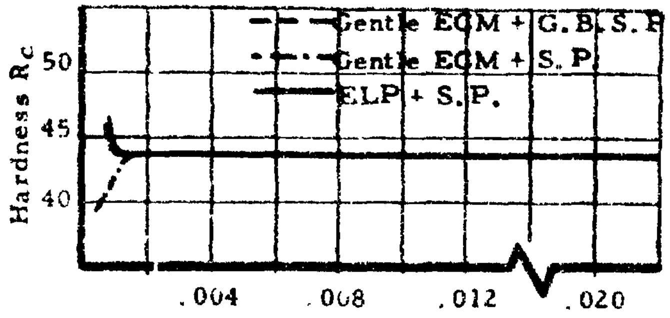
Surface roughening somewhat characteristic of the material removal method is evident in each case. The effect of shot peening is seen as strain hardening and twinning lines in the structure beneath the surface.

Surface Finish: 74AA

Surface Finish: 69AA

Surface Finish: 43AA

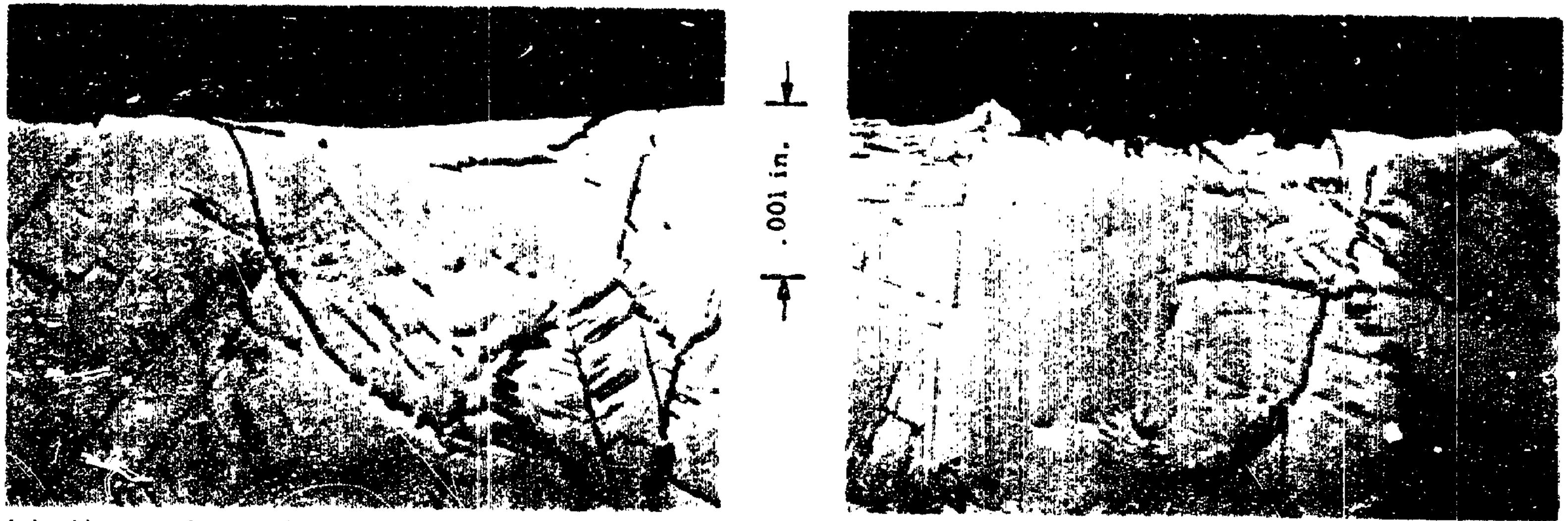
1000X



Depth Beneath Surface, Inches

SURFACE CHARACTERISTICS OF INCONEL 718 (Solution Treated and Aged, 44 R_c) PRODUCED BY ECM AND ELP PLUS SHOT PEENING

Figure 65



(a) Abusive ECM Plus Shot Peening (Level 1)

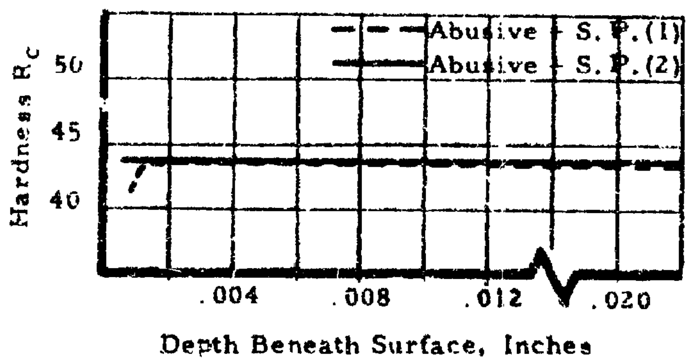
(b) Abusive ECM Plus Shot Peening (Level 2)

Surface roughness similar to that produced by ECM, but with additional tears and cracks, perhaps due to peening action. Subsurface strain lines due to peening are also visible.

Surface Finish: 119AA

Surface Finish: 90AA

1000X



SURFACE CHARACTERISTICS OF
INCONEL 718 (Solution Treated and Aged, 44 R_c)
PRODUCED BY ECM PLUS SHOT PEENING

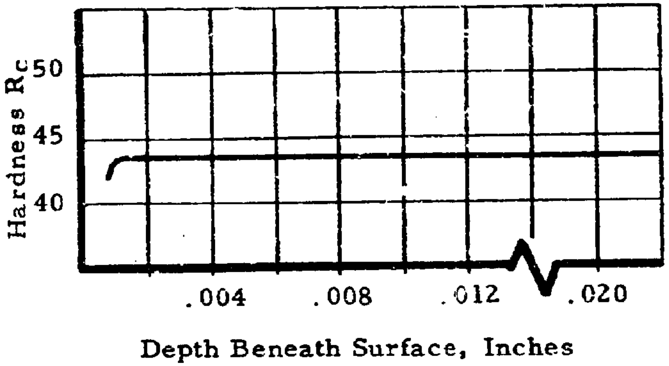
Figure 66

Conventional Grinding Plus Complete Reheat Treatment

Microstructure shows no evidence of distortion. Surface roughness shows no change from as-ground conditions.

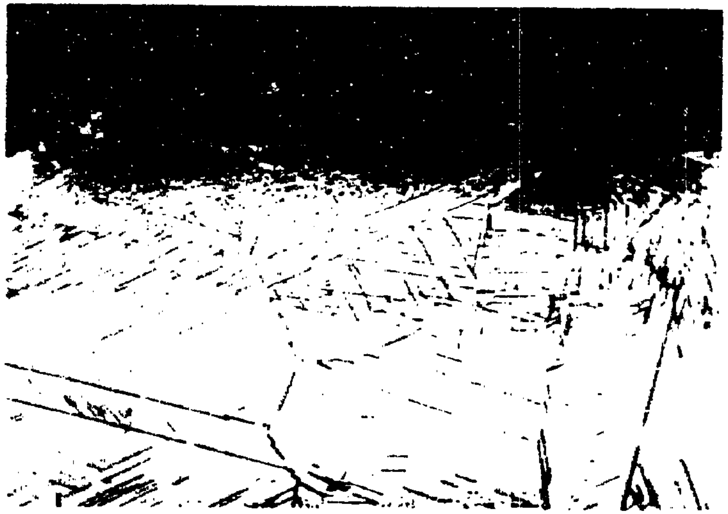
Surface Finish: 26AA

1000X



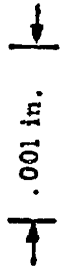
SURFACE CHARACTERISTICS OF
INCONEL 718 (Solution Treated and Aged, 44 R_c)
PRODUCED BY CONVENTIONAL GRINDING
PLUS COMPLETE REHEAT TREATMENT

Figure 67



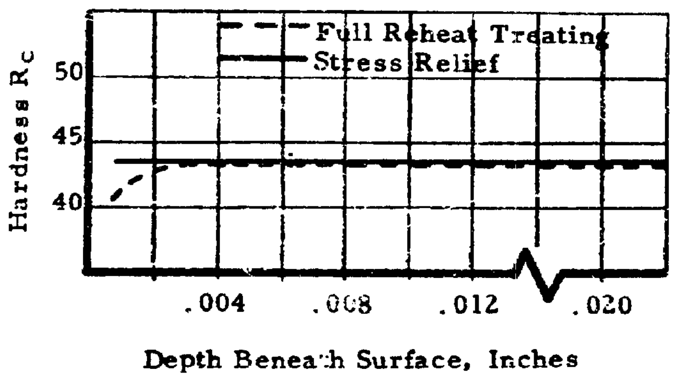
(a) Roughing EDM Plus Complete Reheat Treat - Recast EDM layer partially diffused, although porous surface deposit remains.
Surface Finish: 175AA

1000X



(b) Roughing EDM Plus Aging - No visible microstructure effect was produced by aging (stress relief) cycle.
Surface Finish: 221AA

1000X



SURFACE CHARACTERISTICS OF
INCONEL 718 (Solution Treated and Aged, 44 R_c)
PRODUCED BY EDM PLUS REHEAT TREATMENT

Figure 68

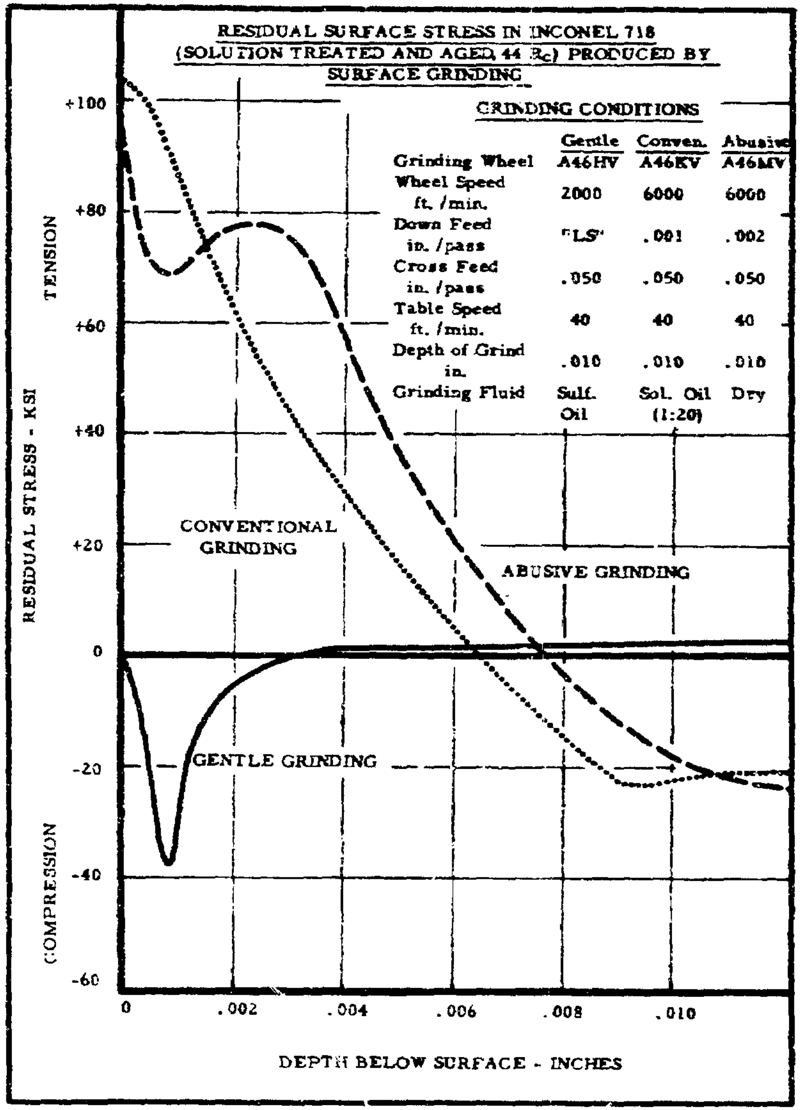


Figure 69

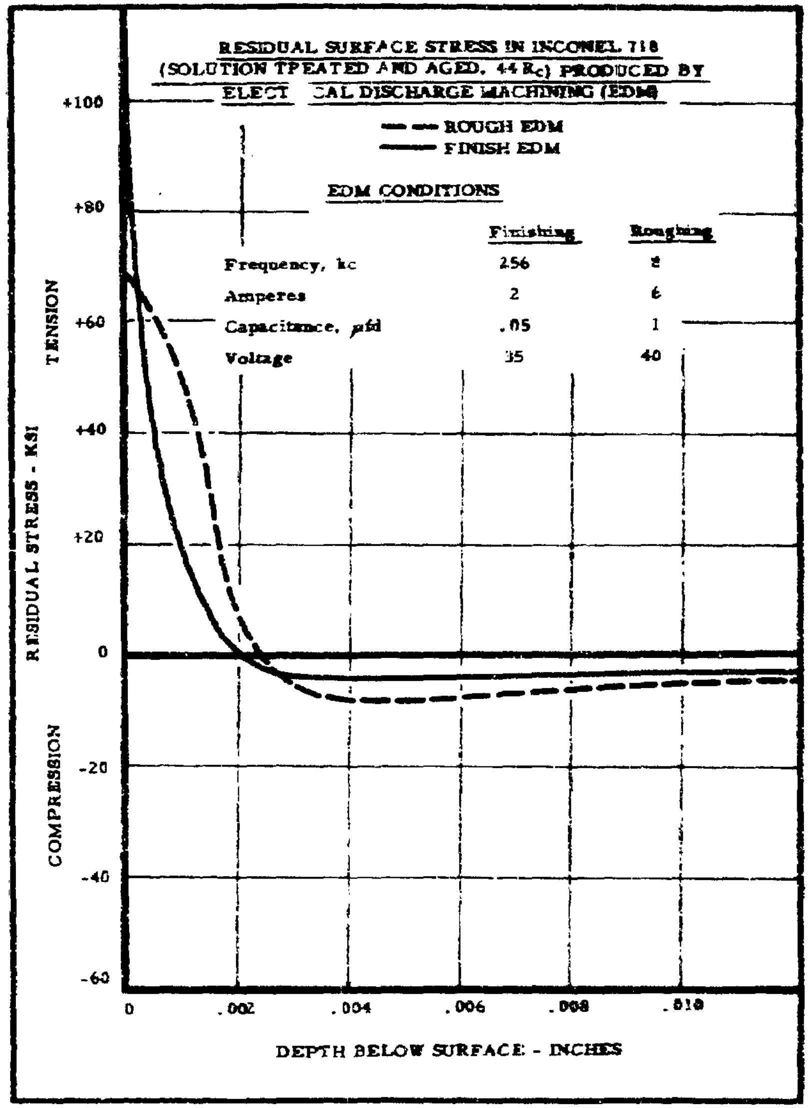


Figure 70

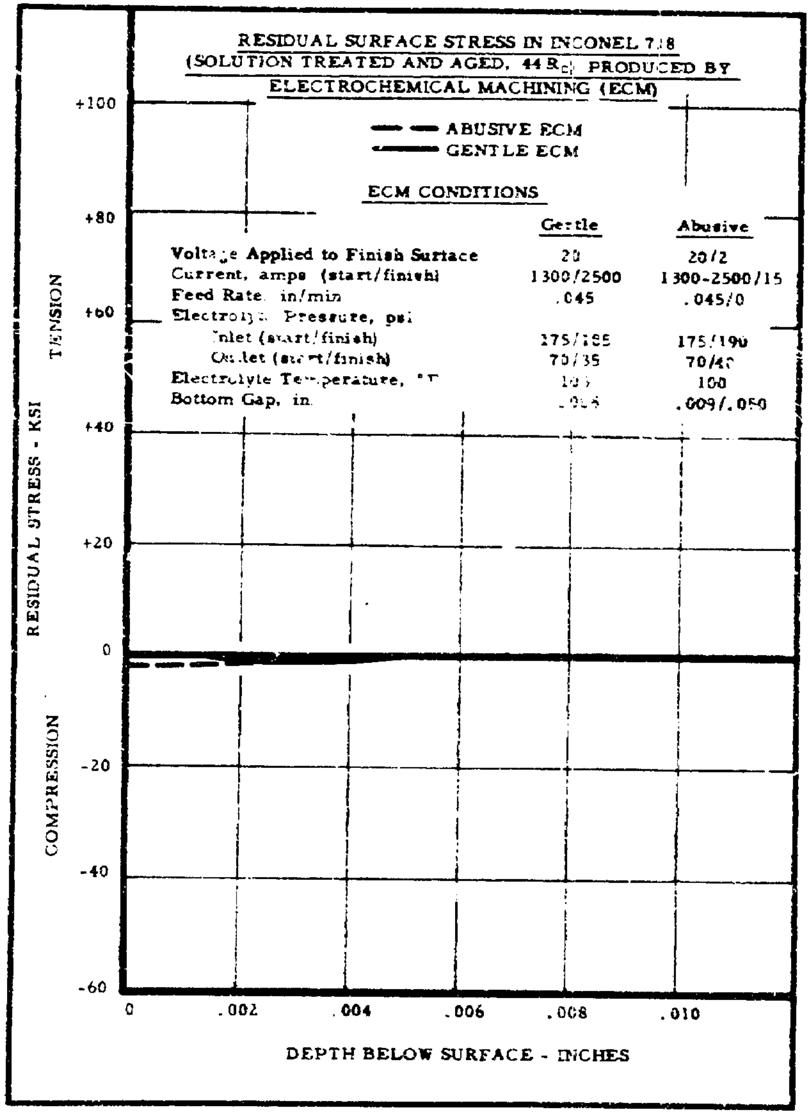


Figure 71

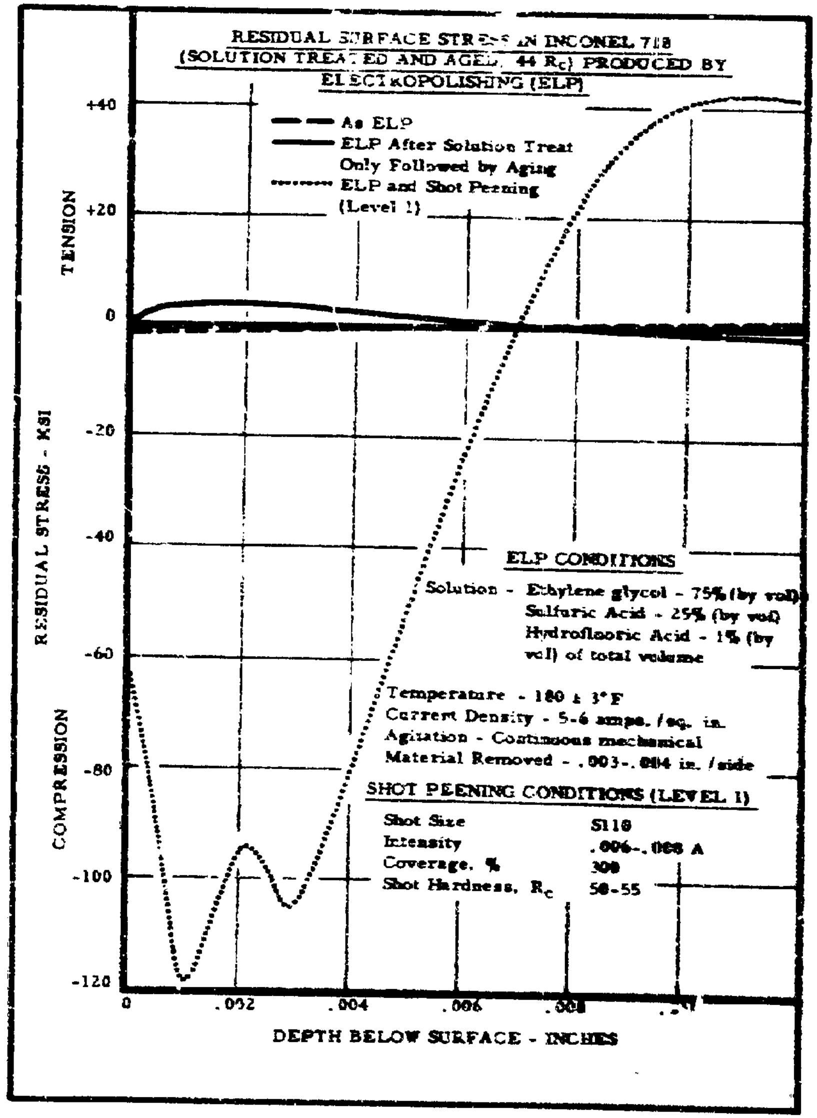


Figure 72

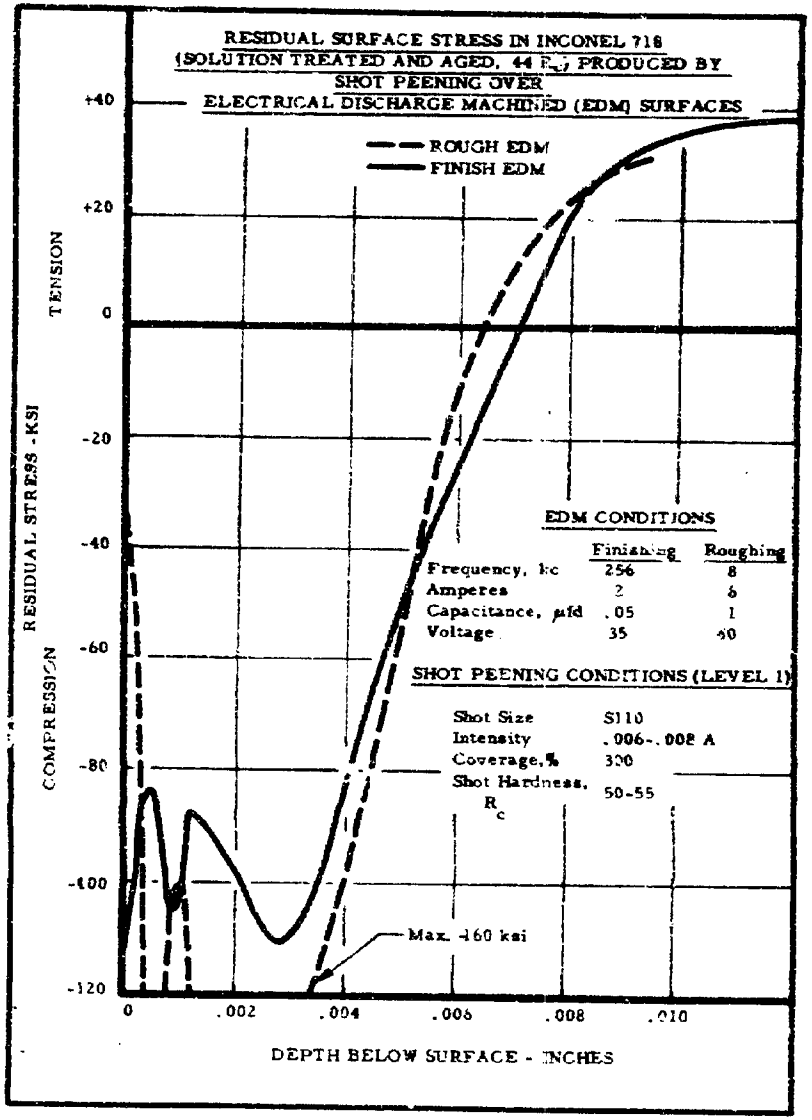


Figure 73

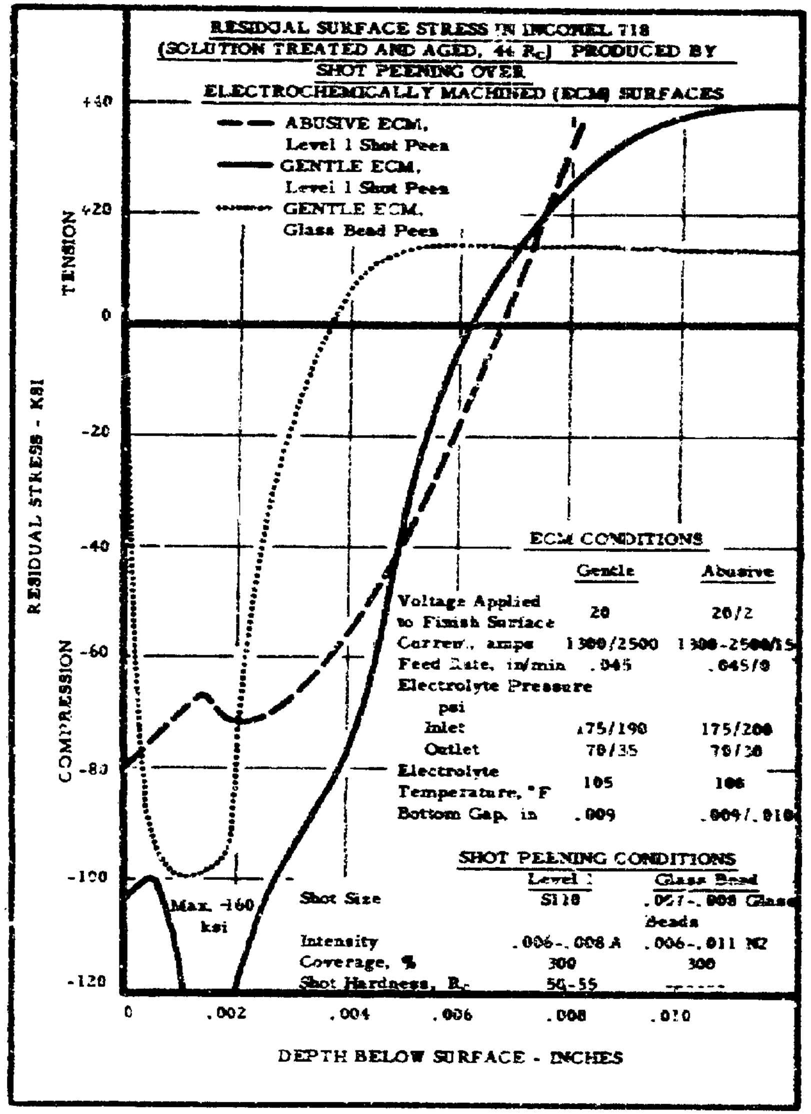


Figure 74

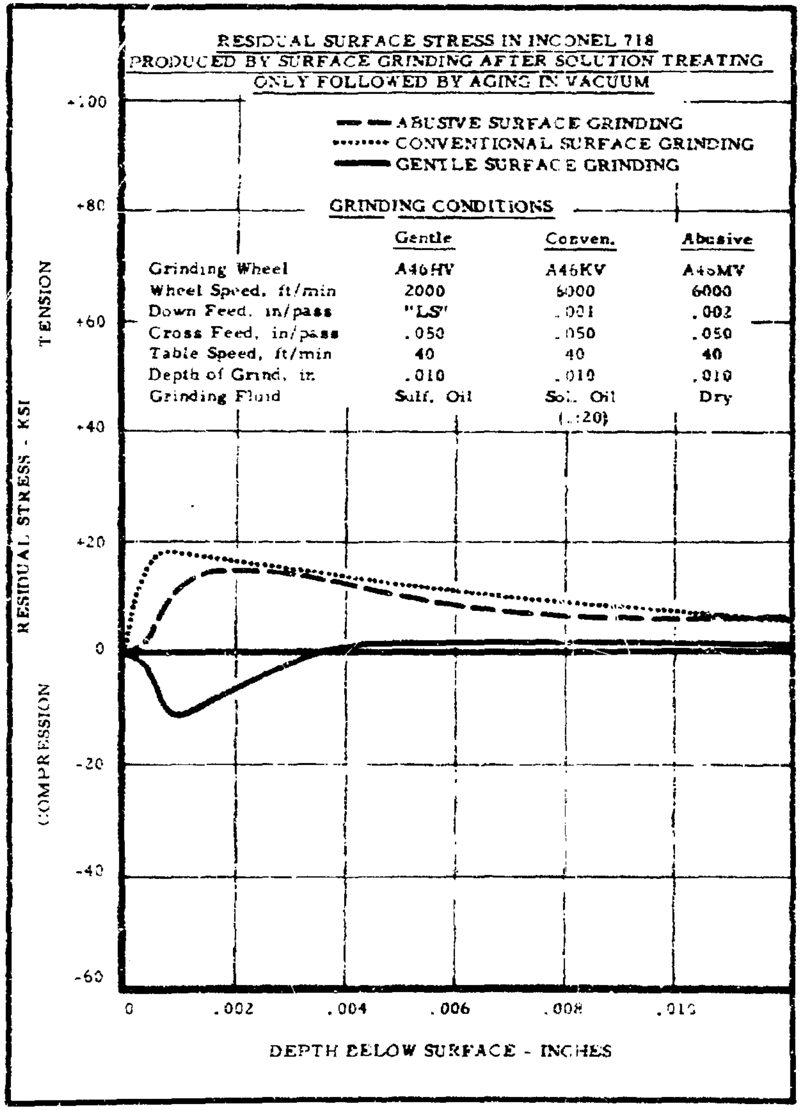


Figure 75

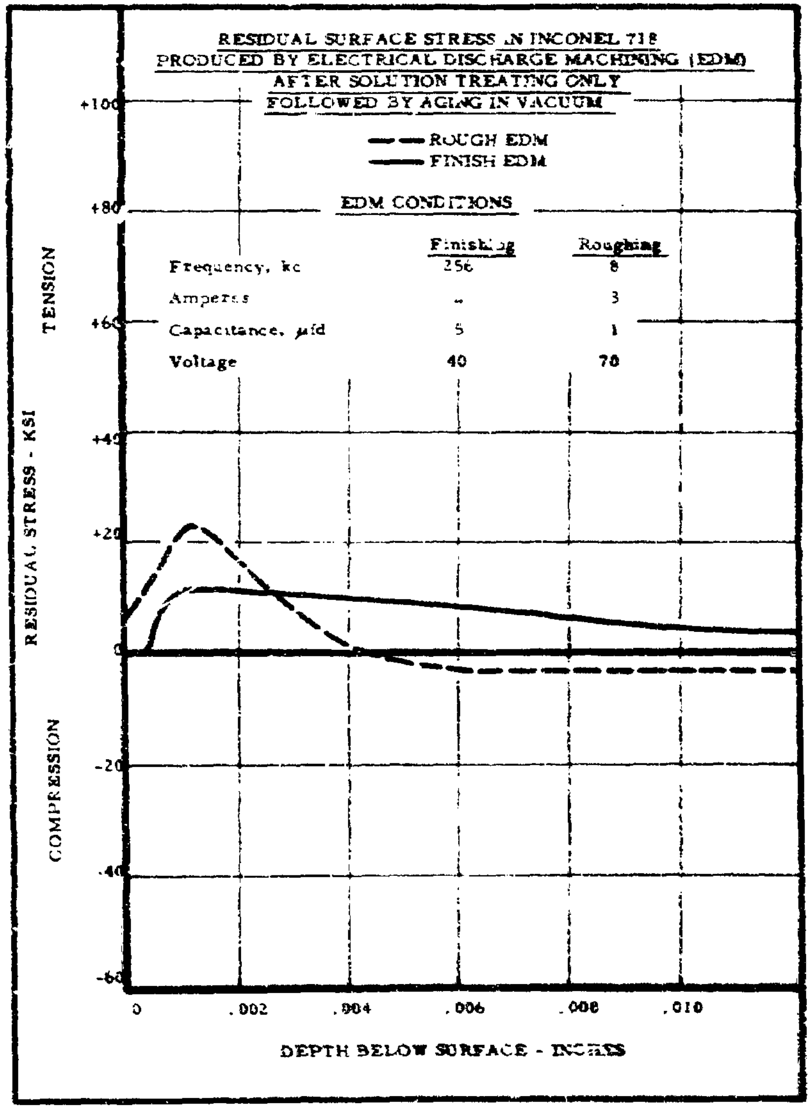


Figure 76

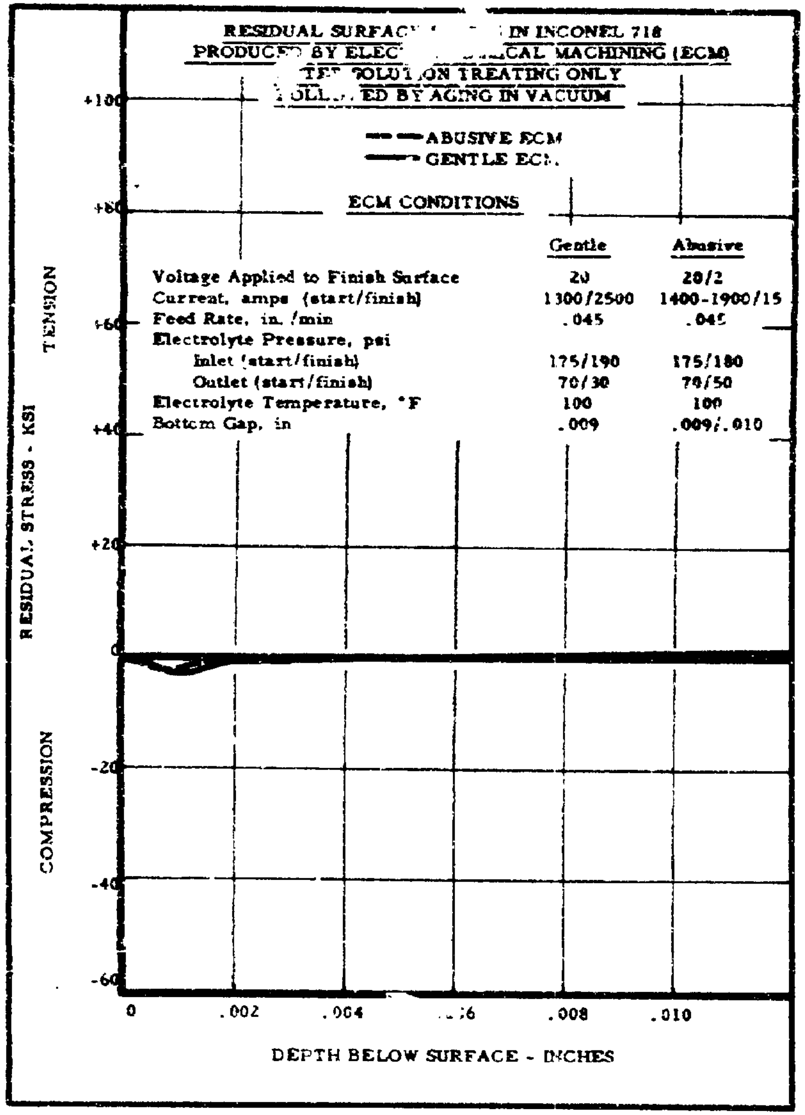


Figure 77

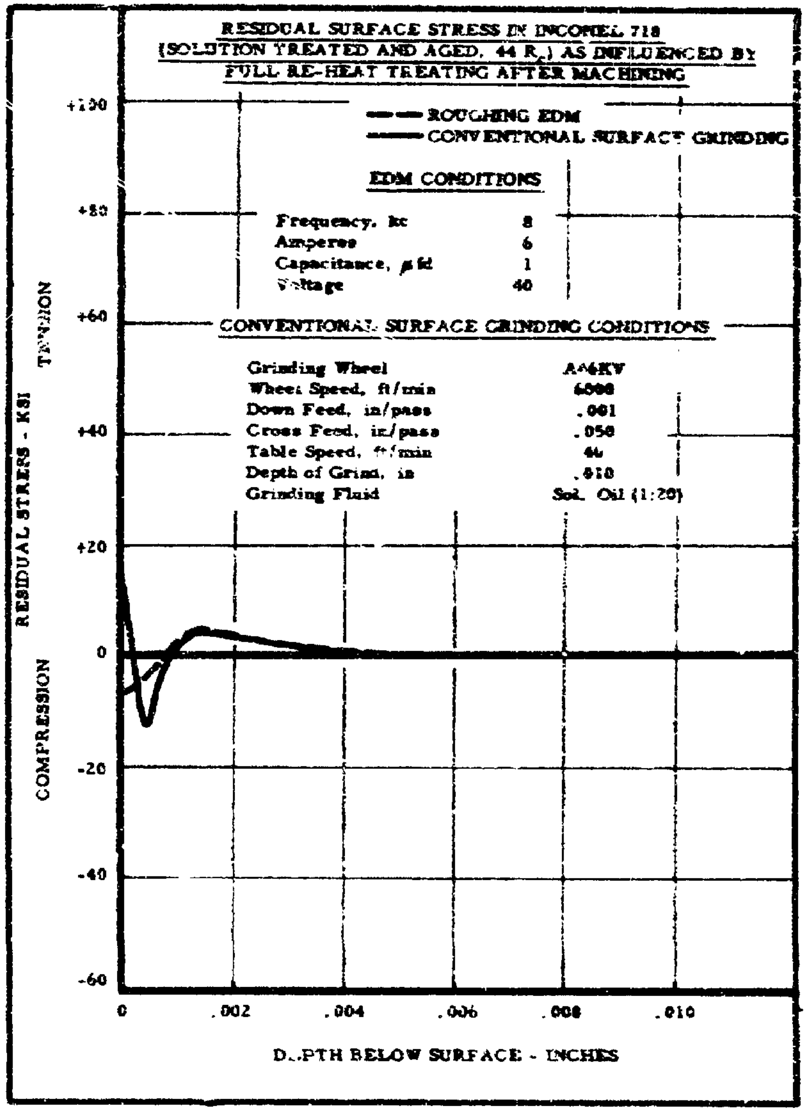
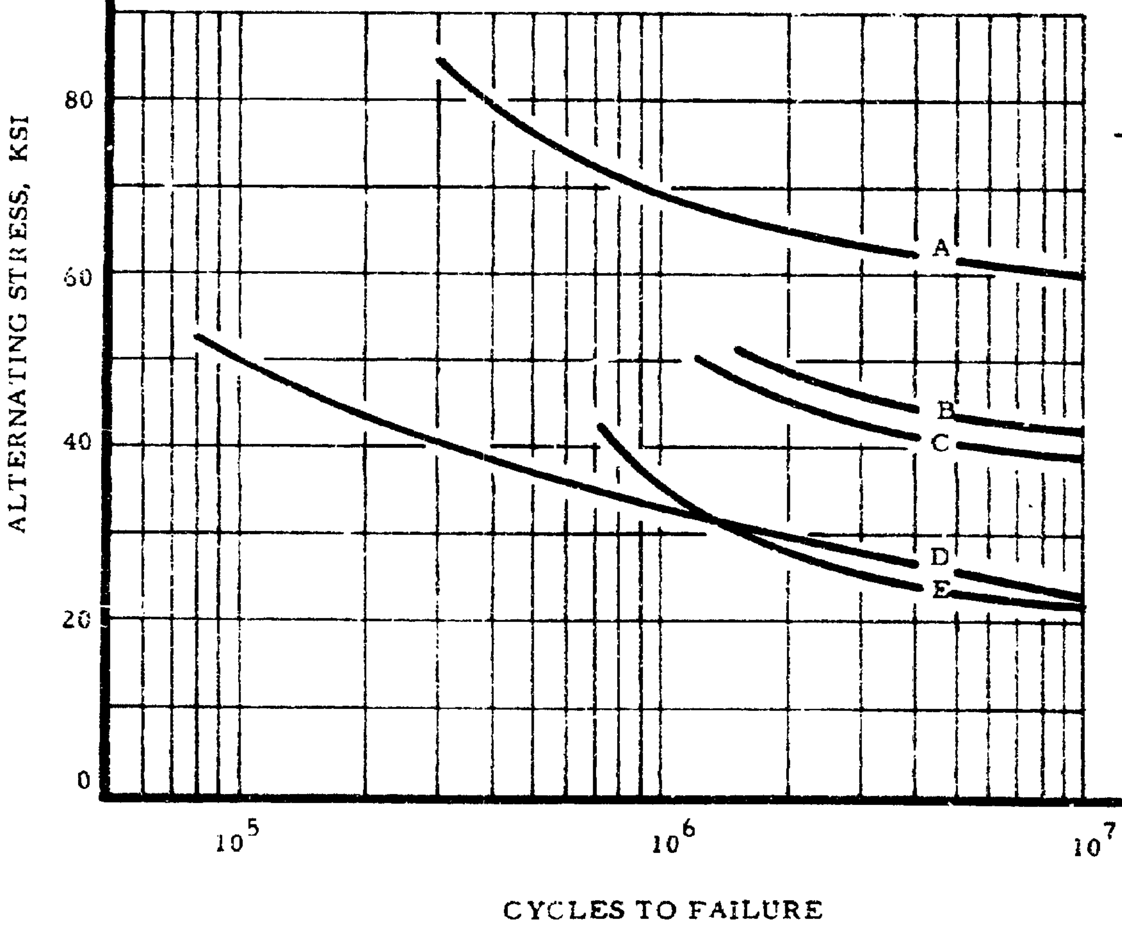


Figure 78

FATIGUE CHARACTERISTICS OF INCONEL 718 MACHINED IN THE SOLUTION TREATED AND AGED CONDITION

METAL REMOVAL CONDITIONS: SURFACE GRINDING, EDM, ECM, ELP
MODE: CANTILEVER BENDING, ZERO MEAN STRESS
TEMPERATURE: 75°F



CURVE	CONDITION	ENDUR. LIMIT KSI	SURFACE FINISH AA
A	GENTLE SURFACE GRIND	60	15
B	ELP	42	15
C	GENTLE ECM	39	43
	ABUSIVE ECM	39	74
D	CONVENTIONAL SURFACE GRIND	24	26
E	FINISHING EDM	22	60
	ROUGHING EDM	22	170

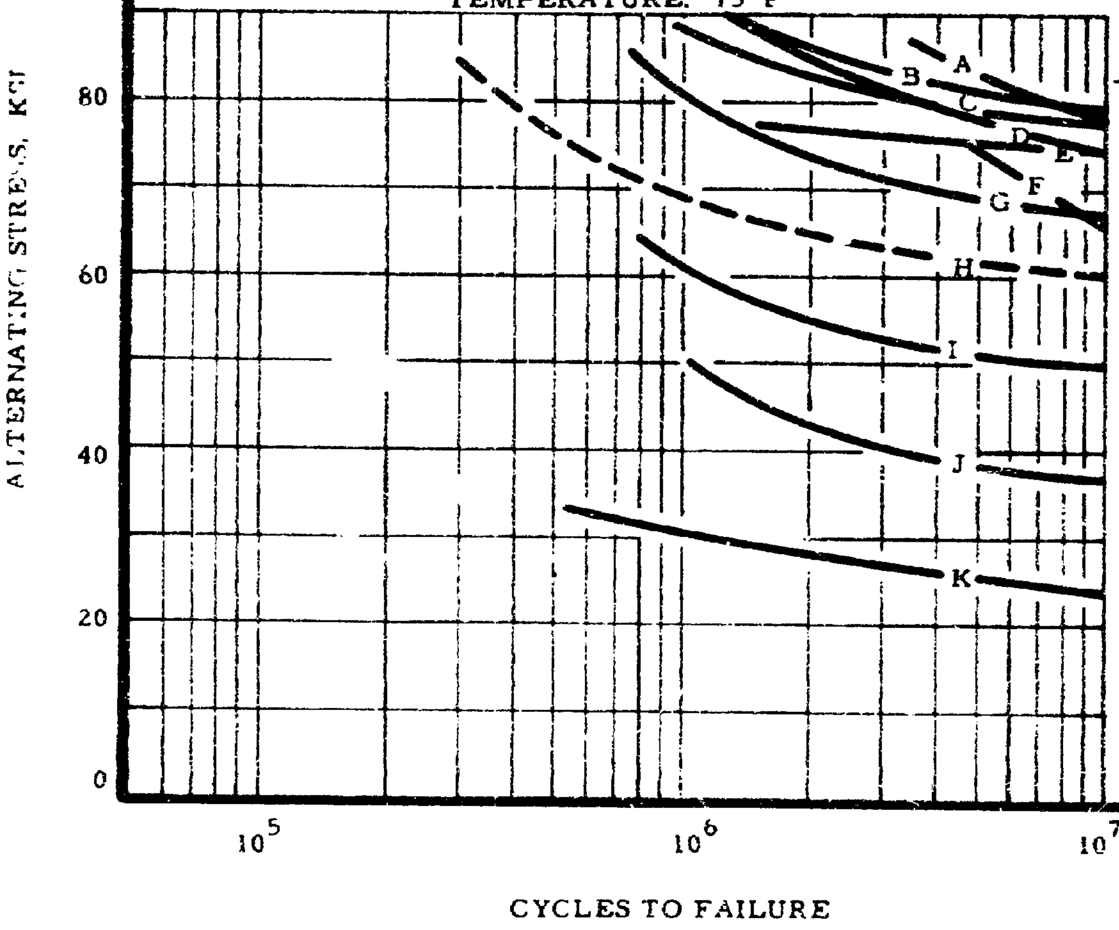
Figure 7?

FATIGUE CHARACTERISTICS OF INCONEL 718 MACHINED IN THE SOLUTION TREATED AND AGED CONDITION

METAL REMOVAL CONDITIONS: MACHINING + SHOT PEENING AND POST HEAT TREATMENT

MODE: CANTILEVER BENDING, ZERO MEAN STRESS

TEMPERATURE: 75°F



Curve	Condition	Endur. Limit (ksi)	Surface Finish (AA)
A	Gentle ECM + Glass Bead Peen	78	69
B	ELP + SP (Level 1)	78	43
C	Gentle ECM + SP (Level 1)	78	74
D	Abusive ECM + SP (Level 2)	75	90
E	Roughing EDM + SP (Level 1)	75	125
F	Finishing EDM + SP (Level 1)	66	43
G	Abusive ECM + SP (Level 1)	67	119
H	Gentle surface grind	60	15
I	Conv. surf. grind + resolution and age (vacuum)	50	26
J	Roughing EDM + resolution and age (vacuum)	38	175
K	Roughing EDM + stress relief	25	221

Figure 80

FATIGUE CHARACTERISTICS OF INCONEL 718 MACHINED IN THE SOLUTION TREATED CONDITION FOLLOWED BY VACUUM AGING AFTER MACHINING

METAL REMOVAL CONDITIONS: SURFACE GRINDING, ECM, EDM, ELP
MODE: CANTILEVER BENDING, ZERO MEAN STRESS
TEMPERATURE: 75° F

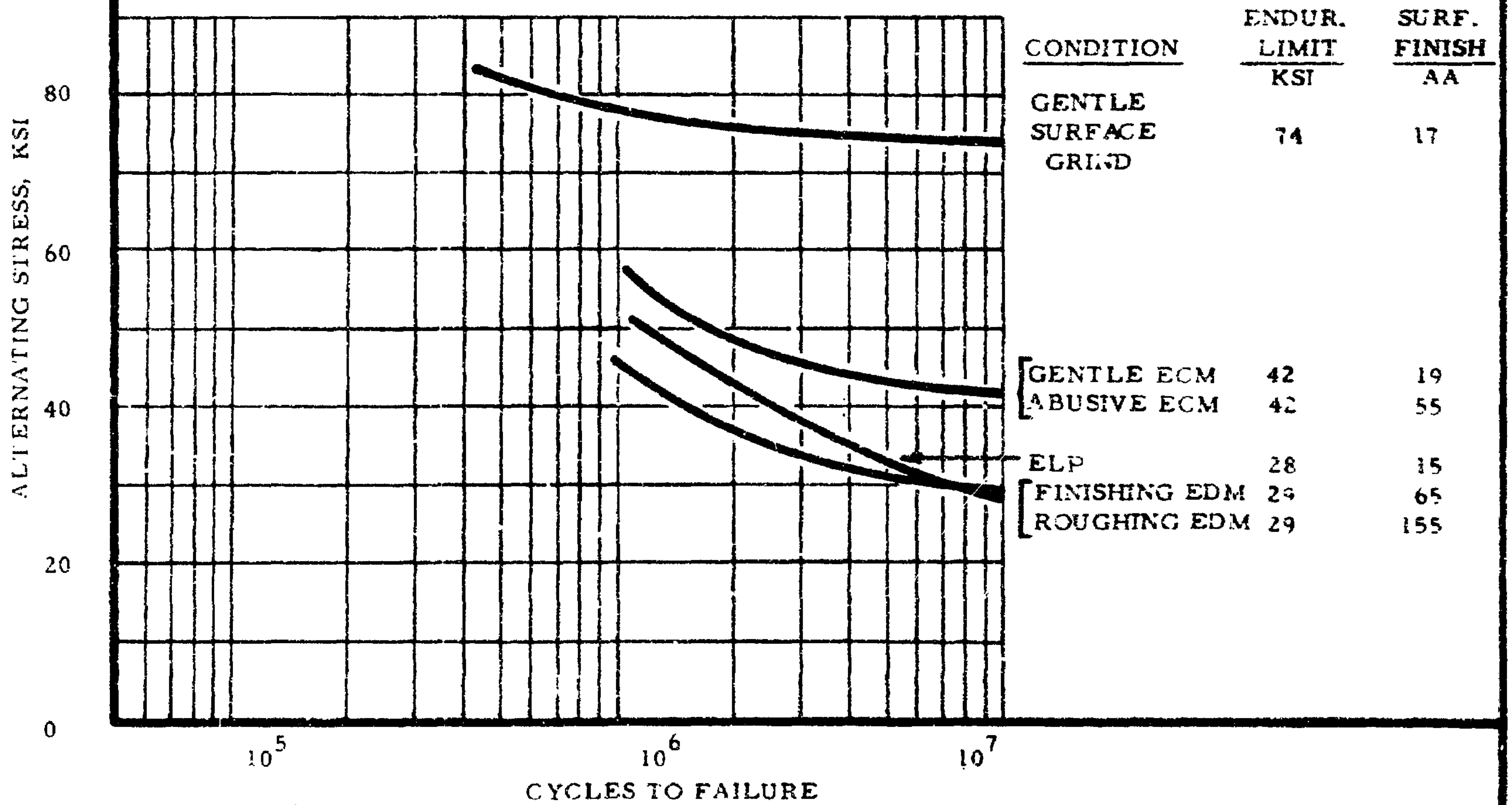


Figure 81

6.4 Data Correlation

A review of the data gathered under this contract and, in the case of 4340 steel, supplemented with other information from industry has permitted analysis of several topics related to the surface integrity behavior of materials. A discussion of these is presented in this section of the report.

6.4.1 Effect of Surface Finish on Surface Integrity Properties

Surface finish has long been used as an index of surface quality. In addition to being valued as a prime control on appearance flatness and interrelations of dimensions and tolerances, limited data have been published showing the dependence of various mechanical properties, especially fatigue, on surface finish. In general, these relationships indicate that highly polished specimens, which have a good surface finish, exhibit the maximum fatigue strength available from the particular material in question. This fatigue strength then is shown to decrease with increasing roughness of the surface. The explanation has been frequently advanced that stress concentrations associated with discontinuities in the surface are responsible for initiating fatigue failure at a lower stress than would occur in a highly polished specimen. It follows in this explanation that the rougher the surface, the lower will be the fatigue strength. In spite of lack of support of this idea with adequate hard data, a historical association between fatigue strength and microinch finish has developed. As a result, control of mechanical properties in many circles is now assumed to be covered by a specification of surface quality solely in terms of microinch finish.

Based on observations which may be made from data obtained under the subject contract, it has been concluded that the effect surface finish, by itself, has been overplayed in its relationship to the mechanical properties of materials. The data available would suggest rather that variations in surface finish within the normally encountered range (for the processes studied in this contract)

6.4.1 Effect of Surface Finish on Surface Integrity Properties (continued)

have no consistent effect on fatigue behavior. Consider, for example, the fatigue data produced for grinding and CHM beta rolled Ti-6Al-4V presented in Figure 29. Gentle hand grinding versus abusive hand grinding yields fatigue strengths of 57 and 30 ksi, respectively, although the surface finish of each is 80 AA. The fatigue strengths exhibited by gentle versus abusive CHM are very close, 51 versus 45 ksi, although the surface finishes are quite different, 20 versus 165 AA. Abusive grinding exhibits a depression in fatigue strength to 13 ksi as compared to 62 ksi produced by gentle grinding. There is also a surface finish deterioration of 80 versus 36 AA, although this surface finish change is hardly proportionate to the 5 to 1 change in fatigue strength. A study of the fatigue strength versus surface finish associated with the 20 different milling conditions shown in Figures 30 and 31 also show no consistent relationship or trend between fatigue behavior and surface finish.

Fatigue data obtained in grinding and also post-processing by peening of AISI 4340 (Figures 48 and 49) also show a lack of specific correlation between fatigue and surface finish. For example, the endurance limits associated with gentle, conventional, and abusive grinding were 102, 70, and 62 ksi, respectively. The surface finish produced by all three processes was in the range of 40 to 50 AA.

Similar effects exhibited by nonconventional machining processes are illustrated in the data obtained on Inconel 718. As may be seen in Figure 79, EDM under both finishing and roughing conditions exhibited an endurance limit of 22 ksi, while the surface finish for the finishing versus roughing conditions was 60 versus 170 AA, respectively. Gentle versus abusive ECM produced surface finishes of 43 versus 74 AA, respectively, although the endurance limit obtained for each was 39 ksi. ELP on Inconel 718 provided a fatigue strength of 42 ksi at a surface finish of 15 AA. In this instance, of course, the characteristics of surface finishes were quite different. Other comparisons leading to essentially the same conclusions may be obtained from other data presented for Inconel 718 in Figures 80 and 81.

In reviewing the data obtained under this contract, two possible correlations were sought. One was the indication of a trend of an overall relationship between fatigue strength and surface roughness, regardless of the machining method used. Quite

6.4.1 Effect of Surface Finish on Surface Integrity Properties (continued)

clearly, the data available do not support the likelihood that this type of correlation is valid. The second possibility was that a relation does exist between fatigue strength and surface finish for a single method of metal removal. In other words, perhaps all grinding data would show a correlation of surface finish to fatigue strength. While the information available provides much smaller sampling for the testing of this second possible type of correlation, the data available again suggest that the correlation does not exist. In any event, it is conclusive that the correlation is not sufficiently sensitive to be of practical value over the range of surface finishes which would normally be encountered in the manufacturing operations studied in this program.

In order to pursue this correlation to a further degree, approximately 250 of the fatigue samples tested under this contract were subjected to a detailed study. The surface finish of each specimen was measured in the area where the failure had nucleated. The surface finish on each specimen was then charted with the data point on the original S/N plots which had been used to produce the final fatigue curves shown in this report (Figures 29, 30, etc.). In constructing the original S/N plots, a well-fitting curve was drawn through all of the data points obtained for a particular metal removal condition. As there is scatter with any experimental data, some of these points fell above the line indicating better than average performance and some fell below the line drawn indicating substandard performance for the group. The purpose of this study was to see if fatigue specimens which performed better than the average for the group had better than average surface finish, and vice versa. After carefully reviewing 40 of the S/N curves developed under this contract, no consistent trend or correlation could be found. On the contrary, it was reasonably clear that a correlation between fatigue behavior and surface finish (within the range of variation encountered) does not exist.

Therefore, it may be inferred that surface finish measurements by themselves are not a useful criteria for evaluating the surface integrity of metallic materials. The use of surface finish as an NDT method of evaluating surface integrity, therefore, appears to offer little promise. It is recognized that very wide difference in surface finish do have effects on

6.4.1 Effect of Surface Finish on Surface Integrity Properties (continued)

mechanical performance and surface integrity, but these extremes are considered to be of academic interest rather than of practical value in the manufacture of aerospace hardware.

6.4.2 Role of Untempered Martensite in the Surface Integrity of Steels

A program was recently completed at Metcut under support of GE/Evendale studying the relationship between the depth of quantity of untempered martensite in ground surfaces of AISI 4340 and the characteristic fatigue strength of those surfaces. In this effort, it was established that untempered martensite does have a deleterious effect on fatigue strength. Furthermore, the magnitude of the effect was about the same, regardless of the quantity of martensite present. A portion of the study indicates that the overtempered martensite produced in the surface simultaneously with the untempered martensite appears to have an equal deleterious effect on the fatigue characteristics of this material. The question is raised as to whether the loss in fatigue strength associated with "grinding burn" or abusive grinding on high strength steels is due to untempered martensite or, on the other hand, the presence of the overtempered softened zone of martensite which occurs whenever a rehardened surface is produced.

This grinding study involved the surface finishing of cantilever bending fatigue specimens, .045 in. thick, under eight different conditions. These involved finish grinding by low stress (or gentle) and several abusive conditions. Depending on the procedure used, various depths of untempered martensite and overtempered martensite were produced. In addition to being evaluated in the as-ground condition, certain samples were ground by modified procedures to remove the untempered martensite (UTM) and expose the previously produced overtempered martensite (OTM) at the surface.

Generally speaking, the martensite formed on the machined surfaces was present in small patches which did not cover the entire area of the test surface. Martensite coverage and depth was determined for each sample by metallographic sectioning after fatigue testing was completed. The characteristic depth recorded the maximum depth of martensite patches observed.

6.4.2 Role of Untempered Martensite in the Surface Integrity of Steels (continued)

In the case of samples reported to contain a maximum UTM depth of .0005 in., there were those samples in the group on which no UTM could be found. To better define the surface characteristics, a survey was made describing the percentage of surface covered with untempered martensite and with overtempered martensite in relation to the characteristic depth of the UTM patches. While this survey was, of course, an approximation, surprisingly consistent data were obtained from sample to sample within each UTM depth group. A summary of these data is as follows:

Depth of UTM	Percent Surface Covered With UTM	OTM
.0005 max.	10	90
.0005/.001	30	70
.0005/.0015	35	65
.001/.002	50	50
.003/.004	100	0

It was very interesting to note that the residual stress distribution patterns exhibited by surfaces containing these various amounts of untempered martensite were all very similar. All exhibited peak subsurface tensile stresses of approximately 90 ksi. The depth of the peak stress, however, increased as the maximum depth of untempered martensite increased. The position of the peak stress occurred approximately at the interface between the untempered martensite and the overtempered martensite. Residual stress data is shown in Figure 82.

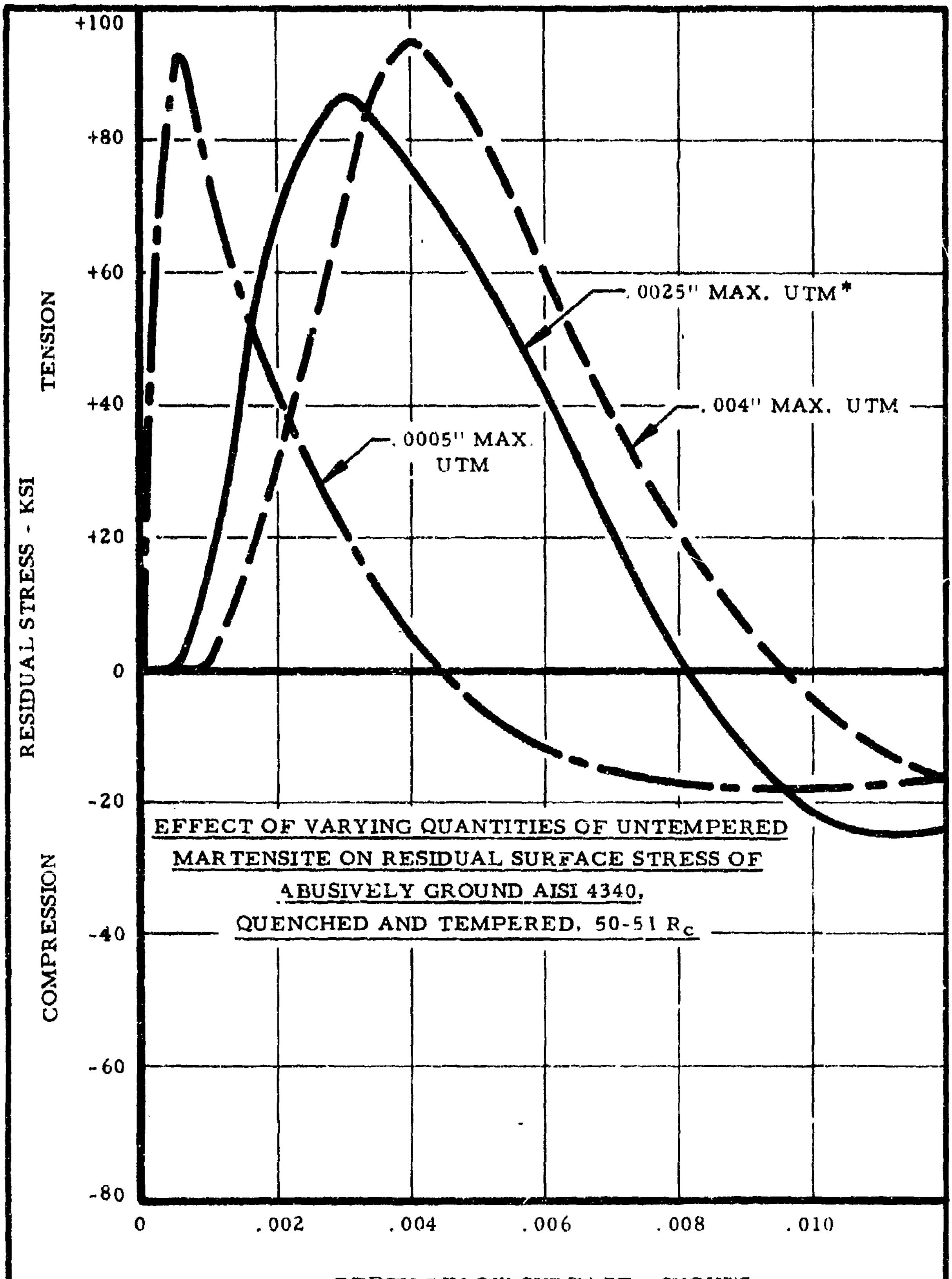
The fatigue behavior of several of these samples in comparison with that of the same heat of material finished by low stress grinding is shown in Figure 83. As can be seen, the fatigue strength associated with abusively ground material falls into a relatively narrow band exhibiting an endurance limit in the range of 70 to 75 ksi, regardless of the amount of martensite present. In comparison, the fatigue strength of the low stress or gently ground material was 110 ksi. These data were taken on a different heat of material than that used for the subject contract, but the relationship between gentle and abusive

6.4.2 Role of Untempered Martensite in the Surface Integrity of Steels (continued)

grinding on this particular heat of 4340 is very similar to that obtained on the contract material, as shown in Figure 48.

A further step in this particular program was to remove untempered martensite from the surface by low stress grinding. Were the untempered martensite the total cause for fatigue strength depression, this action would presumably eliminate the depression. Removing untempered martensite from the surfaces of many fatigue specimens by low stress grinding, however, did not result in restoring fatigue properties to the level exhibited by the low stress grinding. Instead, the fatigue performance of these specimens indicated only a moderate improvement. The scatter band produced by this group of specimens is also shown in Figure 83. In this latter group of specimens, overtempered martensite associated with the untempered martensite as discussed previously in this report (Section 6.2 - Metallography) shows evidence of having a pronounced effect in depressing fatigue behavior. There is a clear indication that the lower fatigue strength associated with this somewhat softened material may be the significant limiting factor in fatigue behavior associated with surface damage of martensitic steels. The hard untempered martensite which may be formed on the surface, along with its brittleness and high cracking tendency, may not be the principal cause for surface integrity deterioration. This is in contradiction to beliefs which have been advanced up to this time.

The final phase of this study involved the retempering of a group of abusively ground samples at 1500°F, the same tempering temperature as had been used in their initial preparation. Checking metallographically, the patches of untempered martensite which had been formed by the abusive grinding and which exhibited hardness in the range of 60-65 R_C are now at 50-52 R_C. The base material now measured at 49-50 R_C, possibly a one point drop in hardness in the previous value. On testing these samples, however, the failure points fell in the same band as had been developed for abusively ground samples containing untempered martensite, as shown in Figure 83. The endurance limit was approximately 74 ksi. This adds further evidence that the presence of hard, brittle untempered martensite is not always a limiting factor in the fatigue behavior of abusively machined steel.



* Untempered Martensite

Figure 82

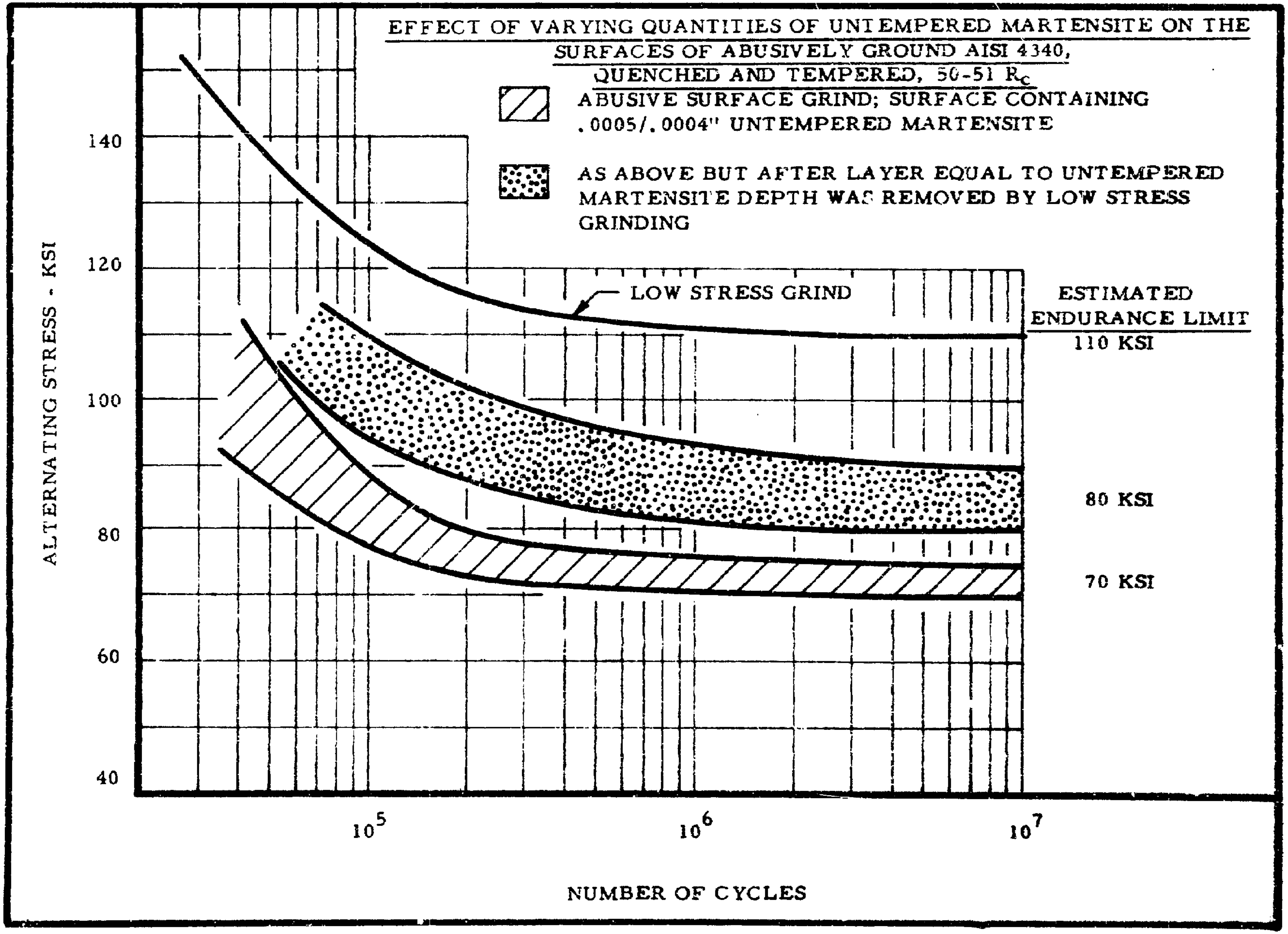

EFFECT OF VARYING QUANTITIES OF UNTEMPERED MARTENSITE ON THE SURFACES OF ABUSIVELY GROUND AISI 4340, QUENCHED AND TEMPERED, 50-51 R_c
ABUSIVE SURFACE GRIND; SURFACE CONTAINING .0005/.0004" UNTEMPERED MARTENSITE
AS ABOVE BUT AFTER LAYER EQUAL TO UNTEMPERED MARTENSITE DEPTH WAS REMOVED BY LOW STRESS GRINDING
LOW STRESS GRIND
ESTIMATED ENDURANCE LIMIT
110 KSI
80 KSI
70 KSI
ALTERNATING STRESS - KSI
140
120
100
80
60
40
10^5
10^6
10^7
NUMBER OF CYCLES

Figure 83

6.4.3 Relationship Between Residual Surface Stress and Fatigue Strength

For many years, it has been recognized that the shot peening of steel has resulted in a significant elevation in its fatigue strength. The technique has been in commercial use for a long time for the finishing of automotive leaf springs and similar highly stressed parts. The elevation in fatigue strength as a result of shot peening has, in turn, been attributed largely to the presence of residual compressive stresses put into the surface by the peening action. A portion of the fatigue improvement has also been attributed to the cold working or strain hardening associated with peening. The development of surface compressive stresses through the use of controlled heat treating procedures (including carburizing) has also been used as a means for elevating the fatigue strength of components. This concept has been extended to describe the behavior of machined surfaces. Like the effect of surface finish, it has been presumed that, when a machining condition produces residual surface compression, this particular condition will also improve fatigue strength. Conversely, it has been presumed that, when a machining operation produces surface layers stressed in tension, the fatigue strength will be reduced. Until completion of the subject program, however, data were not available to evaluate the effect of change in residual stress distribution on fatigue strength of materials, particularly in situations where residual stress changes were due to variations within a particular metal removal process. Previously, limited data were available to compare the effect of a ground surface versus a milled surface versus a shot peened surface. Information just developed, however, now permits the comparison of fatigue behavior as a function of residual stress in many different milled surfaces, different types of ground surfaces, etc. Several of the surface conditions that have been produced have very similar surface finishes. Therefore, fatigue strength comparison can be made with residual stress but without changes in surface finish as a separate variable.

In looking for possible relationships between surface stress and fatigue strength, several correlations were considered. Plots were made of fatigue strength versus residual surface stress, maximum tensile stress (surface or subsurface), and peak stress (maximum tensile or maximum compressive) whether it be surface or subsurface. This was done for all of the metal removal conditions studied under this contract where both

6.4.3 Relationship Between Residual Surface Stress and Fatigue Strength (continued)

fatigue and residual stress data were available. The most consistent correlations were obtained by plotting fatigue strength versus peak residual stress. These plots for titanium, 4340, and Inconel 718 are shown in Figures 84, 85, and 86, respectively. Figure 84 shows the relation for grinding, hand grinding, milling, and CHM of the Ti-6Al-4V. All of these data points are for the alloy in the as-machined condition since no post-processing treatments were performed on titanium in this program. While there is substantial scatter with respect to a linear relation between residual stress and endurance limit, a trend certainly is indicated.

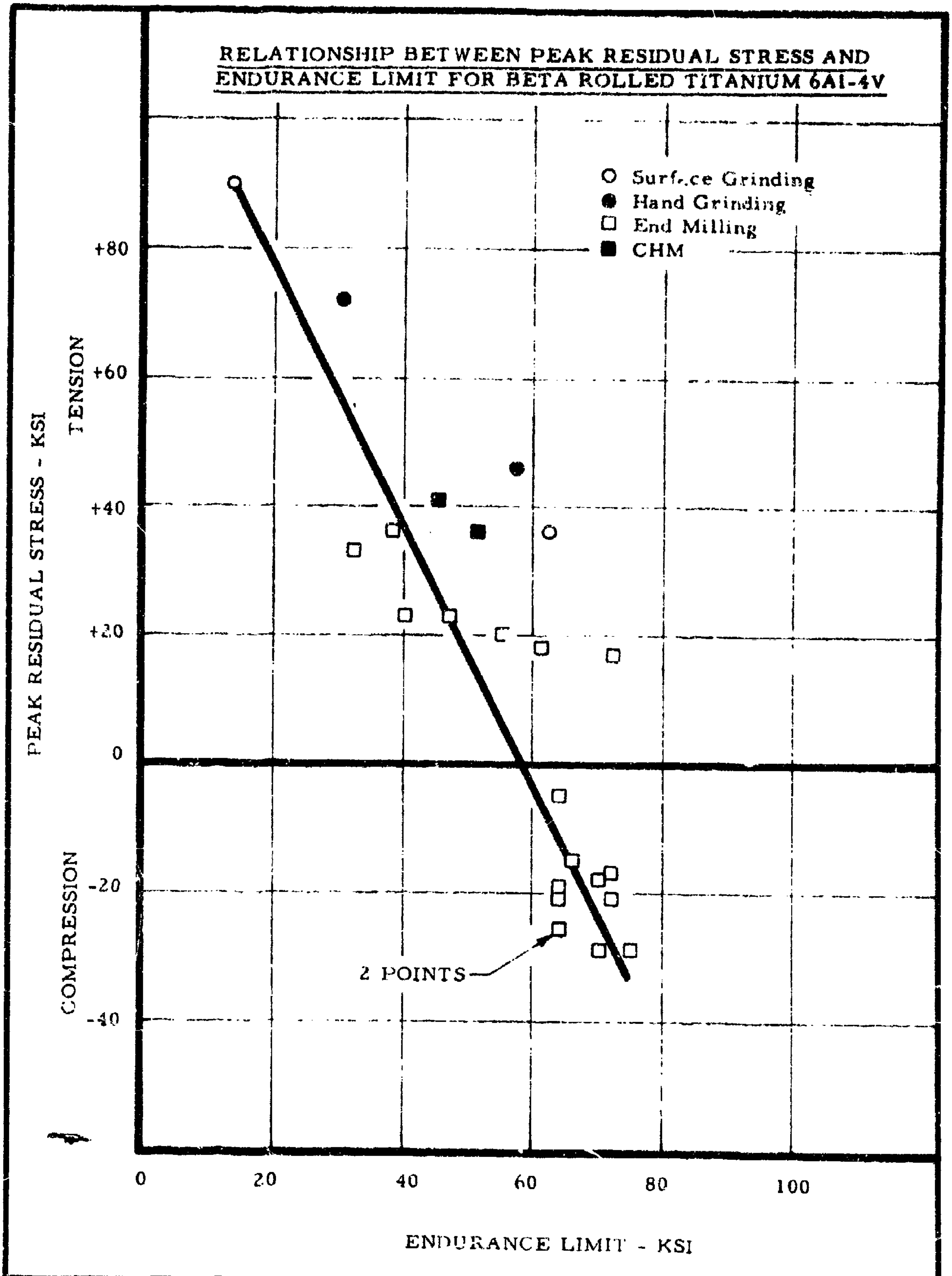
Figure 85 summarizes data obtained during this contract on AISI 4340. The circles summarize data from as-machined specimens and from shot peened specimens as indicated in the code, while the solid line plot indicates a suggested graphing of these data. The open squares in Figure 85 and the dashed line graphing represent data from the separate grinding study on 4340 performed under other sponsorship, which is discussed in Section 6.4.2 of this report. In both of these cases, a trend toward a relationship is indicated as far as the as-machined samples are concerned. Shot peened samples, however, do not conform to the fatigue versus residual stress relationship exhibited by the as-machined samples.

Figure 86 summarizes data available for Inconel 718. The solid line plot describes an approximate relationship for the behavior of as-machined samples which were fully heat treated prior to machining. The various shot peened post processes exhibit somewhat higher endurance limits and higher levels of compressive residual stress, although a linear relationship is not really exhibited by this group of test samples. Notice, however, that the group of specimens which were machined in the solution treated condition, followed by aging in vacuum, show a reasonable correlation but of a much different relationship than that exhibited by specimens which were fully heat treated prior to machining.

In reviewing all of these data, it may be said that there is at least some degree of interrelation between peak residual surface stress and resulting fatigue strength for each of these materials.

6.4.3 Relationship Between Residual Surface Stress and Fatigue Strength (continued)

Data are insufficient to precisely define this relationship but do substantiate its probable existence. In the case of Inconel 718, however, two very different relationships are observed. These are associated with the two different methods of processing the material, even though the final strengths of each are about the same. In considering the type of correlation shown in Figure 86, it must be concluded that, while there does exist an interrelation between fatigue strength and residual stress, residual stress alone is not the sole factor in determination of fatigue strength. Other conditions including surface chemistry, strain hardening, and microcracking must also be considered. However, it would appear that residual stress measurement capability could be developed to the point where this technique would be useful as an NDT device for the evaluation of surface integrity on a production basis. The total pattern of residual stress distribution would be required rather than identification merely of outer fiber surface stresses.



RELATIONSHIP BETWEEN PEAK RESIDUAL STRESS AND ENDURANCE LIMIT FOR BETA ROLLED TITANIUM 6Al-4V
Surface Grinding
Hand Grinding
End Milling
CHM
PEAK RESIDUAL STRESS - KSI
TENSION
COMPRESSION
+80
+60
+40
+20
0
-20
-40
2 POINTS
0
20
40
60
80
100
ENDURANCE LIMIT - KSI

Figure 84

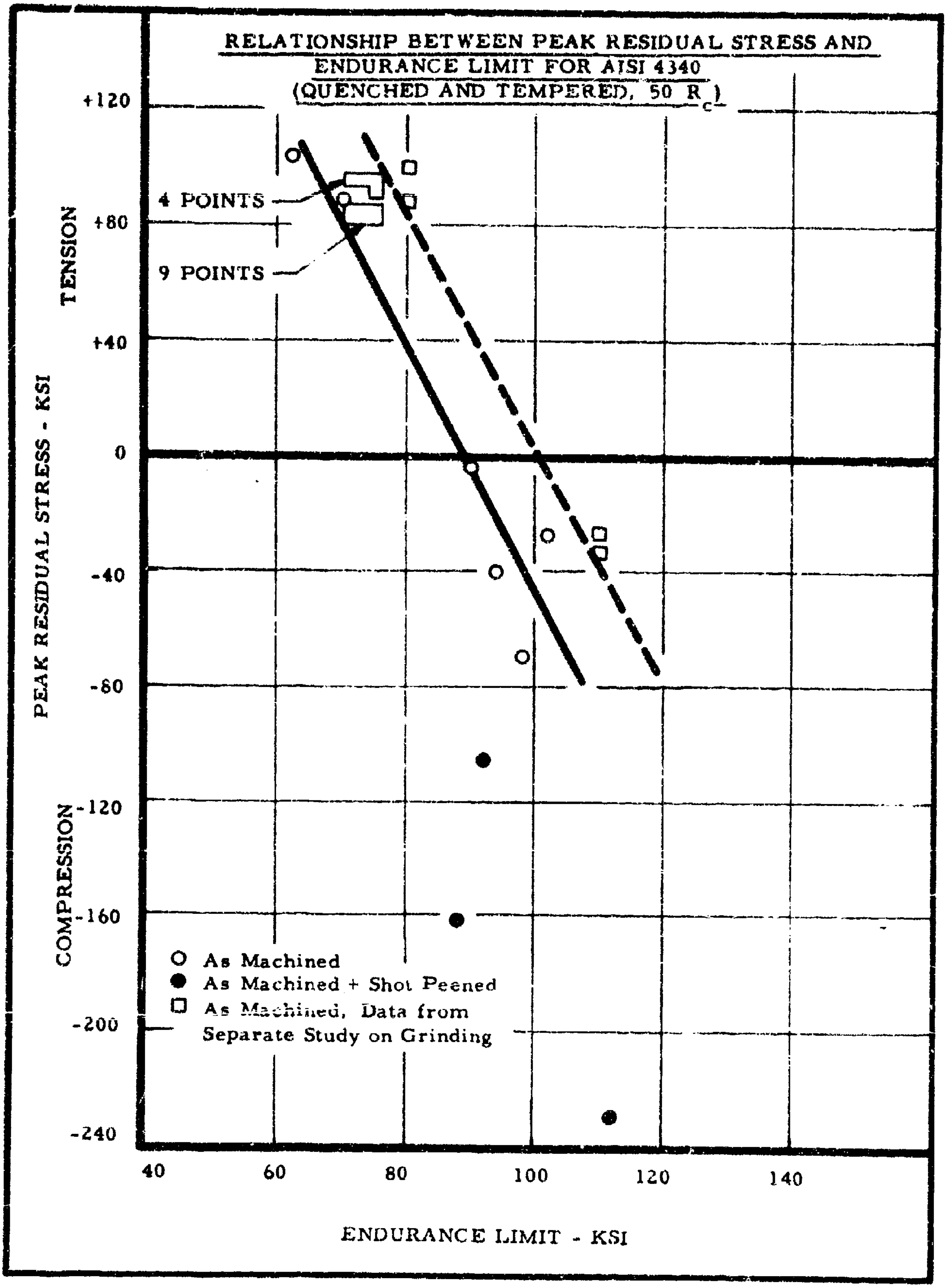

RELATIONSHIP BETWEEN PEAK RESIDUAL STRESS AND ENDURANCE LIMIT FOR AISI 4340 (QUENCHED AND TEMPERED, 50 R_c)
4 POINTS
9 POINTS
TENSION
COMPRESSION
PEAK RESIDUAL STRESS - KSI
+120
+80
+40
0
-40
-80
-120
-160
-200
-240
40
60
80
100
120
140
ENDURANCE LIMIT - KSI
As Machined
As Machined + Shot Peened
As Machined, Data from Separate Study on Grinding

Figure 85

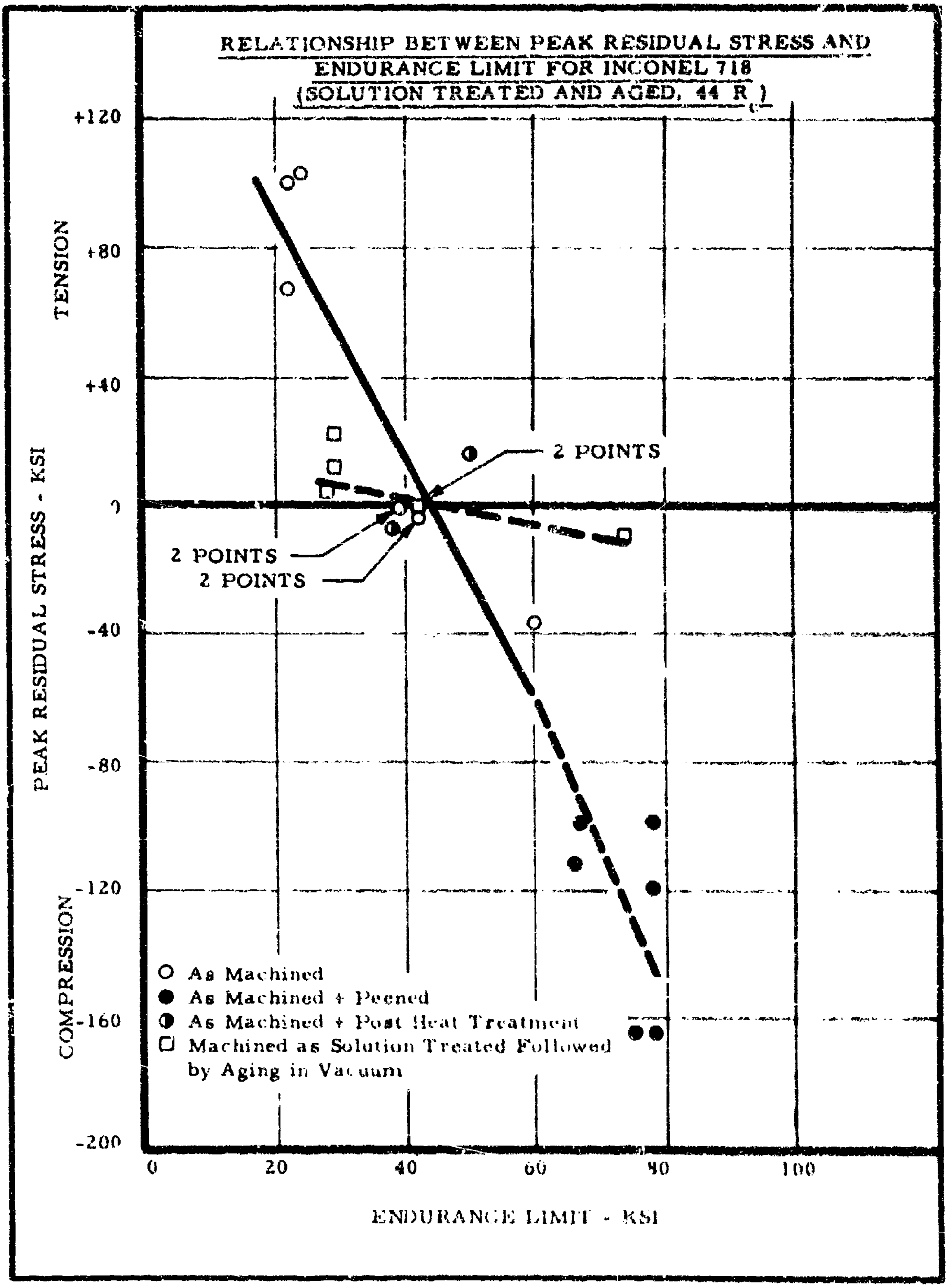

RELATIONSHIP BETWEEN PEAK RESIDUAL STRESS AND
ENDURANCE LIMIT FOR INCONEL 718
(SOLUTION TREATED AND AGED, 44 R)
+120
+80
+40
0
-40
-80
-120
-160
-200
TENSION
COMPRESSION
PEAK RESIDUAL STRESS - KSI
2 POINTS
2 POINTS
2 POINTS
As Machined
As Machined + Peened
As Machined + Post Heat Treatment
Machined as Solution Treated Followed by Aging in Vacuum
0
20
40
60
80
100
ENDURANCE LIMIT - KSI

Figure 86

6.4.4 Fractographic Analysis of Failed Specimens

A detailed analysis of the fractures of approximately 30 fatigue specimens was made. The purpose of this effort was to pinpoint the failure origin and then to correlate this failure location with the residual stress in that region and with the microstructural condition present at the nucleus.

Representative samples were selected and subjected to a fractographic analysis by G. E. /Evendale. The procedure involved the use of fracture surface replication and subsequent fractography of replicas using a transmission electron microscope. Once the nucleus of failure had been pinpointed, samples were sectioned metallographically using the surface integrity mounting technique which had been developed by Metcut. This total procedure is described in Appendix II-6.

A summary of the observations made from this study along with pertinent data obtained from the corresponding residual stress curves is as follows:

Material	Machining Operation	Nucleus Location (in.)*	Residual Stress at Nucleus (ksi)	Peak Residual Stress (ksi)	Structural Condition or Abnormality at Nucleus
Ti-6Al-4V	Gentle Surface Grind	S	+35	+35	Microcrack
	Gentle Surface Grind	S	+35	+35	Plastic deformation and tear
	Abusive Surface Grind	.002	+60	+90	Parent structure (below plastically deformed zone)
	Abusive Surface Grind	S	+90	+90	Plastic deformation and tear
	Abusive End Mill, Cond. X-1	S	--	--	Plastic deformation and microcrack
	Abusive End Mill, Cond. X-1	S	--	--	Parent structure
	Abusive Periph. Mill, Cond. 16	S	+20	+35	Plastic deformation (possible lap)

6.4.4 Fractographic Analysis of Failed Specimens (continued)

Material	Machining Operation	Nucleus Location (in.)*	Residual Stress at Nucleus (ksi)	Peak Residual Stress (ksi)	Structural Condition or Abnormality at Nucleus
AISI 4340	Gentle Surface Grind	S	0	-30	Parent structure
	Gentle Surface Grind	S	0	-30	Parent structure
	Conventional Surface Grind	S	+20	+90	Parent structure
	Abusive Surface Grind	.004	+60	+105	Sulfide inclusion
	Abusive Surface Grind	.008	0	+105	Sulfide inclusion
	Abusive Surface Grind	.005	+40	+105	Sulfide inclusion
Inconel 718	Gentle Surface Grind	S	0	-40	Parent structure
	Gentle Surface Grind	S	0	-40	Plastic deformation and pit
	Gentle Surface Grind	S	0	-40	Plastic deformation and pit
	Gentle Surface Grind (Solution + Grind + Age)	S	0	-10	Plastic deformation
	Roughing EDM	S	0	+70	Recast layer and microcrack
	Roughing EDM + Shot Peen (Level 1)	S	-35	-160	Recast layer and microcrack
	Roughing EDM + Stress Relief	.007	--	--	Band of Ni_3Cb phase
	Gentle ECM	S	0	0	Pit
	Abusive ECM	.008	0	0	Band of Ni_3Cb phase
	ELP	S	0	0	Pit

* S = at surface; Decimal = distance below surface

6.4.4 Fractographic Analysis of Failed Specimens (continued)

A review of the data obtained for titanium indicates that all of the failures, except one, nucleated at the surface. Surface imperfections associated with the machining operation, such as a microcrack or a tear, were found in most of the samples. All of the titanium failures nucleated in an area of residual tensile stress, although not necessarily at the position of the maximum tensile stress which had been measured in the surface on a corresponding sample.

A review of the data available on 4340 shows that samples finished by gentle and conventional grinding failed at the surface where stresses were very low. In the case of gentle grinding, the surface stress was more tensile, however, than the -30 ksi peak stress in compression immediately beneath the surface. In the case of conventional grinding, however, the stress at the surface where the failure nucleated was 20 ksi tension, while the peak stress beneath the surface was calculated as 90 ksi in tension. In the case of the three samples finished by abusive surface grinding, failure nuclei were found a few thousandths of an inch (.004 to .008 in.) beneath the surface. The residual stresses at these points of failure were considerably lower than the peak value of 105 ksi associated with abusive grinding on this alloy. It is also significant to note that all three of the specimens which had been abusively ground failed at sulfide inclusions beneath the surface. The lack of correlation between the fact that these failures did not initiate at the region of peak residual tensile stress in the samples, which occurs at a depth of about .002 in., is also significant. It may be implied that the mechanism of failure is more complex than simply attributing fatigue behavior to changes in residual stress, considering either peak or surface values.

Failures of Inconel 718 machined by all methods were predominantly surface oriented. The two exceptions were in instances where failure initiated at a band of the intermetallic strengthening phase of this alloy. The failure of ground samples appeared to be associated with surface pits or deformation of the microstructure. The EDM samples both failed as a result of microcracks in the brittle recast layer. Allowing for the exceptions made, the balance of the specimens failed at surface discontinuities.

6.4.4 Fractographic Analysis of Failed Specimens (continued)

A review of all of this fractographic data indicates that metallography is valuable in helping to define the surface integrity behavior of machined surfaces. It is reasonably clear that well-recognized surface defects, such as pits, tears and microcracks, can, by virtue of stress concentrations associated with them, lead to premature fatigue failure. From a study of these data, it is also evident that residual stress, while very informative, cannot be relied on as a sole criterion for judging surface integrity behavior. Perhaps the most important role that can be played by electron fractography is that of correlating laboratory experiences with service failure of components. Fractography, therefore, is seen primarily as a tool to help in correlating information gathered, but not as a prime tool for evaluating surface integrity of a specific metal removal process.

7. METALLOGRAPHIC ENCYCLOPEDIA OF SURFACES MACHINED BY NONCONVENTIONAL TECHNIQUES

Surfaces have been made to determine the microstructural effects produced by EDM, ECM, and CHM on a group of 27 different aerospace materials/heat treatment combinations. This work was sponsored jointly by G. E. / Evendale and Metcut in order to increase the information available in this particular area of surface integrity. Since information is considered to be a valuable supplement to published information disseminated on the subject, it is included here in order to supplement and to increase the scope of the subject report.

Photomicrographs of cross sections of surfaces machined in various ways are shown in this section. Each of these illustrations also indicates the hardness characteristics of the surface conditions which are illustrated. The hardness data were obtained using Knoop microhardness measurements taken at loads ranging from 25 to 500 grams. The low load range was used within the first .002 in. of the surface, while 100 and 500 gram readings were taken at greater depths. All of the data have been normalized and converted to Rockwell hardness values using standard conversion techniques for presentation in this report.

7.1 EDM Characteristics

Photomicrographs of cross sections of surfaces produced by EDM under typical finishing and roughing conditions are shown in Figures 87 through 113. In reviewing these figures, the most common characteristic of EDM processing is readily apparent -- the formation of a layer of recast metal on the surface. At higher current densities used for roughing conditions, considerably more molten metal is present on the surface at any one time, hence thicker layers of recast structure are generally deposited as a result of roughing conditions. Some layers of recast metal are continuous and adhere rather tightly to the surface of the test sample. In other cases, the recast layer tends to spall easily or to appear as random spattering rather than as a continuous layer. Most of the recast layers are harder than the base metal. This may be attributed to the formation of martensite in the case of ferrous alloys and/or due to contamination from the electrode or dielectric oil which was adjacent to the molten metal layer during the cutting process. Notice also in reviewing the next 27 figures that some of the recast layers are prone to cracking. A few also induce cracking in the base metal beneath them. Some recast layers exhibit no particular tendency toward cracking under the test conditions used in making samples for this evaluation.

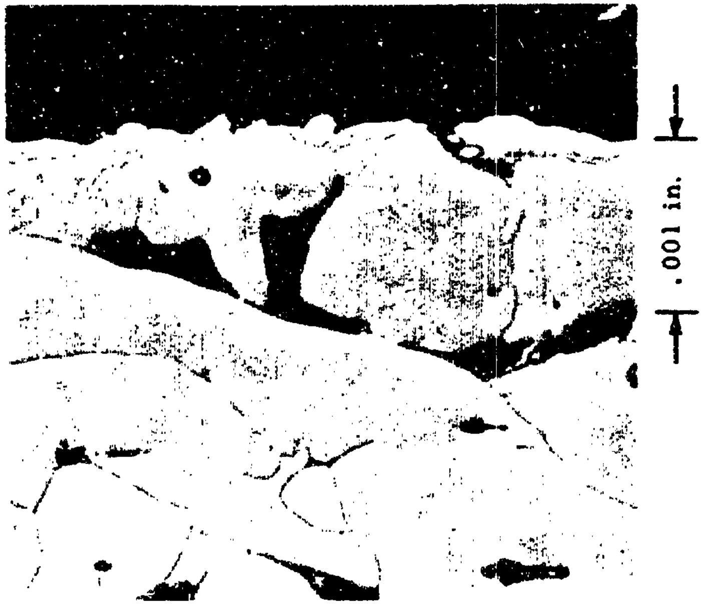
7.1 EDM Characteristics (continued)

Beneath the recast layer, various effects that may be associated with localized surface heating can be observed. In the case of 1018 steel (Figure 87), noticeable distortion of the microstructure is visible, particularly in the sample which was cut under roughing conditions. In the case of the martensitic steels (Figures 88 through 93), these show typically the formation of hardened untempered martensite immediately beneath the recast layer plus an underlying softened zone of overtempered martensite. Fully annealed materials such as the type 410 stainless steel shown in Figure 91, however, do not exhibit the overtempered condition since there was no prior martensite in the structure which could be overtempered or softened by the localized surface heating. The reactions of iron-base tool steel, as shown in Figures 97 and 98, and case 17-4 PH stainless steel, Figure 99, may be put into the same group as those alloys just described.

Conventionally processed Ti-6Al-4V in both the annealed and aged condition was examined. Photomicrographs are presented in Figures 100 and 101. Evidence of thermal distortion can be seen beneath the recast layers formed on this material. Note that distortion of microstructure due to EDM on this material is considerably greater than that produced on the beta rolled version of the same alloy illustrated in Figure 17.

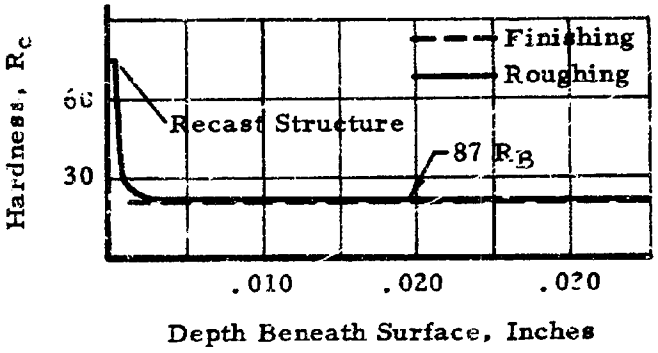
The refractory alloys studied, molybdenum and tungsten, Figures 102 and 103, exhibit no microstructural alterations as a result of EDM processing. Recast surface layers are absent as well as is any evidence of microhardness change. In the case of the tungsten, however, some grain boundary attack and undermining was evidenced as a result of the roughing EDM conditions.

The balance of the illustrations in this section describe the surface effects produced on a variety of wrought and cast nickel base alloys in both the solution treated and aged condition. Alloys otherwise unspecified are samples of wrought material from either forgings or bar stock. Those alloys which are cast are specifically so designated. In general, these high temperature alloys are relatively stable when subjected to surface heating of the magnitude produced by the EDM process. The variation in microhardness characteristics observed is indicated along with the illustrations of the various microstructures.



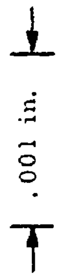
(a) Finishing Conditions - A thin discontinuous recast layer averaging .0001" deep was formed on the surface.
1000X

(b) Roughing Conditions - A variable continuous recast layer up to .002" thick and extensively cracked was formed on the surface. The structure was affected by heat for an additional .002" beneath this surface layer.
1000X



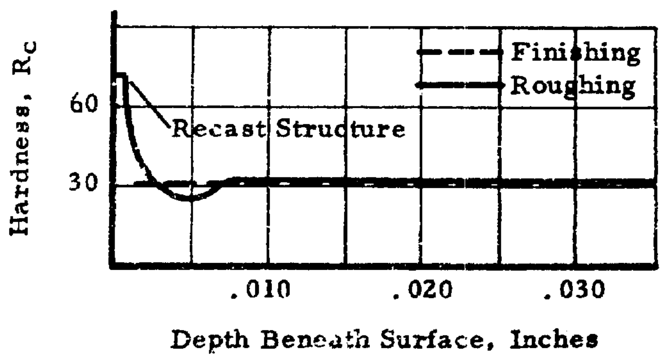
SURFACE CHARACTERISTICS OF
1018 STEEL (Hot Rolled, 87 R_B) PRODUCED
BY EDM

Figure 87



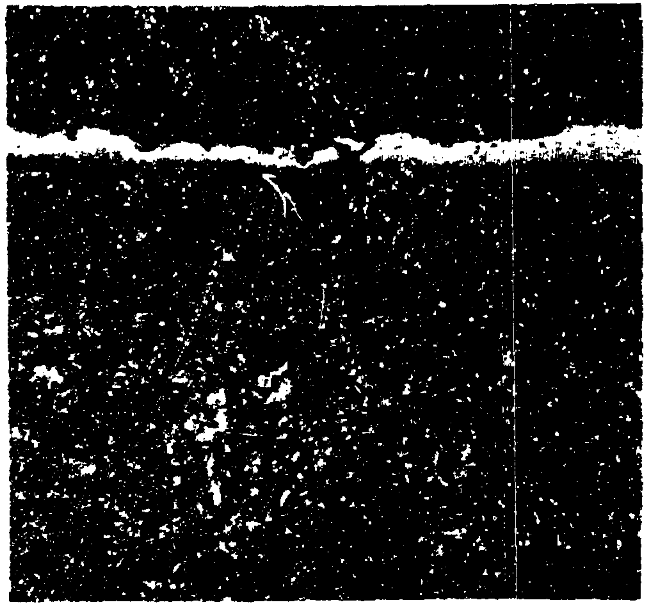
(a) Finishing Conditions - A thin recast layer approximately .0001" deep was formed on the surface but with no visible subsurface changes. 1000X

(b) Roughing Conditions - A random spattering of recast metal up to .002" deep was formed on the surface. A total heat affected zone of .008" was detected by microhardness measurements. 1000X

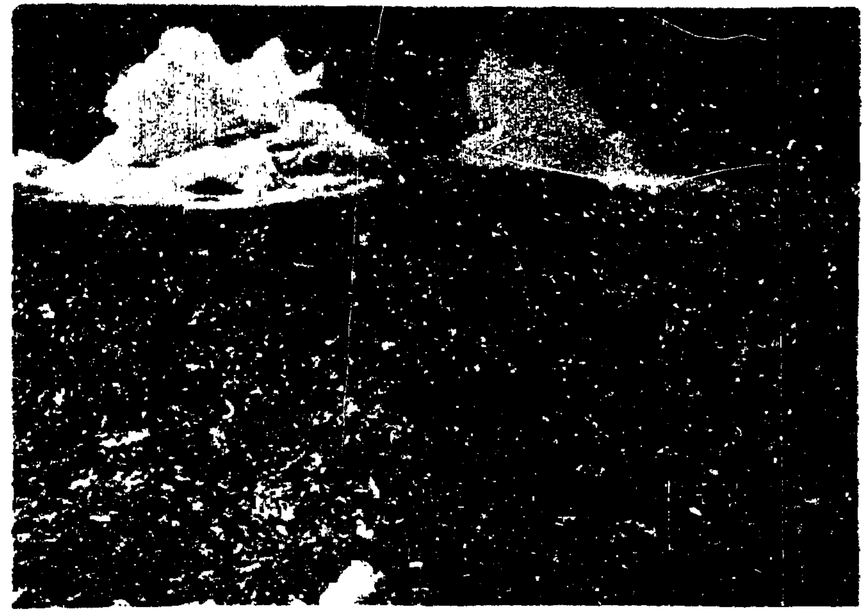


SURFACE CHARACTERISTICS OF 4340 STEEL (Annealed, 31-36 R_c) PRODUCED BY EDM

Figure 88



.001 in.

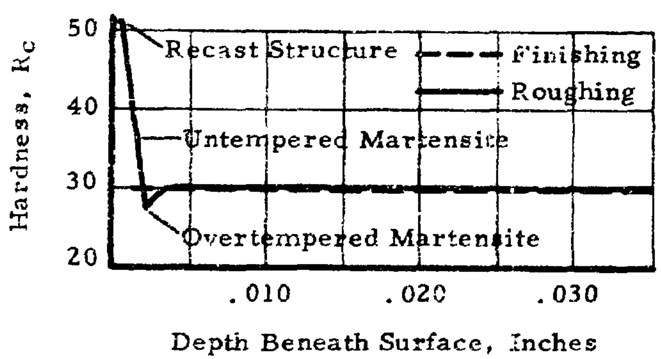


(a) Finishing Conditions - A fairly uniform recast layer .0002" deep was formed on the surface but without other visible changes.

1000X

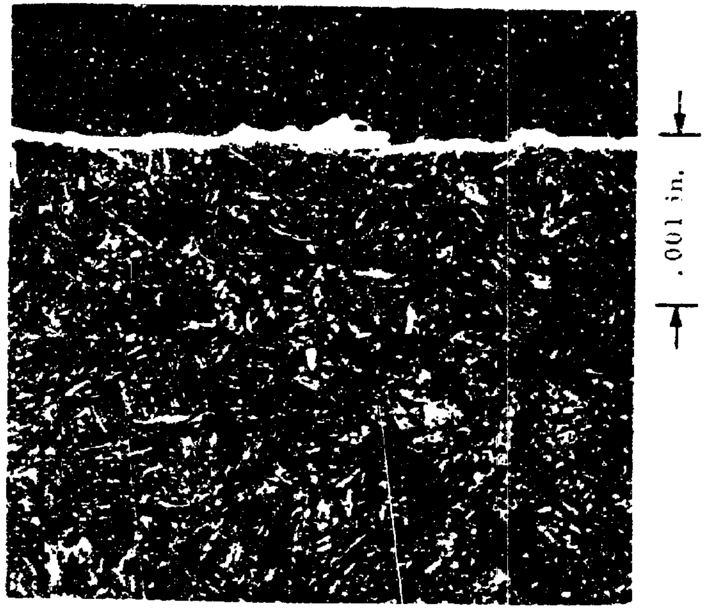
(b) Roughing Conditions - Spattered recast metal up to .001" deep was formed on the surface. Discontinuous bands or layers of untempered martensite and overtempered martensite beneath it were also produced.

1000X

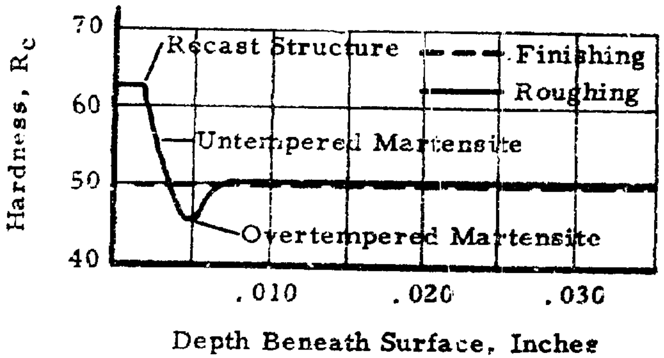


SURFACE CHARACTERISTICS OF
4340 STEEL (Quenched and Tempered, 30 R_c)
PRODUCED BY EDM

Figure 89



(a) Finishing Conditions - A discontinuous layer of recast metal generally less than .0001" was produced on the surface. No other effects were observed.
1000X



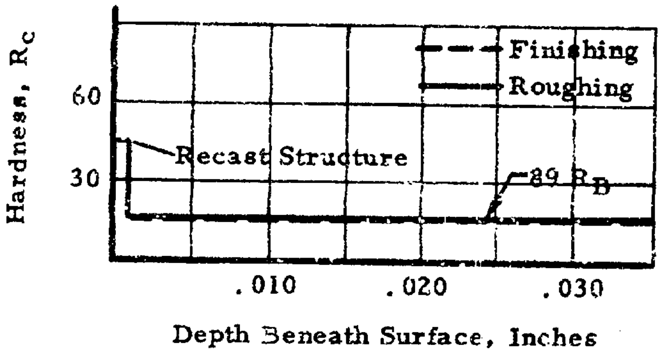
(b) Roughing Conditions - A variable discontinuous recast layer up to .002" deep was observed. Beneath it a relatively uniform layer of untempered martensite .001-.002" deep and an underlying band of overtempered martensite of equal thickness were produced.
1000X

SURFACE CHARACTERISTICS OF 4340 STEEL (Quenched and Tempered, 50 R_c) PRODUCED BY EDM

Figure 90

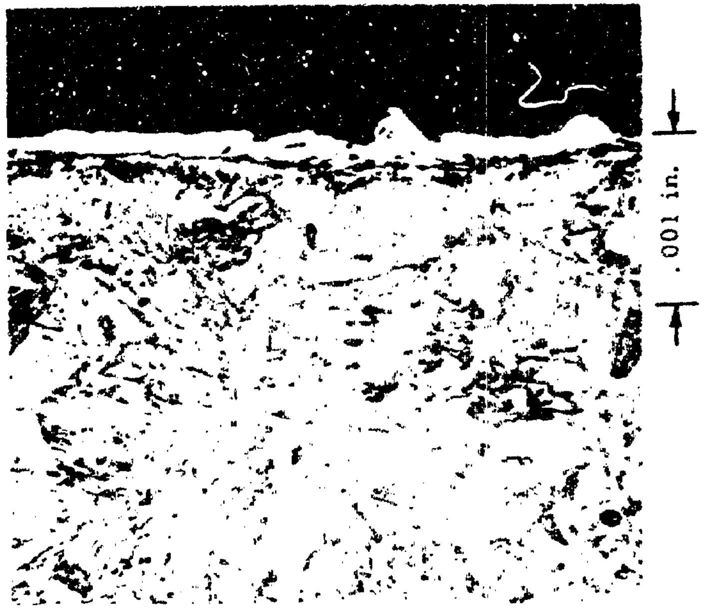
(a) Finishing Conditions - A very thin discontinuous recast layer was produced on the surface.
1000X

(b) Roughing Conditions - A uniform recast layer, .0005-.001" deep, frequently cracked, was produced on the surface. No other alterations were visible.
1000X



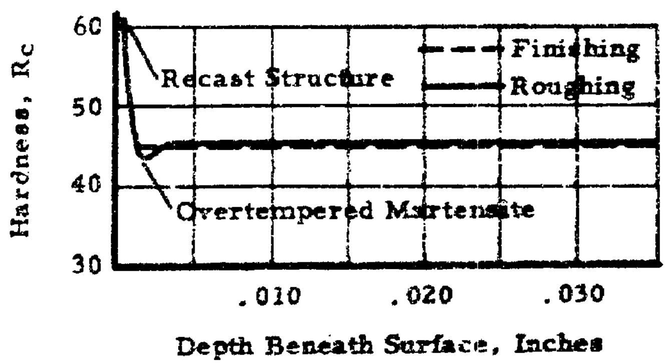
SURFACE CHARACTERISTICS OF
TYPE 410 STAINLESS STEEL (Annealed, 89 R_B)
PRODUCED BY EDM

Figure 91



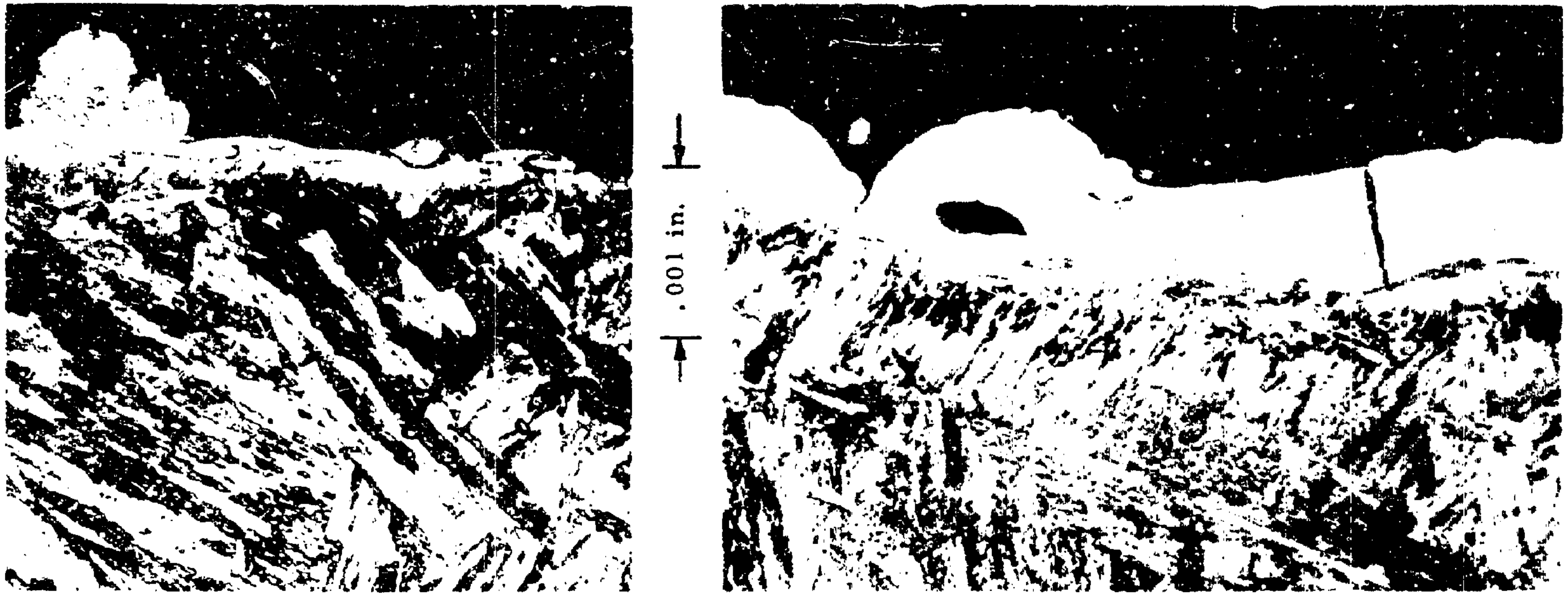
(a) Finishing Conditions - A continuous recast layer approximately .0001" deep was formed on the surface but without other obvious effects. 1000X

(b) Roughing Conditions - A variable recast layer up to .001" deep was produced. Thin bands of overtempered martensite less than .001" deep were found beneath the recast structure. 1000X



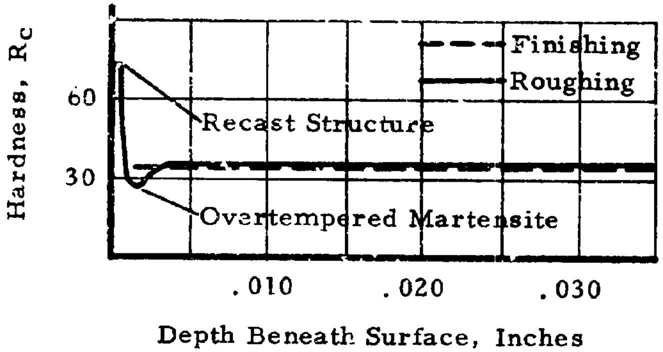
SURFACE CHARACTERISTICS OF TYPE 410 STAINLESS STEEL (Quenched and Tempered, 45 R_c) PRODUCED BY EDM

Figure 92



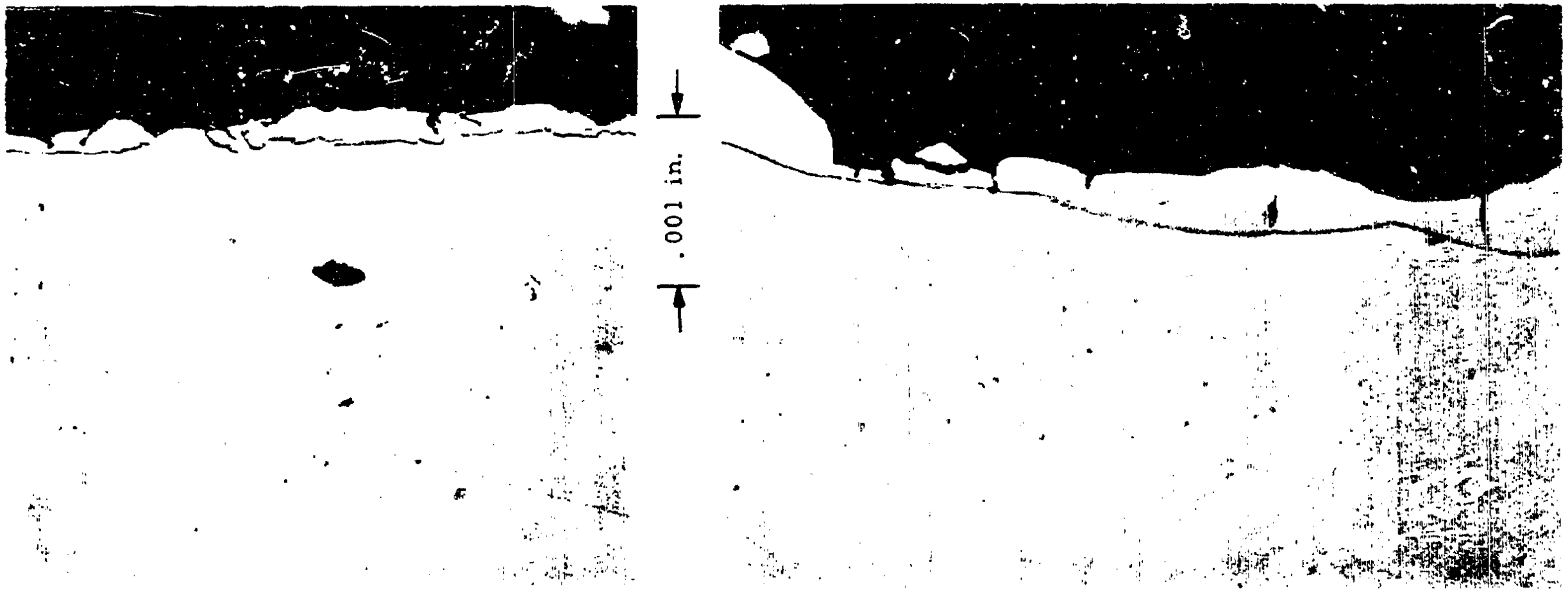
(a) Finishing Conditions - A spotty layer of recast metal averaging .0001" deep was formed on the surface. 1000X

(b) Roughing Conditions - A continuous layer of recast metal averaging .0008" deep was produced. An underlying layer of overtempered martensite approximately .002" deep was also noted. 1000X



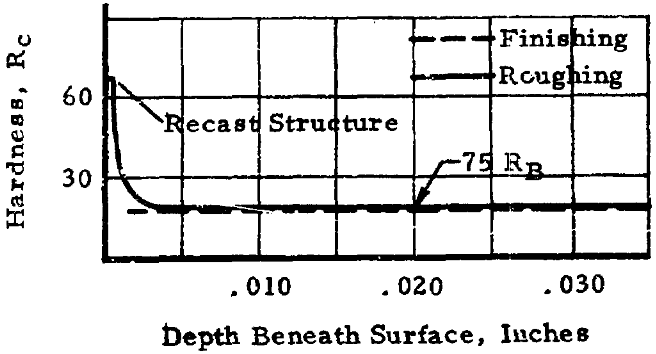
SURFACE CHARACTERISTICS OF CAST TYPE 410 STAINLESS STEEL (Quenched and Tempered, 35 R_c) PRODUCED BY EDM

Figure 93



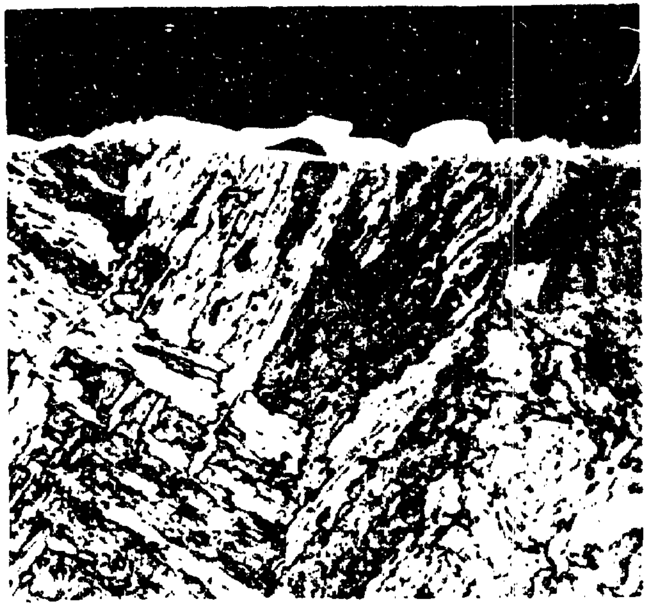
(a) Finishing Conditions - A reasonably continuous recast layer approximately .0002" thick was observed although microhardness changes could not be detected in this thin layer. 1000X

(b) Roughing Conditions - A continuous recast layer up to .0005" thick, and exhibiting high hardness, was observed. This layer was extensively cracked. 1000X



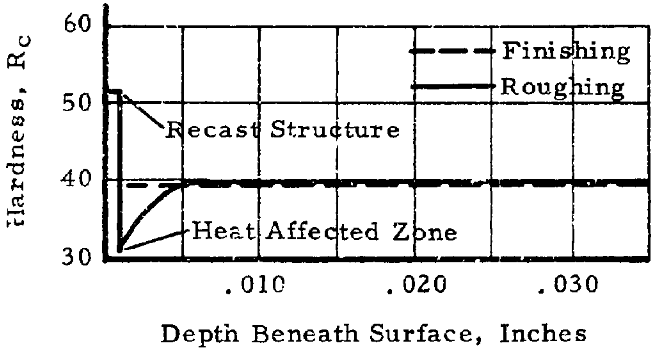
SURFACE CHARACTERISTICS OF TYPE 302 STAINLESS STEEL (Annealed, 75 R_B) PRODUCED BY EDM

Figure 94



(a) Finishing Conditions - A thin continuous recast layer averaging .0001" deep was formed on the surface.
1000X

(b) Roughing Conditions - A recast layer up to .002" was formed on the surface. A softened zone approximately .004" deep was found beneath the recast layer. In general, cracking of the surface layer did not occur.
1000X



SURFACE CHARACTERISTICS OF
GRADE 250 MARAGING STEEL (Annealed, 39 R_c)
PRODUCED BY EDM

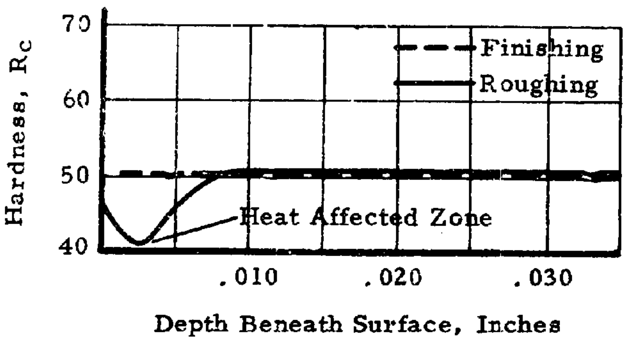
Figure 95

(a) Finishing Conditions - A thin continuous recast layer averaging .0001" deep was formed on the surface.

1000X

(b) Roughing Conditions - A fused recast and heat affected zone having a total depth of .008" was found on the surface. Cracking was generally absent.

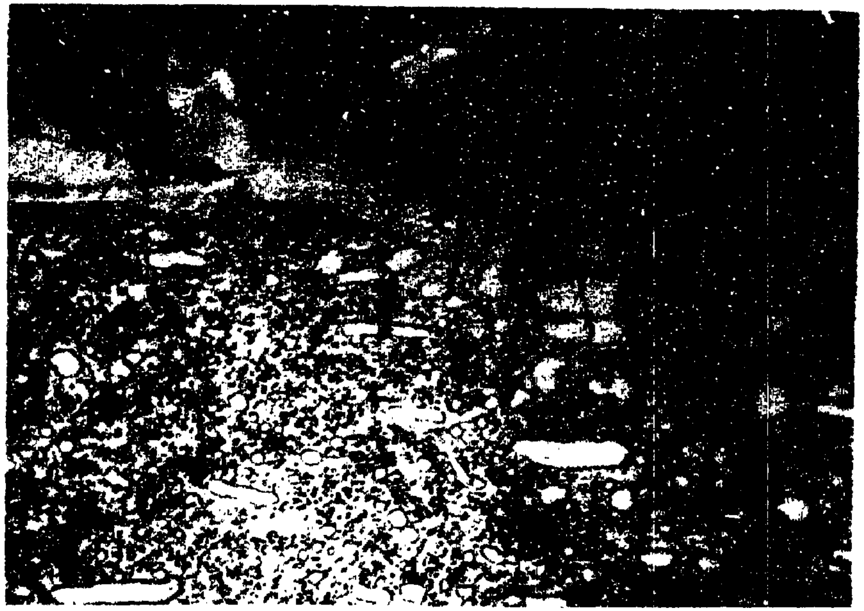
1000X



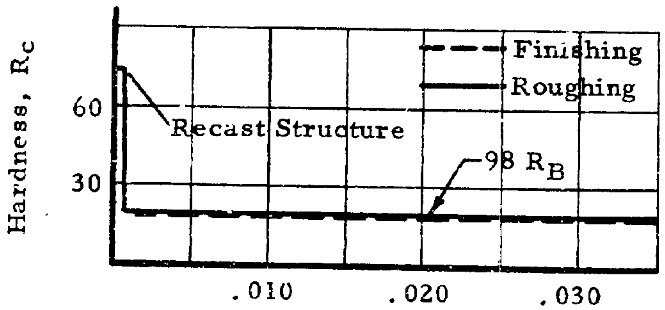
SURFACE CHARACTERISTICS OF GRADE 250 MARAGING STEEL (Aged, 51 R_c) PRODUCED BY EDM

Figure 96

(a) Finishing Conditions - Occasional thin bands of recast metal were formed on the surface but without other visible effects.
1000X



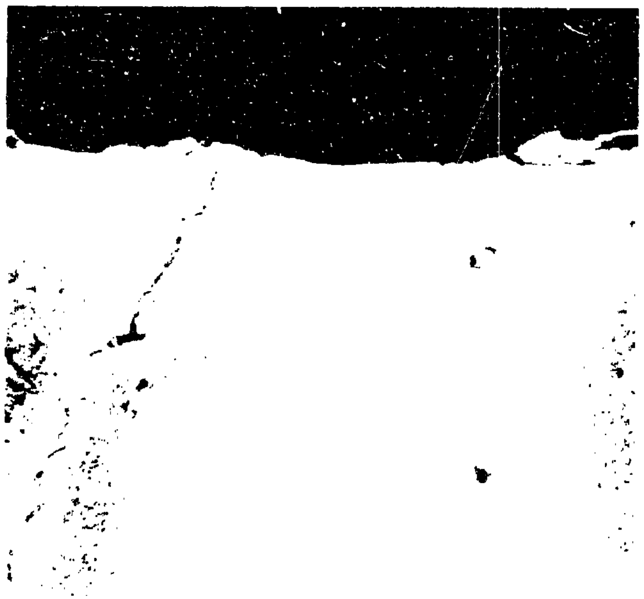
(b) Roughing Conditions - Discontinuous spattered recast metal up to .0005" deep was formed on the surface. No other structural or microhardness alterations were observed.
1000X



Depth Beneath Surface, Inches

SURFACE CHARACTERISTICS OF
TYPE D2 TOOL STEEL (Annealed, 98 R_B)
PRODUCED BY EDM

Figure 97



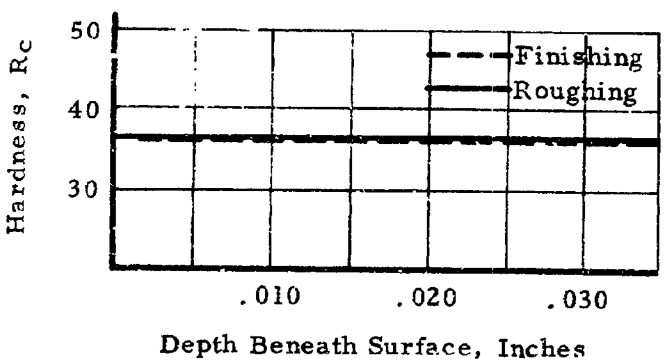
.001 in.

(a) Finishing Conditions - A continuous recast layer approximately .0001" deep was formed on the surface but without other noticeable affects.

1000X

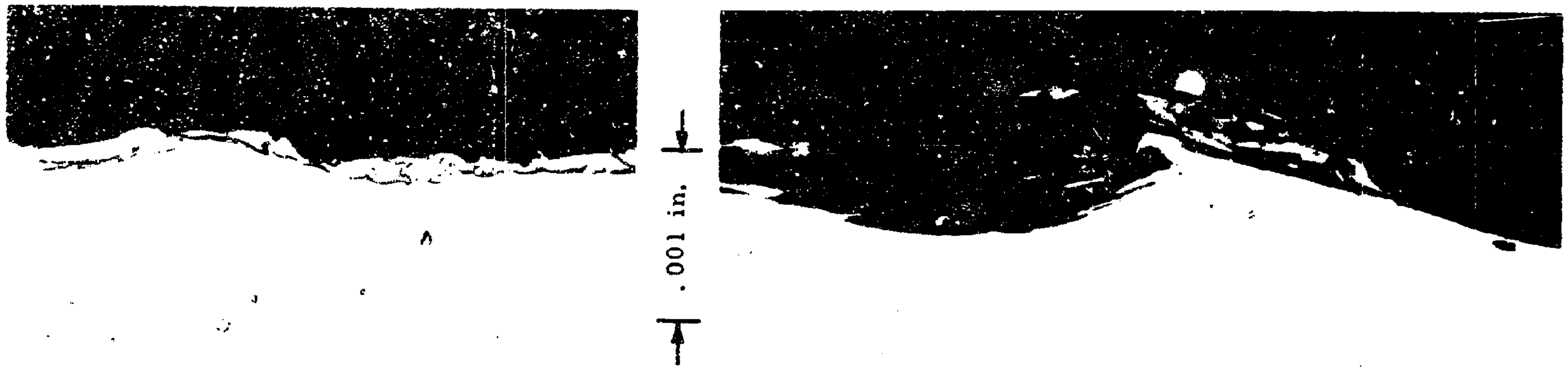
(b) Roughing Conditions - A continuous recast layer averaging .001" deep was produced on the surface. In general, this layer tended to crack at grain boundary intersections with the surface. No micro-hardness changes were observed.

1000X



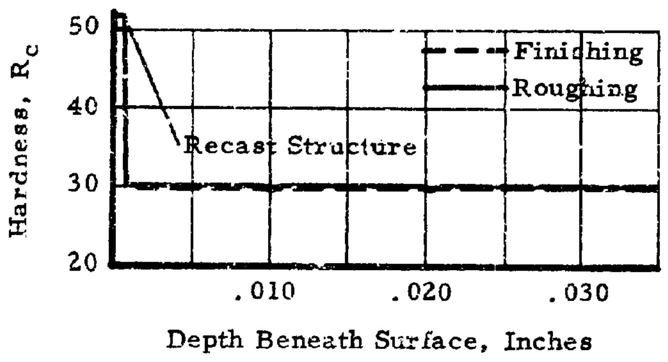
SURFACE CHARACTERISTICS OF CAST RENE' 41 (Aged, 37 R_c) PRODUCED BY EDM

Figure 108



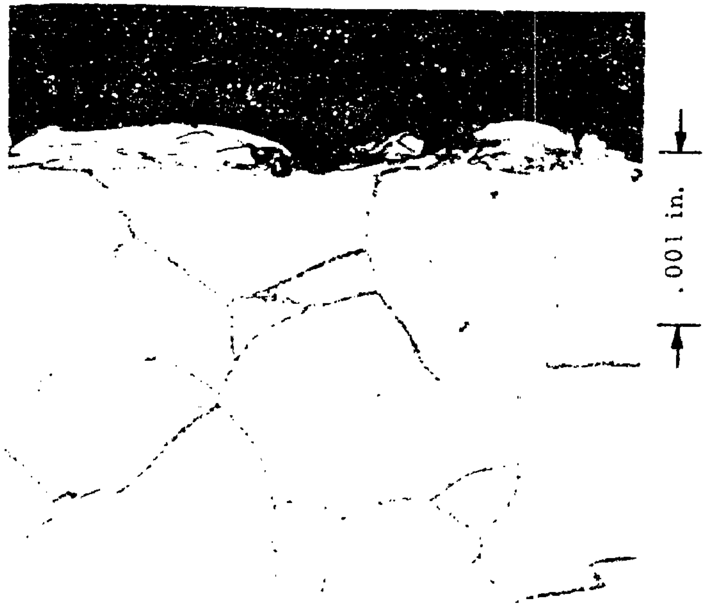
(a) Finishing Conditions - A thin recast layer approximately .0001" deep was produced on the surface. 1000X

(b) Roughing Conditions - A recast layer averaging .0007" deep was produced on the surface. Except for high hardness of the recast layer no other hardness changes were noted. 1000X



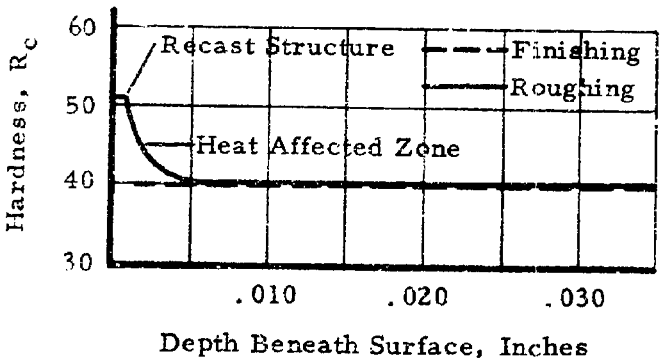
SURFACE CHARACTERISTICS OF WASPALOY (Solution Treated, 30 R_c) PRODUCED BY EDM

Figure 109



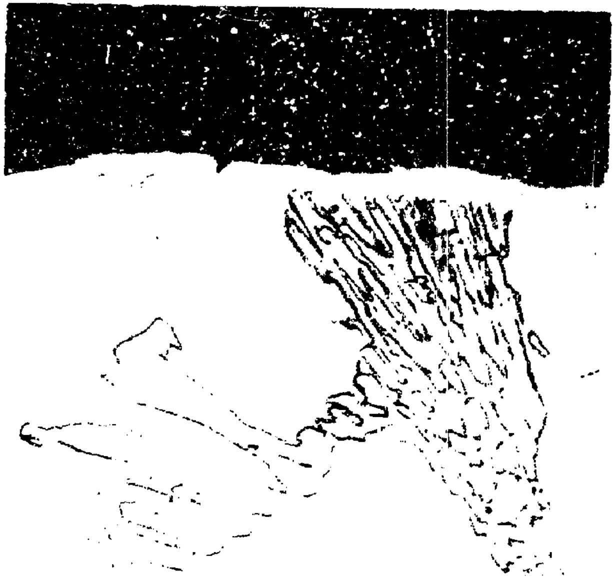
(a) Finishing Conditions - A discontinuous recast layer averaging .0002" deep was produced on this surface.
1000X

(b) Roughing Conditions - A recast layer approximately .0005" deep plus a heat affected microstructure averaging .001" deep, both frequently cracked, were produced on the surface. Microhardness measurements indicate a total heat affected depth of .005".
1000X



SURFACE CHARACTERISTICS OF
WASPALOY (Aged, 40 R_c) PRODUCED BY EDM

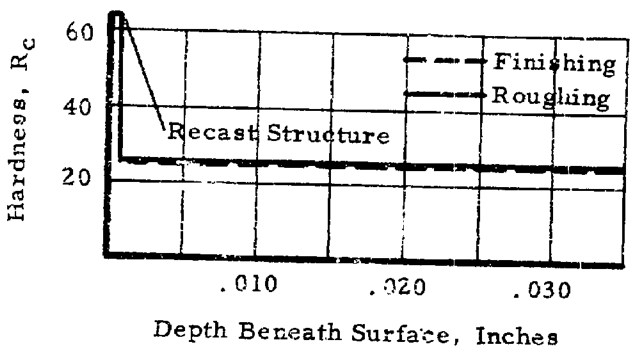
Figure 110



(a) Finishing Conditions - A very thin recast layer averaging less than .0001" was formed on the surface. 1000X

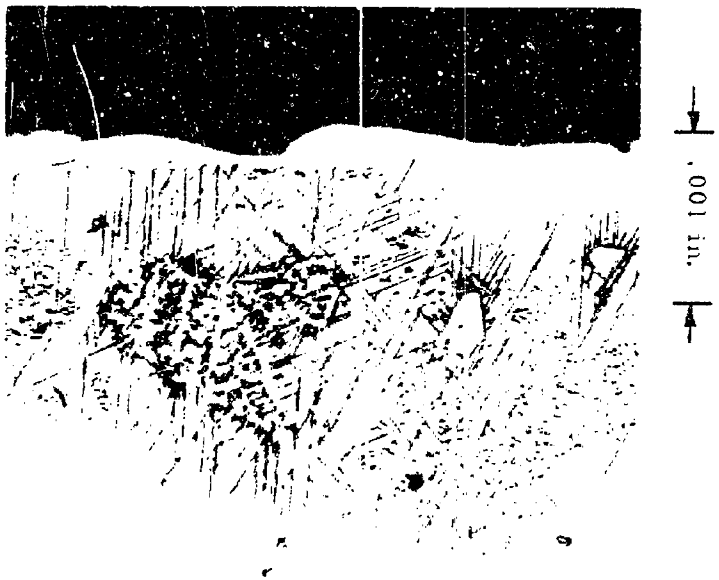
(b) Roughing Conditions - A recast and occasionally cracked layer .001" deep was formed on the surface. No microhardness changes other than the high hardness of the recast layer were observed.

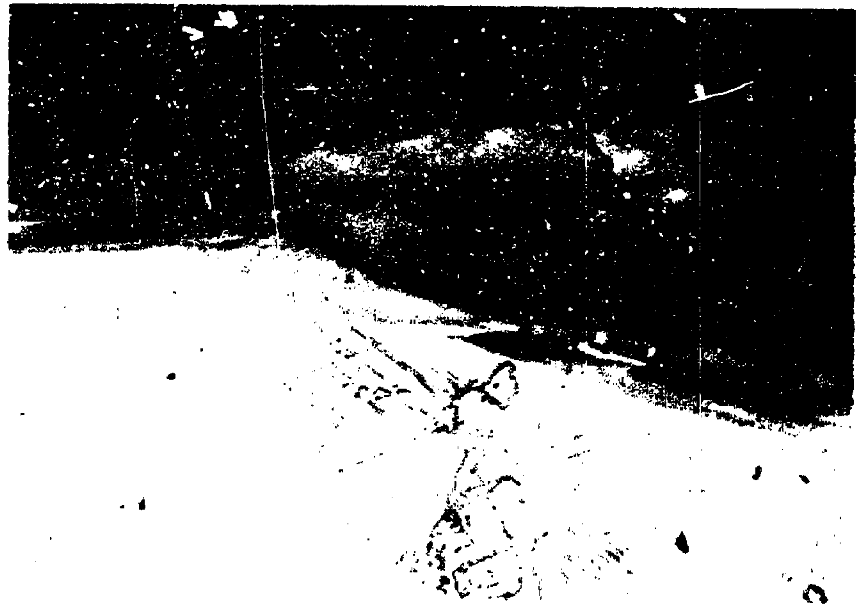
1000X



SURFACE CHARACTERISTICS OF HAYNES ALLOY NO. 31 (Cast, 23 R_c) PRODUCED BY EDM

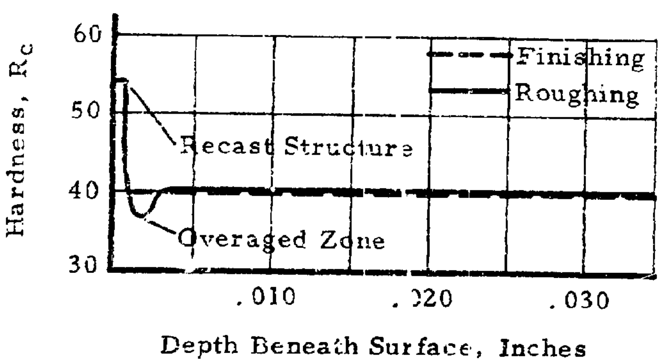
Figure 111





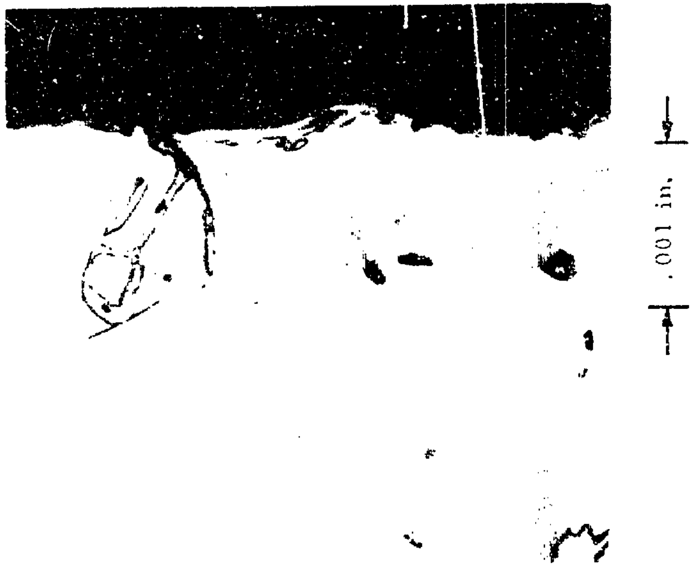
(a) Finishing Conditions - A variable recast layer averaging .0002" thick was formed on the surface.
1000X

(b) Roughing Conditions - A variable recast layer, extensively cracked, up to .002" thick, was formed on the surface. Slight overaging due to the localized surface overheating was also noted. The random acicular structure is not related to the surface phenomena.
1000X



SURFACE CHARACTERISTICS OF CAST INCONEL 718 (Aged, 40 R_c) PRODUCED BY EDM

Figure 112

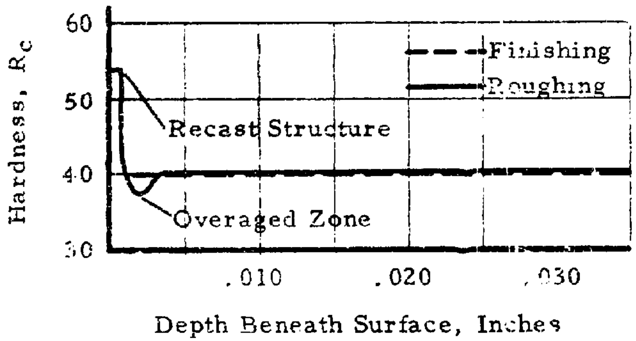


(a) Finishing Conditions - A continuous recast layer averaging less than .0001" was found on the surface. A crack through a carbide intersecting the surface may also be noted.

1000X

(b) Roughing Conditions - A surface recast layer averaging .0002" plus extensive recast spattered metal was found on the surface. A overaged zone beneath the recast metal was detected by microhardness measurements.

1000X



SURFACE CHARACTERISTICS OF CAST UDIMET 700 (Aged, 40 R_c) PRODUCED BY EDM

Figure 113

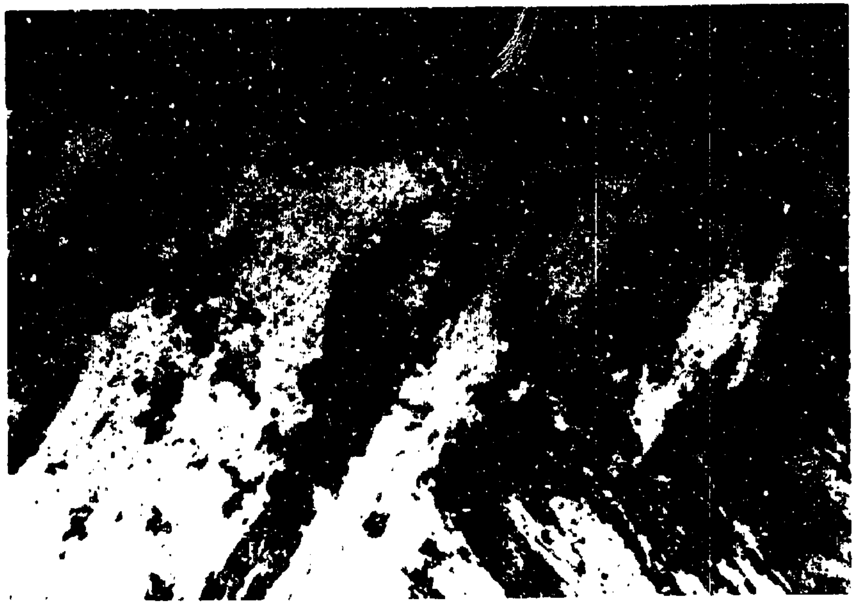
7.2 ECM Characteristics

Metallography data obtained on these 27 aerospace materials/heat treatment combinations finished by electrochemical machining (ECM) are shown in Figures 114 through 140. The electrochemical machining was performed by G. E. /Evendale. ECM under gentle conditions involved the use of those parameters which would be used for a standard finishing cut on the various materials involved. ECM under abusive conditions was performed by intentionally shifting several of these variables to produce a condition representing poor ECM practice. Since several of the details of the ECM processing are proprietary, details of the metal removal conditions for the various materials are not available for publication. The photomicrographs presented in this section should be considered as representing the range of characteristics which can be produced by ECM. The effects observed as a result of gentle ECM processing should not be considered indicative of the best possible processing available for the various materials involved. It is likely that added development of the ECM process as applied to some of these materials would result in improved ECM surface characteristics.

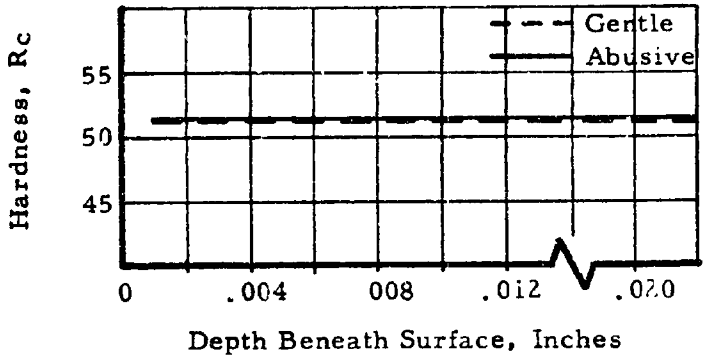
In reviewing the following 27 figures, it can be observed that the ECM process does not produce a visible alteration to the microstructure. In general, gentle conditions result in a smooth, plane surface or one with very fine pitting or irregularities. Abusive conditions tend to produce various degrees of pitting; a few of the samples exhibited rather severe intergranular attack as a result of abusive processing.

The low alloy steels covered by this study (Figures 114 through 118) were all processed quite successfully using ECM. Roughing conditions tended to produce some surface roughening or pitting on quenched and tempered 4340 steel (Figures 116 and 117). The finishing operations all gave what appeared to be a satisfactory surface. The stainless grades of steel, however, were considerably more prone to surface pitting. Observe the moderate pitting exhibited by type 410 stainless steel (Figure 118) and the severe surface and subsurface pitting exhibited by type 302 stainless steel (Figure 121). The maraging steel also exhibited surface pitting and irregularities, although to a lesser degree than the other stainless grades. This may be seen in Figures 122 and 123. The D2 tool steel (Figures 124 and 125) exhibited a curious behavior in that the carbide phase was relatively untouched by the ECM conditions which were employed. This condition, clearly evident in these photomicrographs, might tend to make the material surface behave in a somewhat abrasive manner. The effect of this type of condition on surface integrity, however, has not been established.

(a) Gentle Conditions - No significant surface effects including no measurable change in hardness.
Surface Finish: 10 AA 1000X

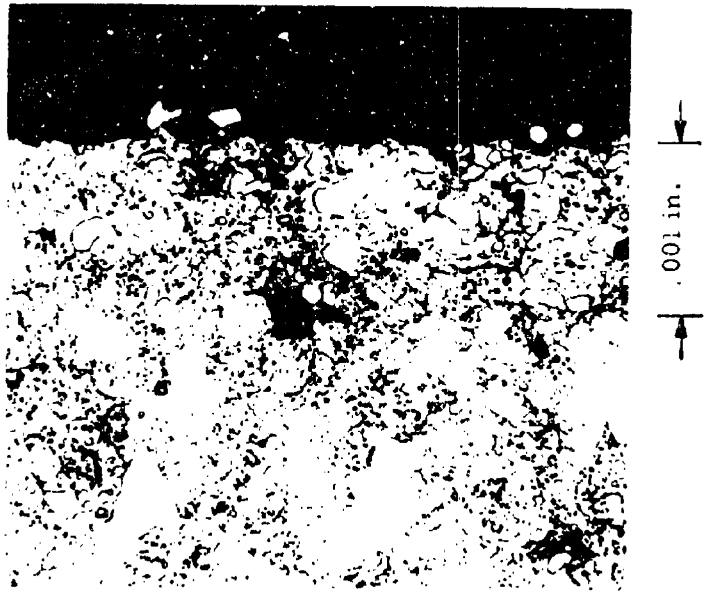


(b) Abusive Conditions - Slight surface roughening but without measurable hardness loss.
Surface Finish: 40 AA 1000X

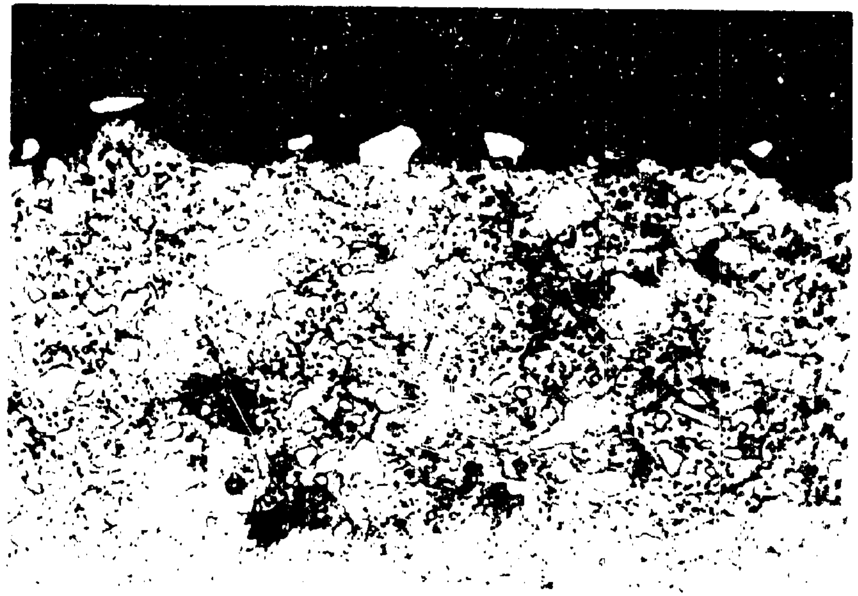


SURFACE CHARACTERISTICS OF
GRADE 250 MARAGING STEEL (Aged, 51 R_c)
PRODUCED BY ECM

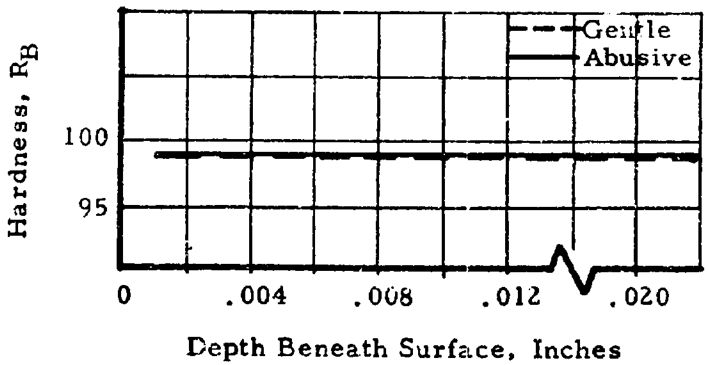
Figure 123



(a) Gentle Conditions - Surface roughening to the extent that the carbide phase was not removed by the ECM process.
Surface Finish: 35 AA 1000X



(b) Abusive Conditions - Surface roughening slightly more pronounced than under Gentle conditions because of non-solution of the carbide phase.
Surface Finish: 60 AA 1000X



SURFACE CHARACTERISTICS OF
TYPE D2 TOOL STEEL (Annealed, 98 R_B)
PRODUCED BY ECM

Figure 124

7.2 ECM Characteristics (continued)

Photomicrographs of cast 17-4 PH are shown in Figure 126. Notice the surface roughening and severe intergranular attack exhibited by this alloy when processed by abusive ECM.

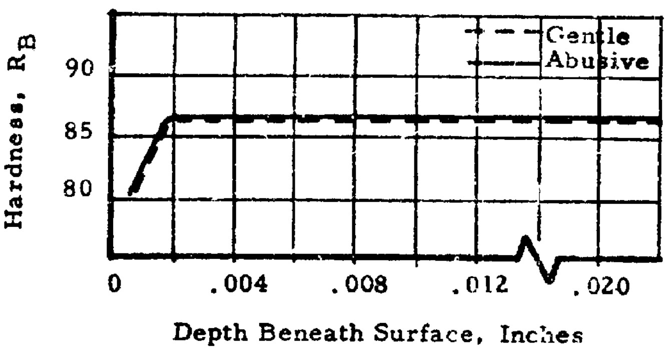
Titanium and nolybdenum, as indicated in Figures 127 through 129, show no unusual effects from ECM processing. Tungsten, however, as indicated in Figure 130, is excessively sensitive to intergranular attack under the abusive ECM conditions chosen for this study.

The ECM processing of the high temperature alloys resulted in a variety of surface behaviors, as may be seen from a review of Figures 131 through 140. In general, ECM processing of a wrought alloy in the solution treated condition results in a smooth surface with no significant intergranular attack, even under abusive conditions. Observe the satisfactory surfaces in Figures 133 and 136. ECM, however, tends to produce intergranular cracking in wrought alloys in the aged condition (Figure 137) as well as in cast materials (Figures 135 and 126). In addition, ECM of cast alloys tends to produce an irregular or rough surface, presumably due to the presence of large, segregated carbide phases (Figures 131, 138, 139, and 140).

In reviewing the microhardness characteristics produced by ECM processing, many of the materials exhibited a slight surface softening, approximately .001 in. deep. An explanation for this hardness loss is not available at the present time.

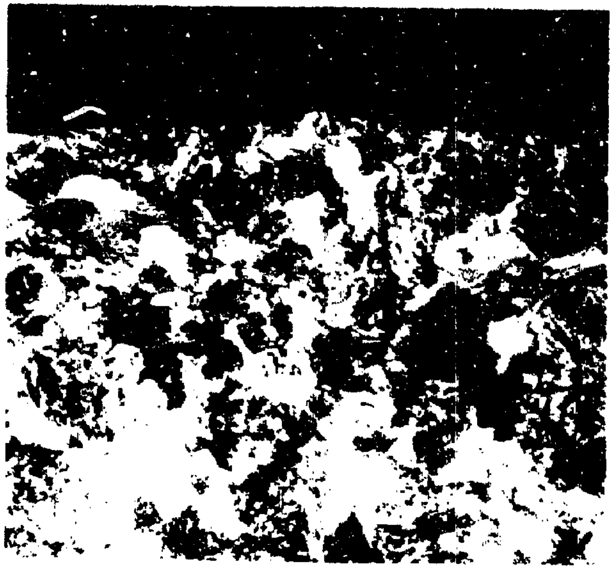
(a) Gentle Conditions - Slight surface roughening and noticeable loss of surface hardness.
Surface Finish: 15 AA 1000X

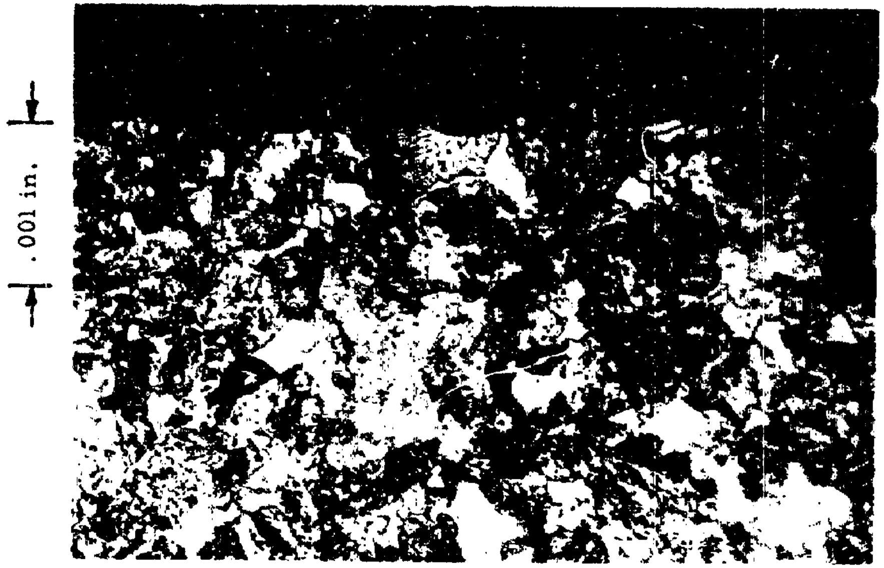
(b) Abusive Conditions - Moderate surface roughening and surface hardness loss but without evidence of alteration in microstructure.
Surface Finish: 70 AA 1000X



SURFACE CHARACTERISTICS OF
1018 STEEL (Hot Rolled, 87 R_B) PRODUCED
BY ECM

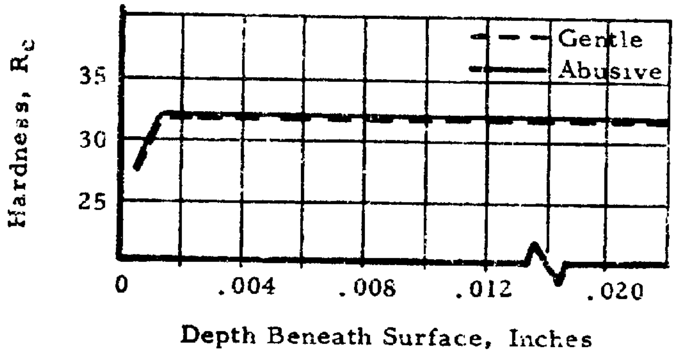
Figure 114





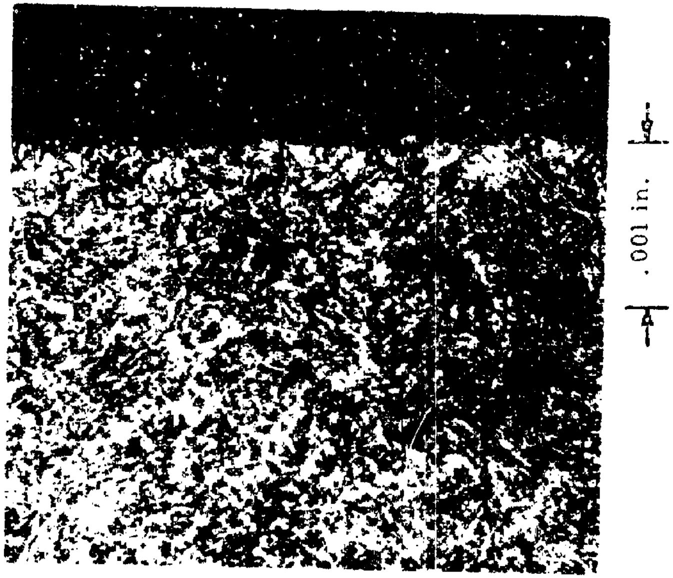
(a) Gentle Conditions - No visible surface effects except for shallow hardness loss.
Surface Finish: 10 AA 1000X

(b) Abusive Conditions - Slight surface roughening plus the same hardness loss as noted for Gentle ECM conditions.
Surface Finish: 40 AA 1000X

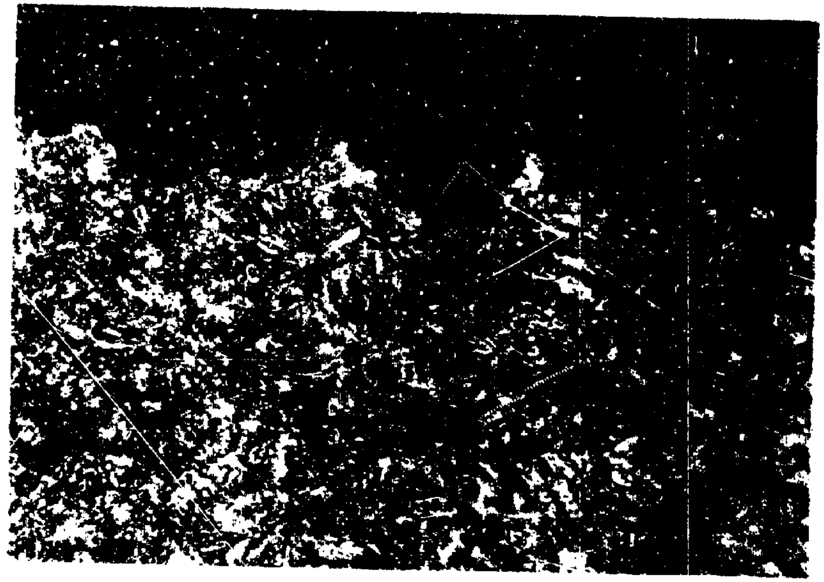


SURFACE CHARACTERISTICS OF
4340 STEEL (Annealed, 31-36 R_c) PRODUCED
BY ECM

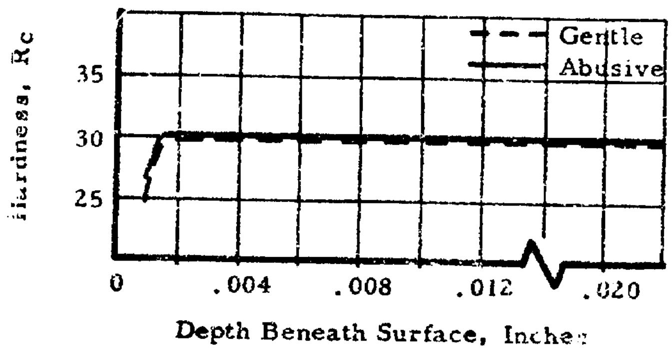
Figure 115



(a) Gentle Conditions - Slight surface pitting and hardness loss but without other visible changes.
Surface Finish: 10 AA 1000X

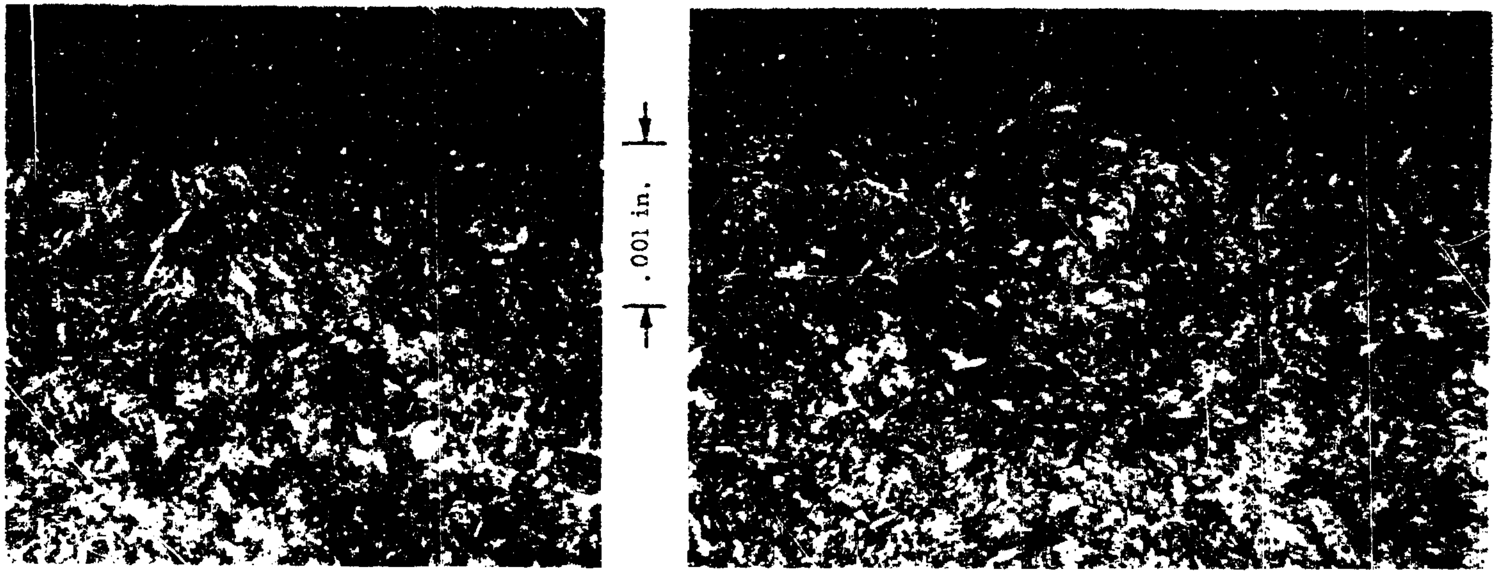


(b) Abusive Conditions - Pronounced surface roughening plus hardness loss but without visible effect on microstructure.
Surface Finish: 140 AA 1000X



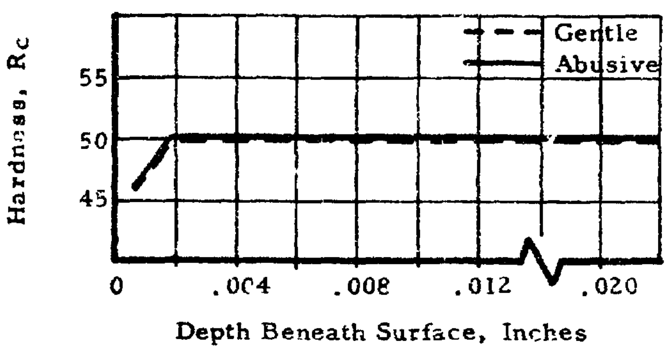
SURFACE CHARACTERISTICS OF
4340 STEEL (Quenched and Tempered, 30 R_c)
PRODUCED BY ECM

Figure 116



(a) Gentle Conditions - No visible surface effects except for hardness loss.
Surface Finish: 10AA 1000X

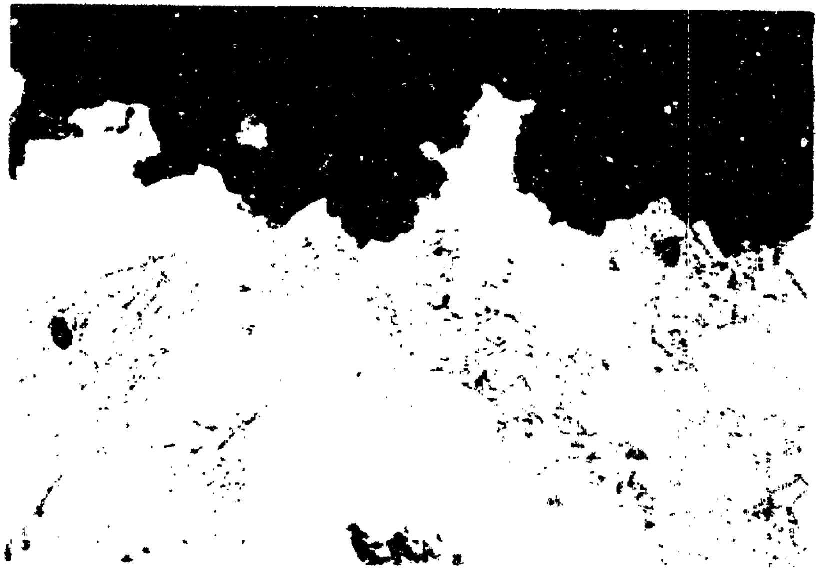
(b) Abusive Conditions - Moderate surface roughening plus hardness loss.
Surface Finish: 30 AA 1000X



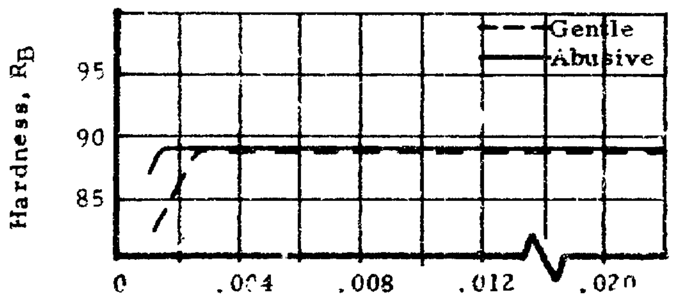
SURFACE CHARACTERISTICS OF
4340 STEEL (Quenched and Tempered, 50 R_c)
PRODUCED BY ECM

Figure 117

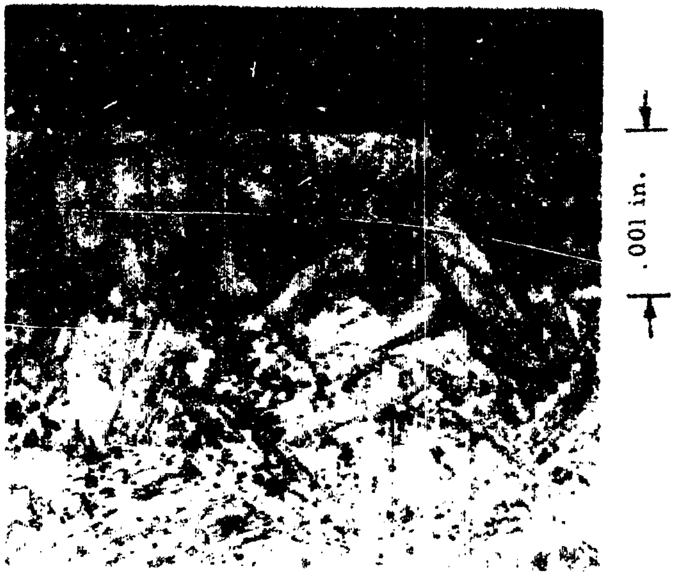
(a) Gentle Conditions - Pronounced microscopic roughening and tendency toward intergranular attack plus slight surface hardness loss.
Surface Finish: 40 AA 1000X



(b) Abusive Conditions - Pronounced surface roughening plus moderate surface hardness loss.
Surface Finish: 400 AA 1000X

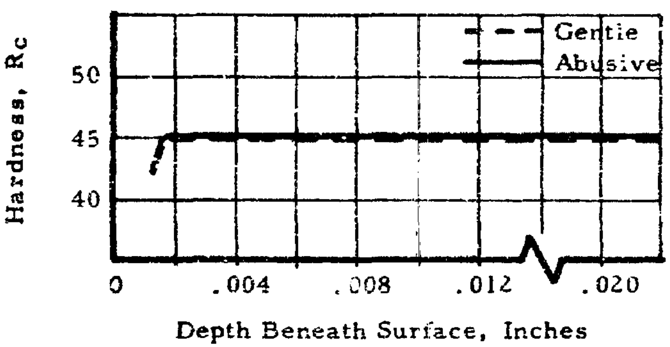


SURFACE CHARACTERISTICS OF
TYPE 410 STAINLESS STEEL (Annealed, 89 R_B)
PRODUCED BY ECM



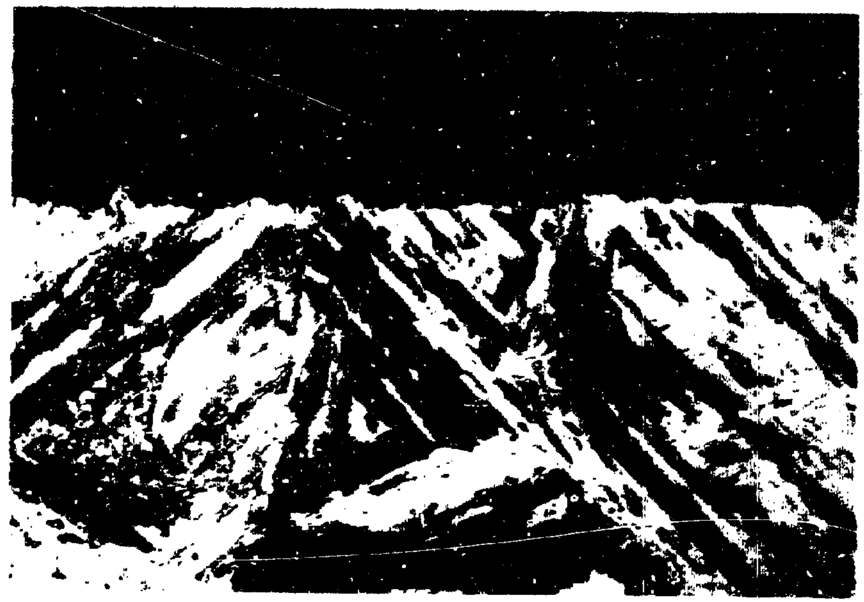
(a) Gentle Conditions - Slight surface texturing plus superficial drop in hardness.
Surface Finish: 15 AA 1000X

(b) Abusive Conditions - Moderate surface roughening and pitting plus localized hardness loss.
Surface Finish: 40 AA 1000X



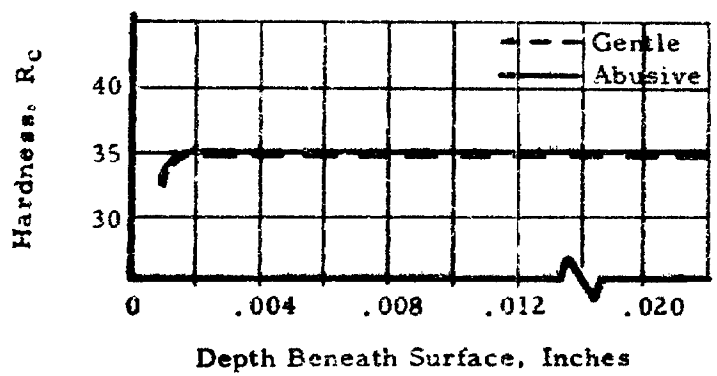
SURFACE CHARACTERISTICS OF TYPE 410 STAINLESS STEEL (Quenched and Tempered, 45 R_c) PRODUCED BY ECM

Figure 119



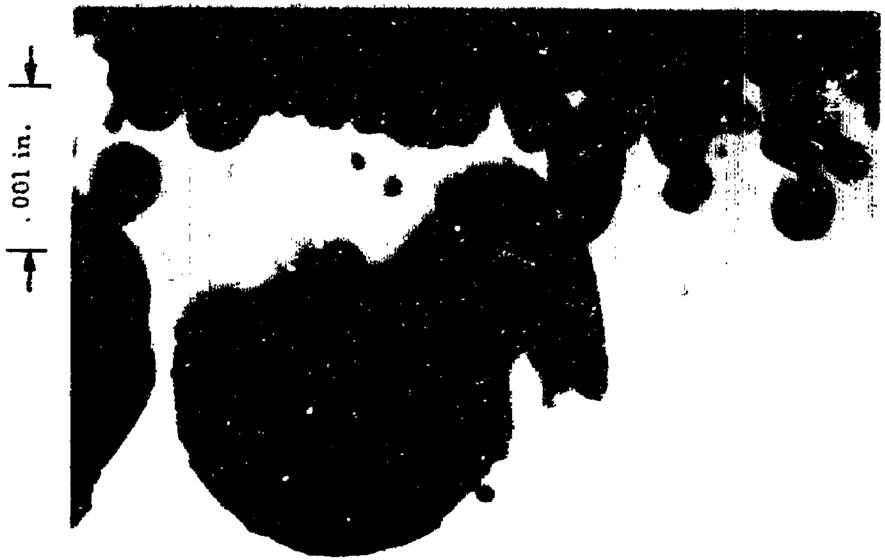
(a) Gentle Conditions - Slight surface pitting and tendency toward inter-granular attack.
Surface Finish: 20 AA 1000X

(b) Abusive Conditions - Surface roughening and hardness loss similar to that produced by Gentle conditions.
Surface Finish: 25 AA 1000X



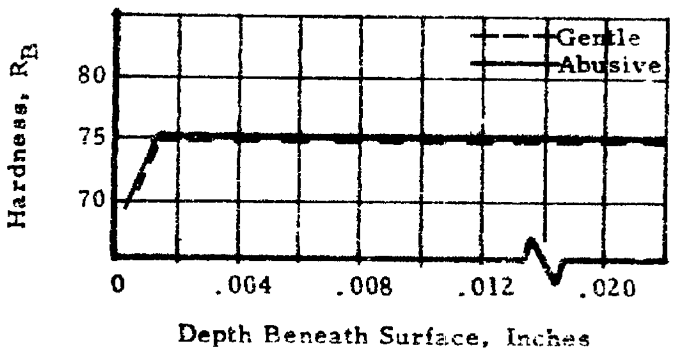
SURFACE CHARACTERISTICS OF
CAST TYPE 410 STAINLESS STEEL (Quenched and Tempered, 35 R_c) PRODUCED BY ECM

Figure 120



(a) Gentle Conditions - No visible surface effects except for measured hardness loss.
Surface Finish: 10 AA 1000X

(b) Abusive Conditions - Severe surface and subsurface pitting.
Surface Finish: 80 AA 1000X



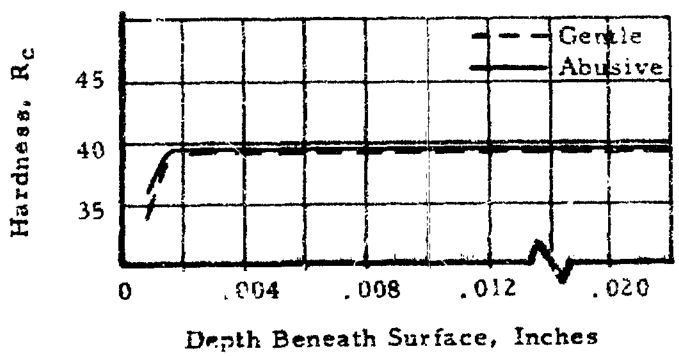
SURFACE CHARACTERISTICS OF
TYPE 302 STAINLESS STEEL (Annealed, 75 R_B)
PRODUCED BY ECM

Figure 121

.001 in.

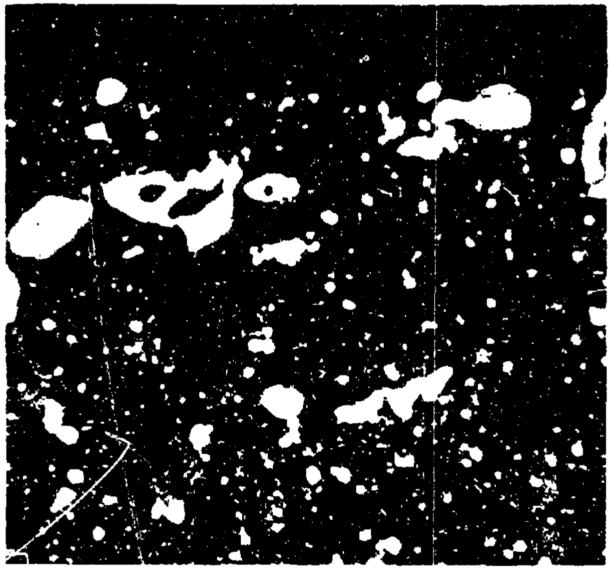
(a) Gentle Conditions - Microscopic surface roughening and shallow hardness loss.
Surface Finish: 25 AA 1000X

(b) Abusive Conditions - Extensive surface roughening and pitting plus shallow hardness loss.
Surface Finish: 160 AA 1000X

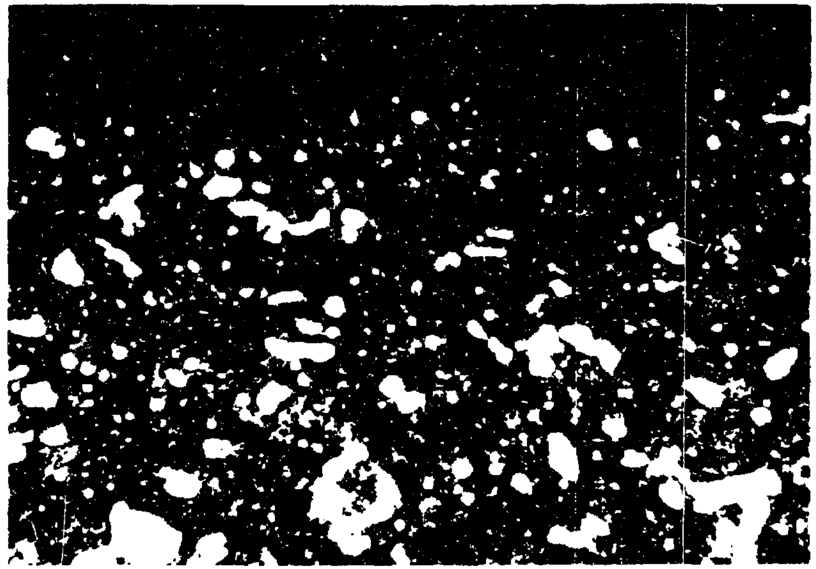


SURFACE CHARACTERISTICS OF
GRADE 250 MARAGING STEEL (Annealed, 39 R_c)
PRODUCED BY ECM

Figure 122

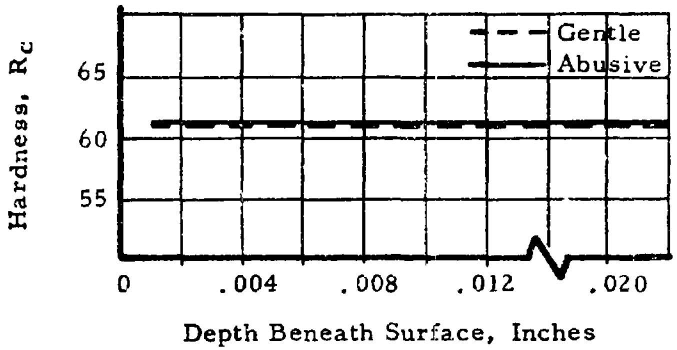


.001 in.



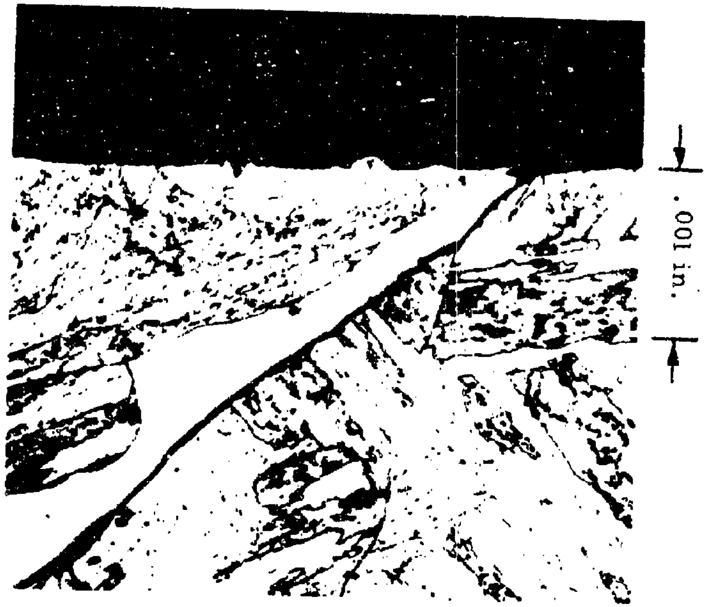
(a) Gentle Conditions - Surface roughening to the extent that the carbide phase was not removed by the ECM process.
Surface Finish: 40 AA 1000X

(b) Abusive Conditions - Surface roughening due to uneven machining action on both carbides and matrix.
Surface Finish: 140 AA 1000X



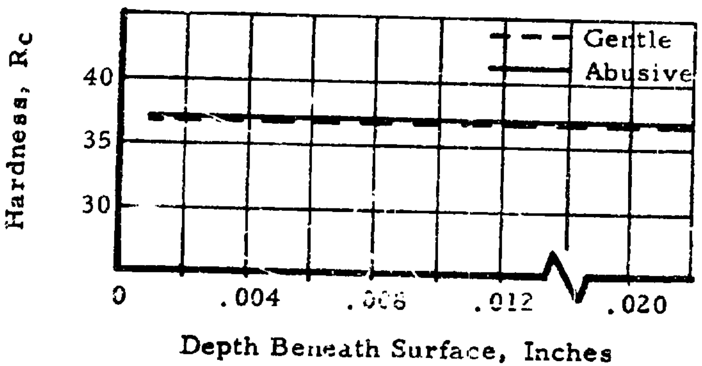
SURFACE CHARACTERISTICS OF
TYPE D2 TOOL STEEL (Quenched and Tempered, 61 R_c)
PRODUCED BY ECM

Figure 125



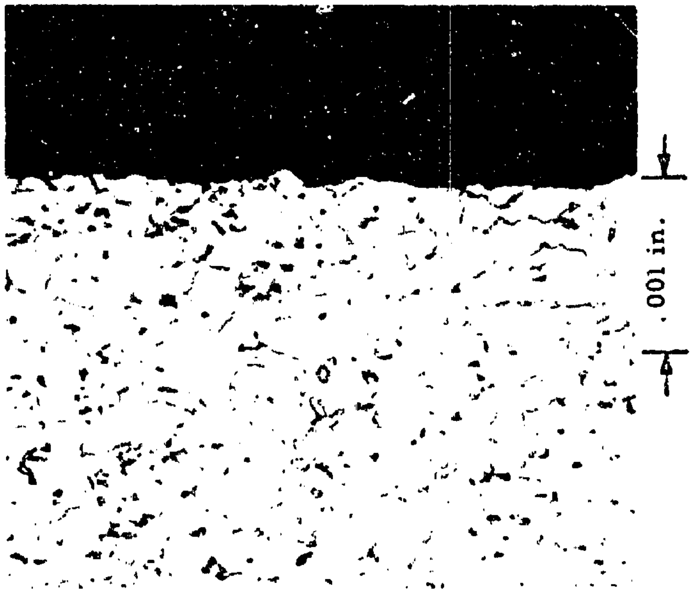
(a) Gentle Conditions - Slight surface roughening with tendency toward intergranular attack.
Surface Finish: 15 AA 1000X

(b) Abusive Conditions - Moderate surface roughening and severe intergranular attack.
Surface Finish: 85 AA 1000X

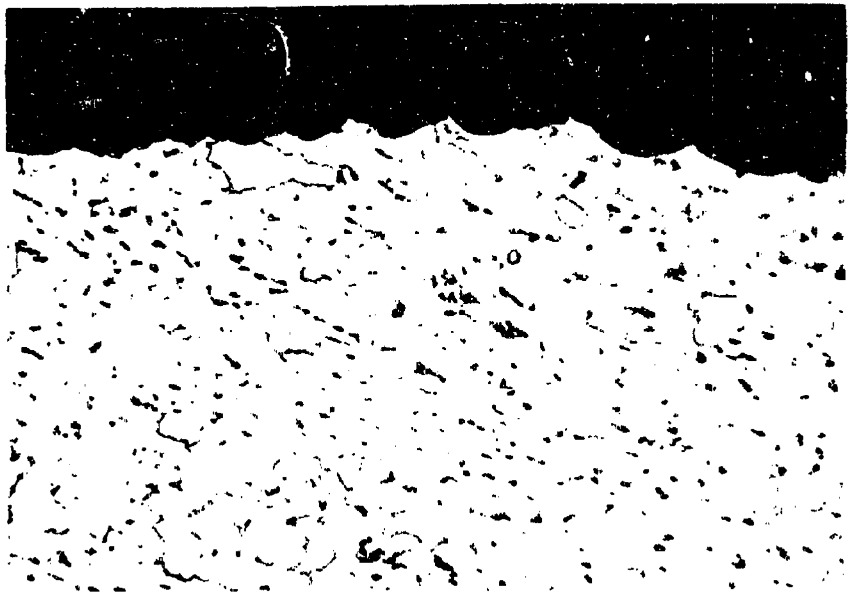


SURFACE CHARACTERISTICS OF
CAST 17-4PH STAINLESS STEEL (Aged, 37 R_c)
PRODUCED BY ECM

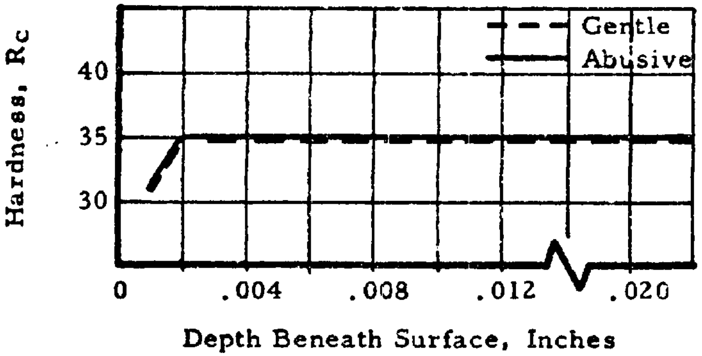
Figure 126



(a) Gentle Conditions - Slight surface irregularity but without evidence of microstructure change. Note hardness loss indicated.
Surface Finish: 15 AA 1000X

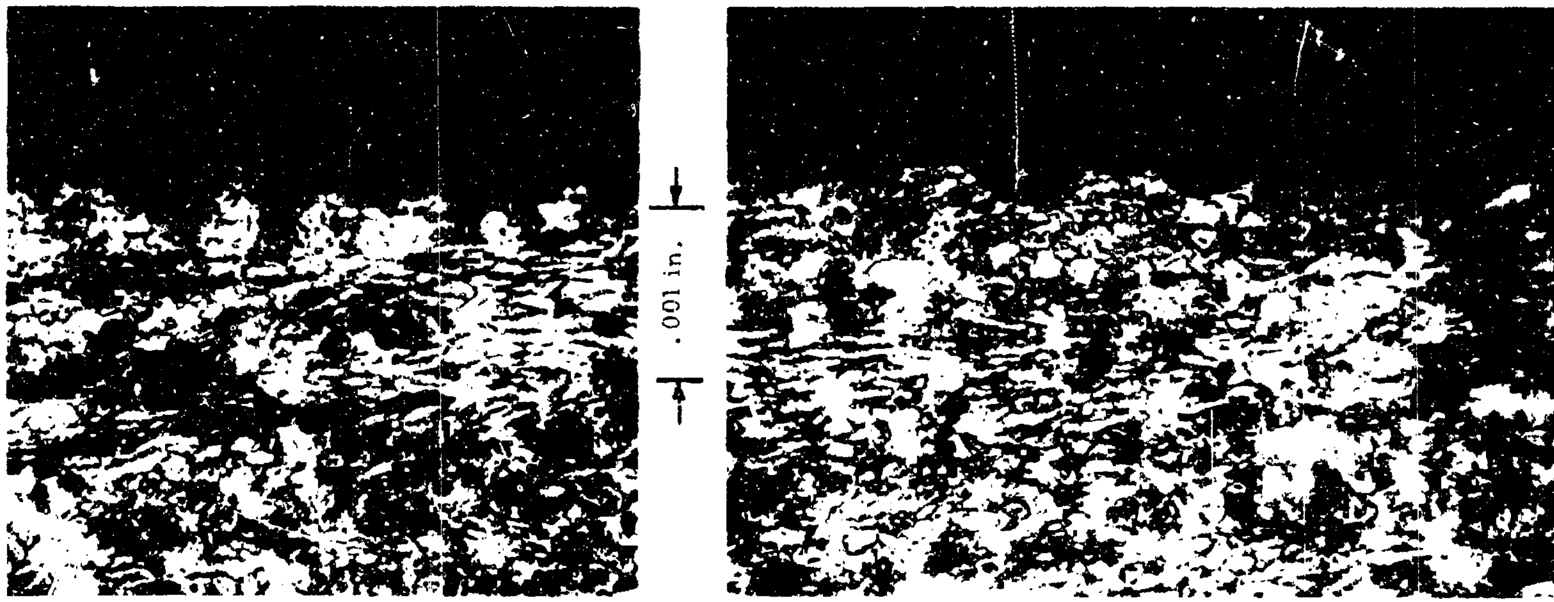


(b) Abusive Conditions - Moderate level of surface roughening plus slight drop in microhardness.
Surface Finish: 90 AA 1000X



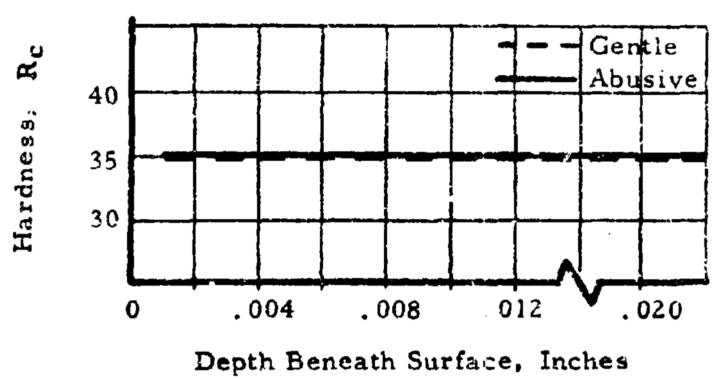
SURFACE CHARACTERISTICS OF TITANIUM 6Al-4V (Annealed, 35 R_c) PRODUCED BY ECM

Figure 127



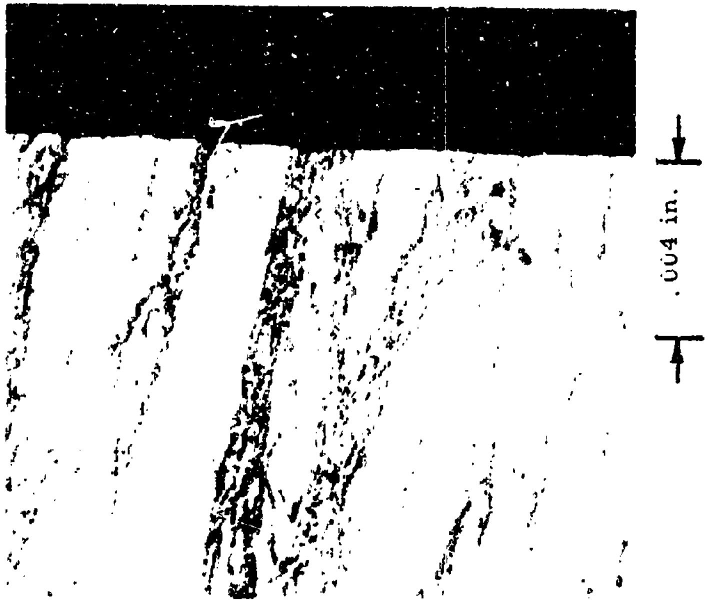
(a) Gentle Conditions - Moderate surface roughening.
Surface Finish: 20 AA 1000X

(b) Abusive Conditions - Moderate surface roughening tending to be more irregular than that produced by Gentle conditions.
Surface Finish: 180 AA 1000X



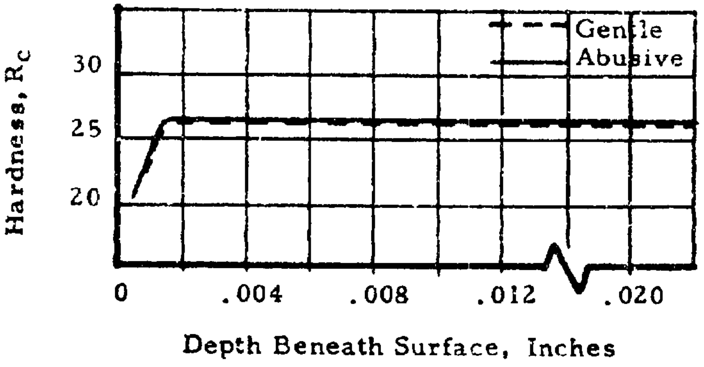
SURFACE CHARACTERISTICS OF TITANIUM 6Al-4V (Aged, 35 R_c) PRODUCED BY ECM

Figure 128



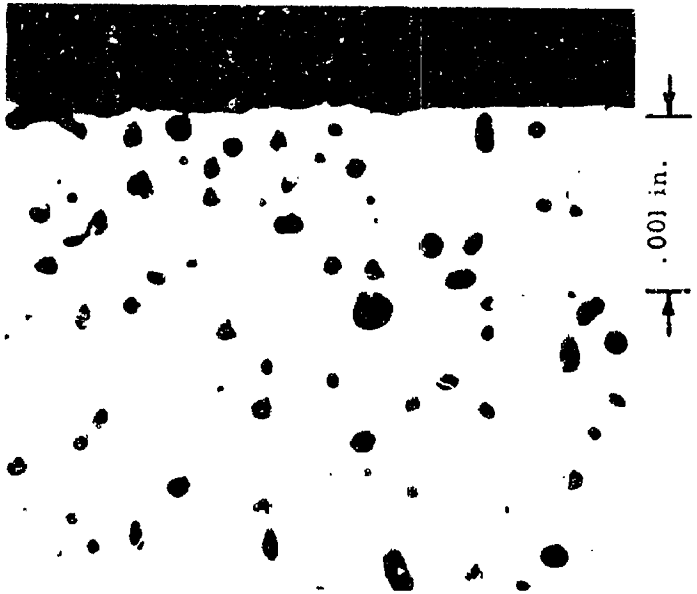
(a) Gentle Conditions - No visible surface effects. Note hardness change below.
Surface Finish: 10 AA 250X

(b) Abusive Conditions - Very slight surface roughening tending toward intergranular attack plus hardness loss noted.
Surface Finish: 30 AA 250X



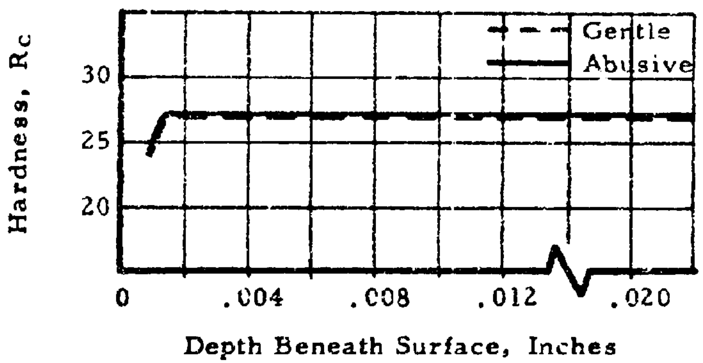
SURFACE CHARACTERISTICS OF MOLYBDENUM ALLOY TZM (Forged and Stress Relieved, 26 R_c) PRODUCED BY ECM

Figure 129



(a) Gentle Conditions - Microscopic surface pitting probably due to attack of pores in the material.
Surface Finish: 70 AA 1000X

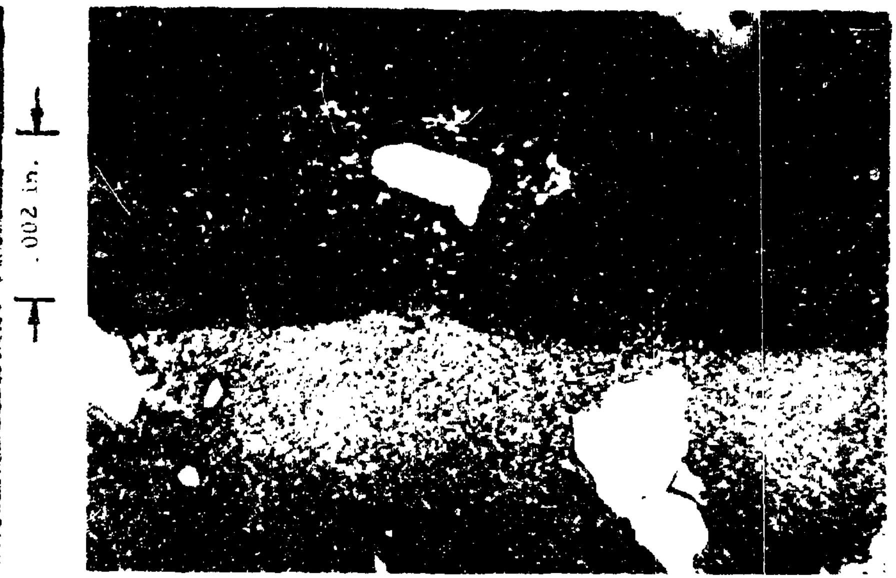
(b) Abusive Conditions - Pronounced surface roughening and intergranular attack. Note the slight hardness loss resulting from ECM under both Gentle and Abusive conditions.
Surface Finish: 200 AA 1000X



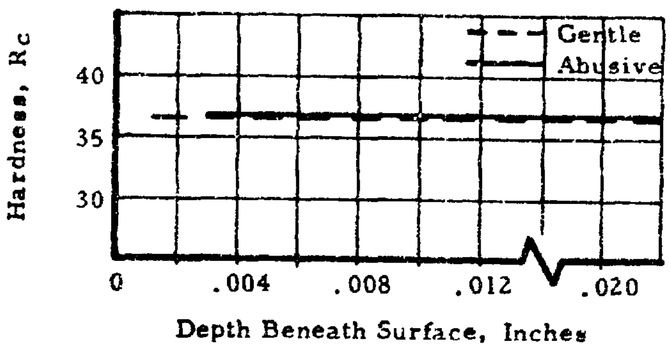
SURFACE CHARACTERISTICS OF UNALLOYED TUNGSTEN (Pressed and Sintered, 93% Density, 27 R_c) PRODUCED BY ECM

Figure 130

(a) Gentle Conditions - No surface effects other than caused by nonuniform machining of different phases.
Surface Finish: 40 AA 500X

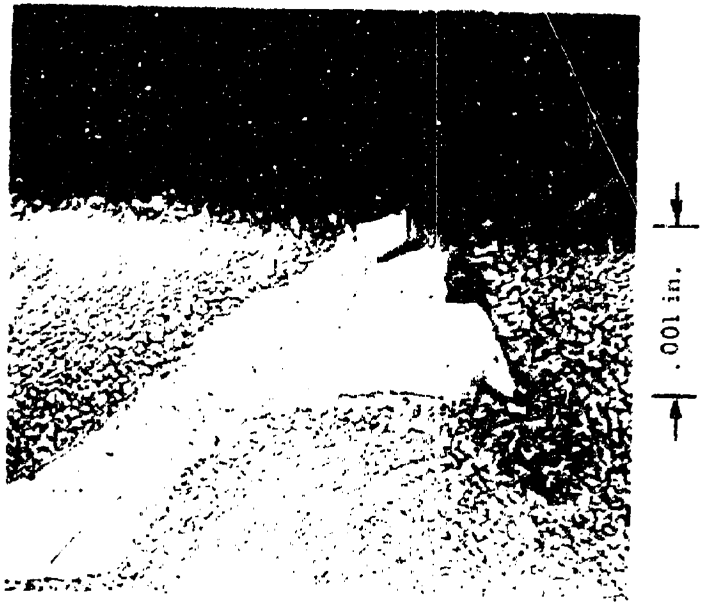


(b) Abrasive Conditions - Significant surface roughening caused by nature of chemical attack and nonuniform machining rates.
Surface Finish: 85 AA 500X

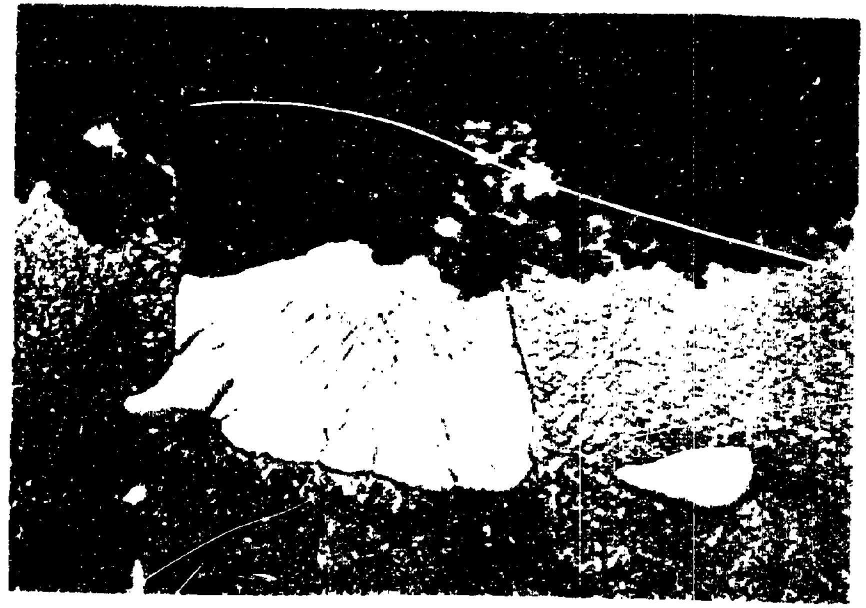


SURFACE CHARACTERISTICS OF
CAST IN 100 (As Cast, 37 R_c) PRODUCED BY ECM

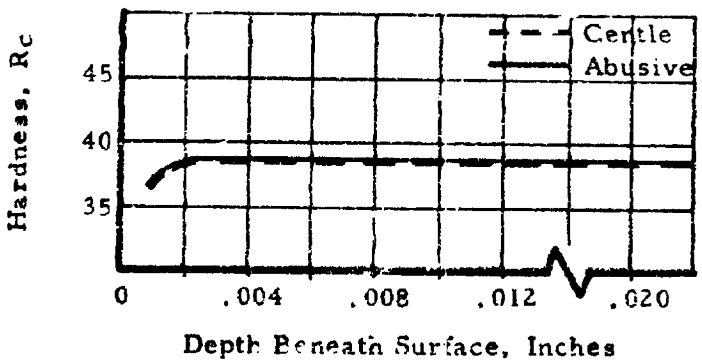
Figure 131



(a) Gentle Conditions - Microscopic surface roughening and slight loss in hardness.
Surface Finish: 25 AA 1000X

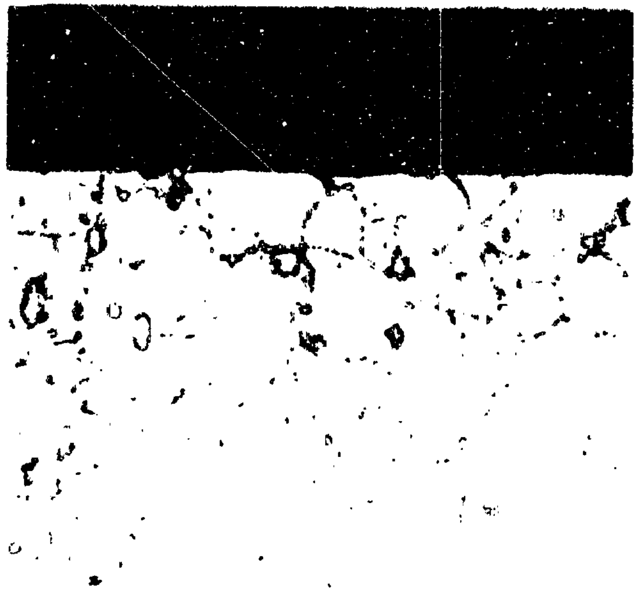


(b) Abusive Conditions - Pronounced surface roughening due to uneven attack of different phases present.
Surface Finish: 140 AA 1000X

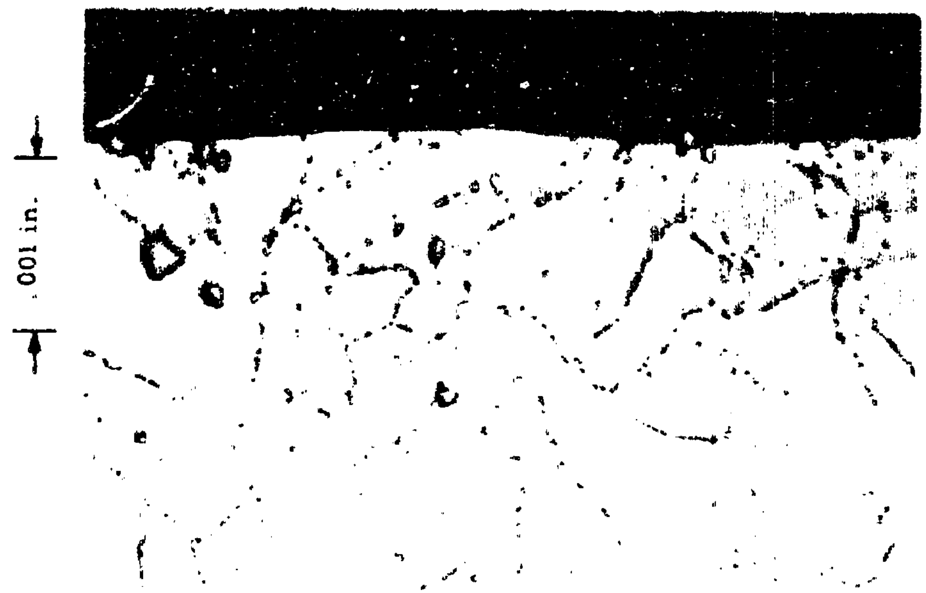


SURFACE CHARACTERISTICS OF
CAST IN 100 (Aged, 38 R_c) PRODUCED BY ECM

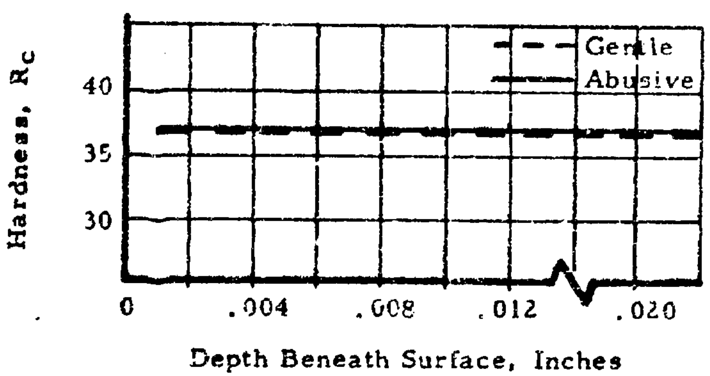
Figure 132



(a) Gentle Conditions - Essentially no surface effect.
Surface Finish: 10 AA 1000X

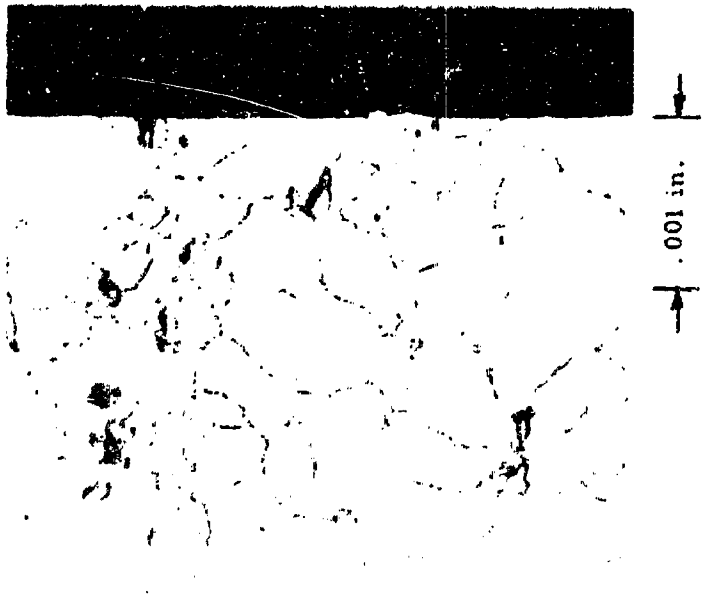


(b) Abusive Conditions - No significant effect except for slight unleveling and tendency toward nonuniform attack on carbide phase.
Surface Finish: 40 AA 1000X

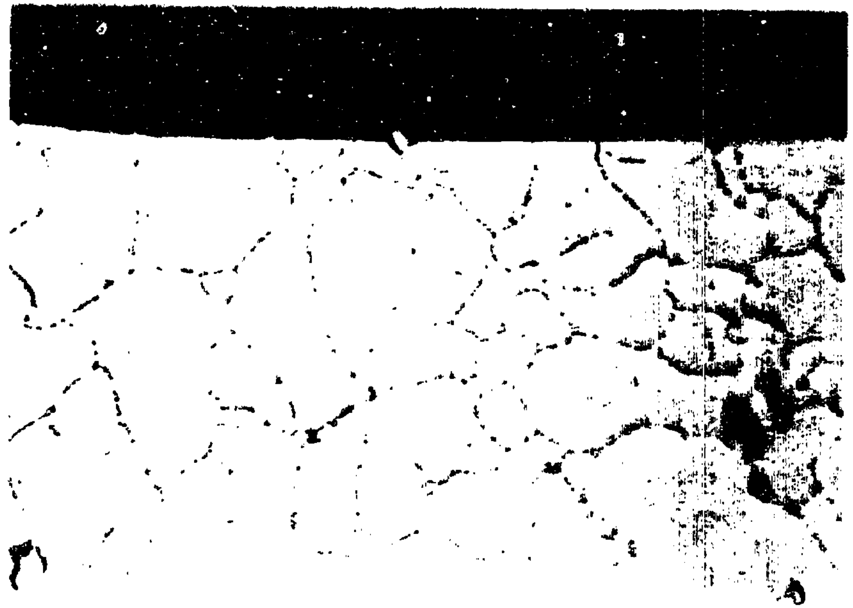


SURFACE CHARACTERISTICS OF RENE' 41 (Solution Treated, 37 R_c) PRODUCED BY ECM

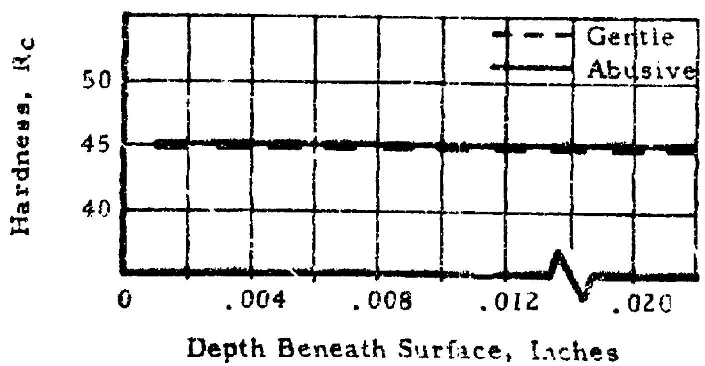
Figure 133



(a) Gentle Conditions - No significant effect except slight pitting or projection of carbide.
Surface Finish: 10 AA 1000X

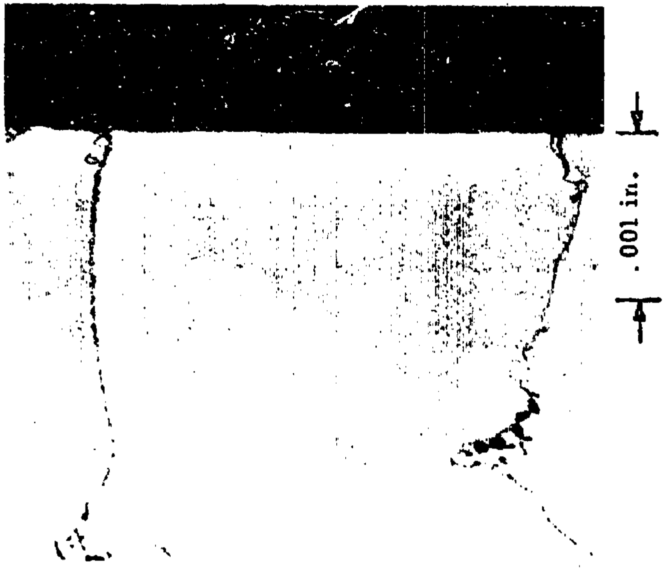


(b) Abusive Conditions - Same general appearance as noted for sample produced by Gentle ECM.
Surface Finish: 50 AA 1000X



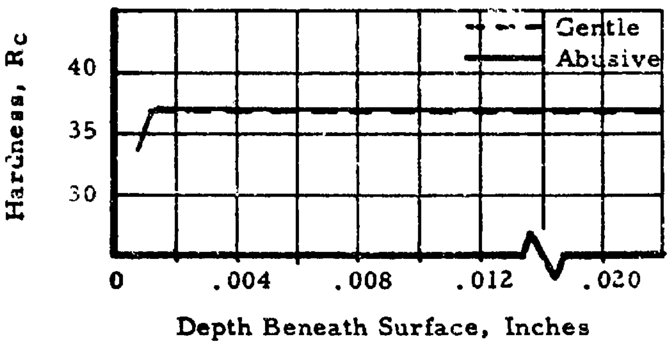
SURFACE CHARACTERISTICS OF
RENE' 41 (Aged, 45 R_c) PRODUCED BY ECM

Figure 134



(a) Gentle Conditions - No significant surface effects.
Surface Finish: 15 AA 1000X

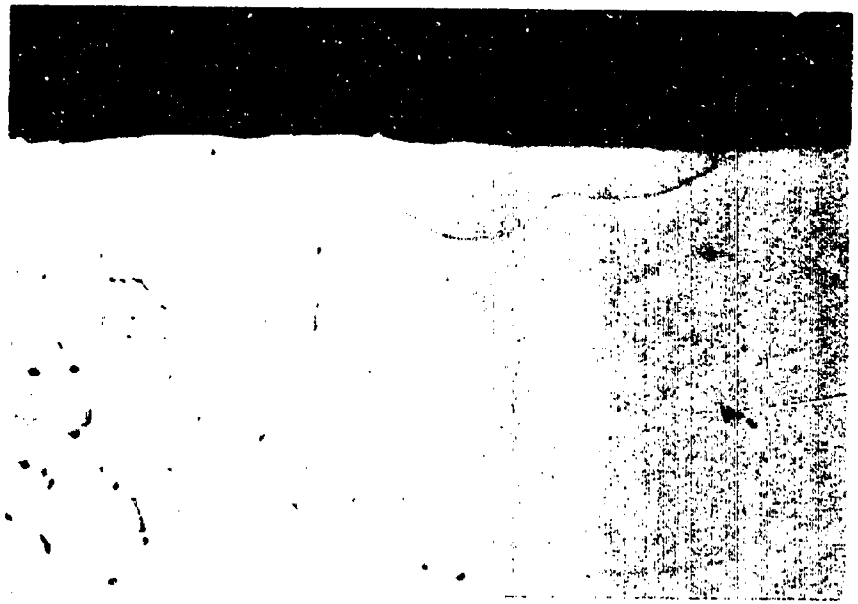
(b) Abusive Conditions - Pronounced tendency toward intergranular attack of carbides plus slight loss in surface microhardness.
Surface Finish: 90 AA 1000X



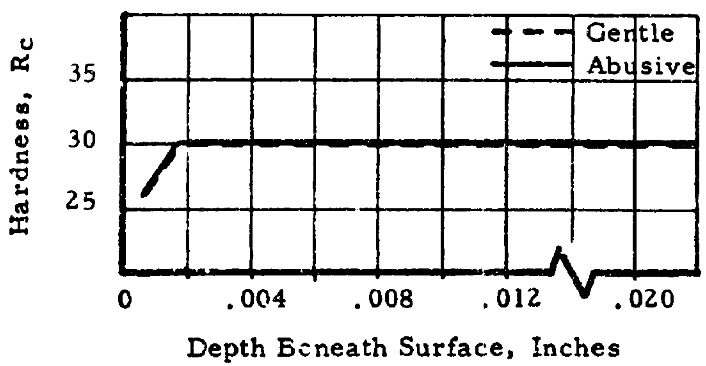
SURFACE CHARACTERISTICS OF CAST RENE' 41 (Aged, 37 R_c) PRODUCED BY ECM

Figure 135

(a) Gentle Conditions - No significant surface effects other than slight loss in hardness.
Surface Finish: 10 AA 1000X

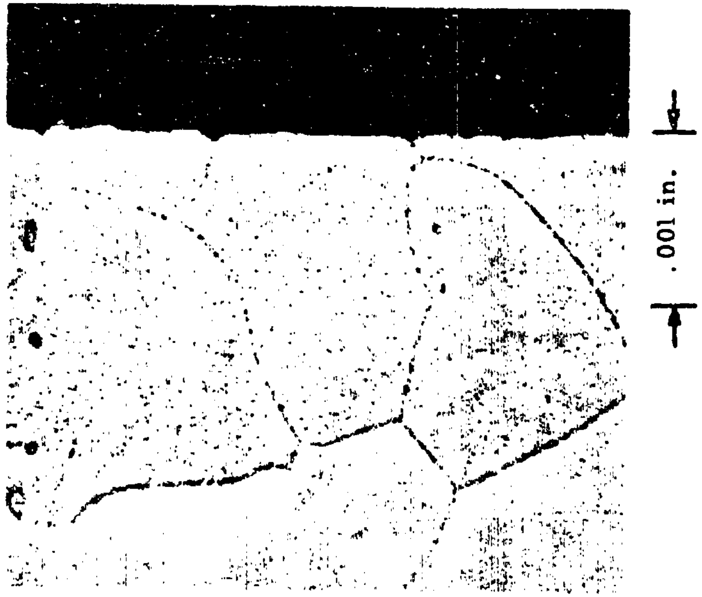


(b) Abusive Conditions - Slight unleveling but otherwise the same behavior as noted for Gentle conditions.
Surface Finish: 35 AA 1000X



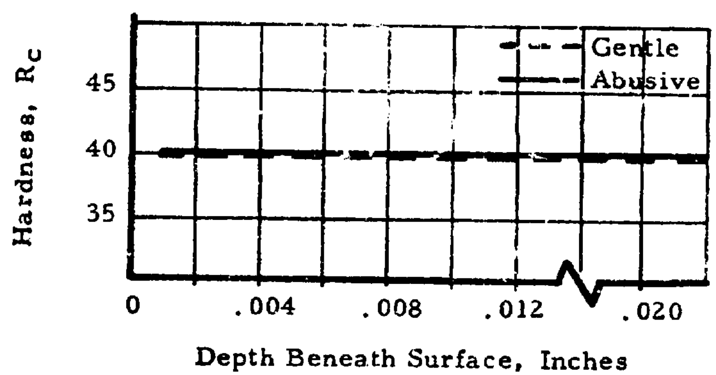
SURFACE CHARACTERISTICS OF WASPALOY (Solution Treated, 30 R_c) PRODUCED BY ECM

Figure 136



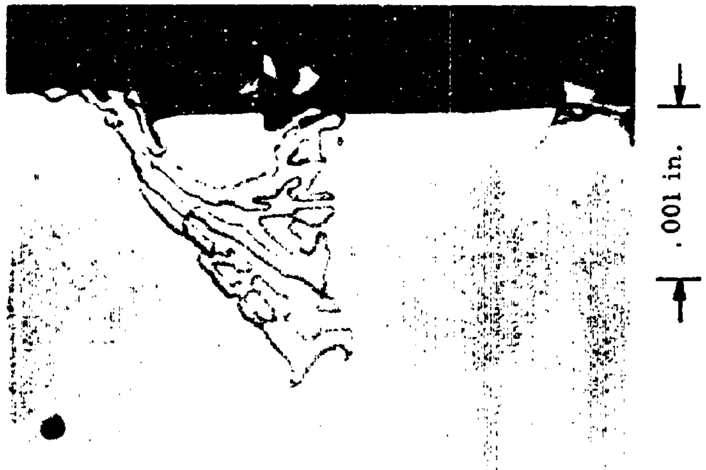
(a) Gentle Conditions - Very slight surface roughening tending toward intergranular attack.
Surface Finish: 15 AA 1000X

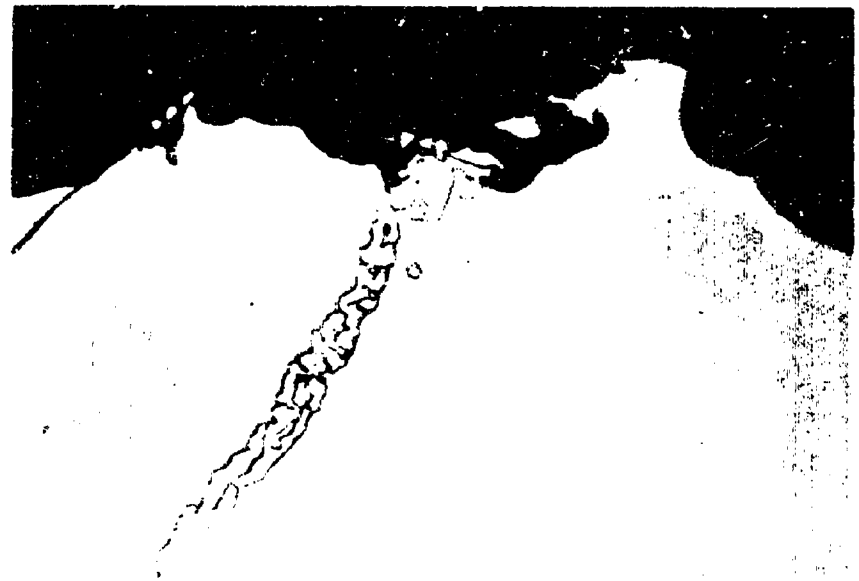
(b) Abusive Conditions - Severe intergranular attack.
Surface Finish: 75 AA 1000X



SURFACE CHARACTERISTICS OF WASPALOY (Aged, 40 R_c) PRODUCED BY ECM

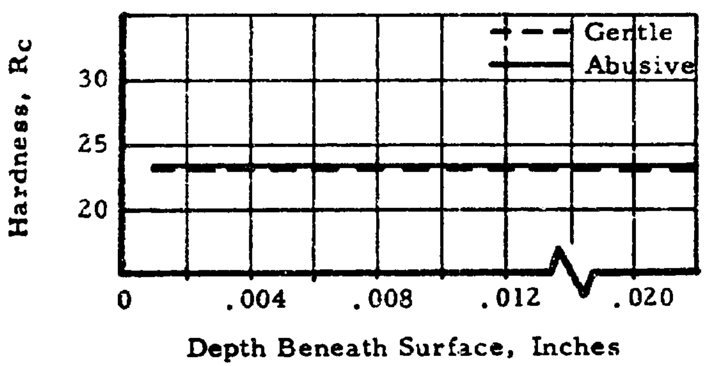
Figure 137





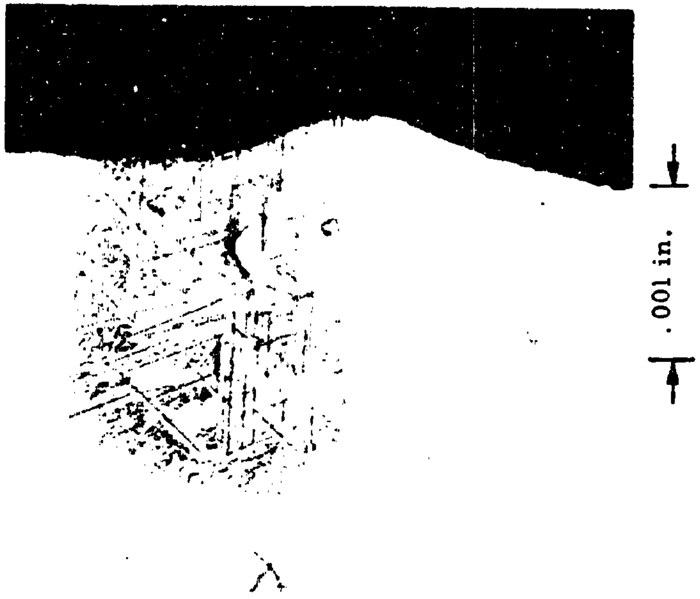
(a) Gentle Conditions - Surface roughening due to nonuniform attack of second phase and also to different grains of the matrix.
Surface Finish: 25 AA 1000X

(b) Abusive Conditions - Result is similar but more severe than that observed for Gentle conditions. Different crystallographic orientation of adjacent grains is responsible for differing rates of metal removal.
Surface Finish: 110 AA 1000X



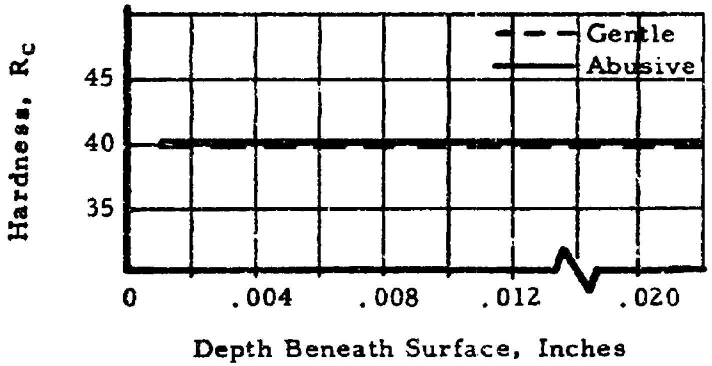
SURFACE CHARACTERISTICS OF
HAYNES ALLOY NO. 31 (Cast, 23 R_c)
PRODUCED BY ECM

Figure 138



(a) Gentle Conditions - Moderate surface unleveling.
Surface Finish: 110 AA 1000X

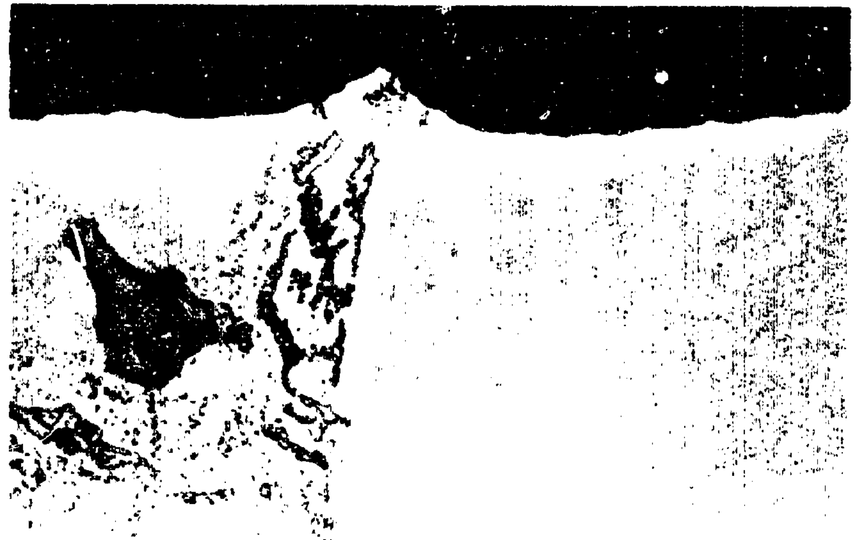
(b) Abusive Conditions - Rather severe surface unleveling due to rate of metal removal varying with grain orientation.
Surface Finish: 160 AA 1000X



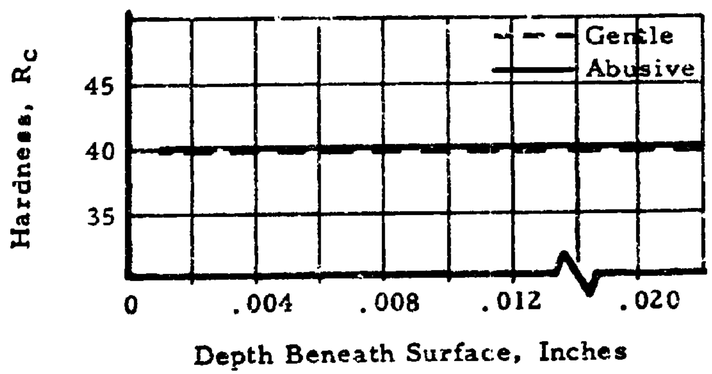
SURFACE CHARACTERISTICS OF
CAST INCONEL 718 (Aged, 40 R_c) PRODUCED
BY ECM

Figure 139

(a) Gentle Conditions - Surface roughening due to variable rate of metal removal.
Surface Finish: 20 AA 1000X



(b) Abusive Conditions - Surface roughening similar to that produced by Gentle conditions.
Surface Finish: 100 AA 1000X



SURFACE CHARACTERISTICS OF
CAST UDIMET 700 (Aged, 40 R_c) PRODUCED
BY ECM

Figure 140

7.3 CHM Characteristics

Photomicrographs, predominantly at 1000X, of cross sections of surfaces produced by CHM are presented in Figures 141 through 167. In performing CHM under gentle conditions, the several variables involved including choice of electrolyte and its concentration, temperature, agitation, etc. were selected in accordance with what was thought to represent good practice for the particular material involved. CHM under abusive conditions was performed by intentionally shifting several of these variables to produce a condition thought to represent poor CHM practice. All chemical machining was performed by G. E. /Evendale under license from Turco Products, Inc. Since the reagents and procedures are proprietary, details of metal removal conditions for the various materials are not available. The photomicrographs presented in this section should be considered as representing the range of characteristics which can be produced by CHM. The effects observed as a result of gentle CHM processing should not be considered indicative of the best possible processing available for the various materials involved. It is likely that added development of the CHM process as applied to some of these materials would result in improved CHM surface characteristics.

In reviewing the following 27 figures, it can be observed that CHM produces no visible alteration to the microstructure. In general, the gentle conditions result in a smooth, plane surface. Abusive conditions tend to produce various degrees of pitting and unleveling.

The iron base alloys reviewed in this study (Figures 141 through 153) were all processed quite successfully using chemical machining. The stainless grades gave some evidence of surface roughening under abusive conditions, although intergranular attack and subsurface cracking were not evident. Likewise, Ti-6Al-4V (Figures 154 and 155) was processed successfully insofar as surface roughness was concerned.

Molybdenum, as shown in Figure 156, exhibited a CHM surface free of intergranular attack and deep pits, although some roughening was evident. Tungsten, on the other hand, as shown in Figure 157, gave evidence of subsurface intergranular cracking under both gentle and abusive conditions. The abusive condition evidence a much more severe degree of this subsurface attack.

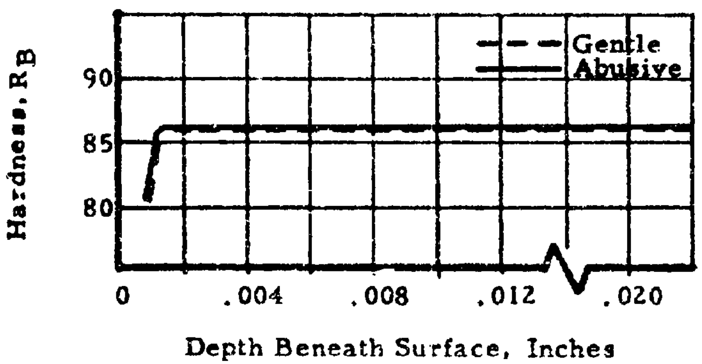
7.3 CHM Characteristics (continued)

The CHM processing of the high temperature alloys resulted in somewhat less satisfactory surface conditions. A review of Figures 158 and 167 indicates a variety of surface attack characteristics. IN-100 is subjected to selective attack as well as matrix attack resulting in a rough spongy surface (Figures 158 and 159). Rene' 41 (Figures 160 through 162) shows evidence of being subject to rather extensive intergranular attack under both gentle and abusive conditions. This was evidenced in solution treated, aged and cast forms of this alloy. Similar effects were exhibited in various degrees by the other high temperature alloys.

In reviewing the microhardness characteristics produced by CHM processing, a number of materials exhibited a slight surface softening for a depth of approximately .001 in. The typical softening level is three to five points R_c, or the equivalent. Where this has been observed, it is generally found as a result of both gentle and abusive processing of a particular material. There also is a tendency for surface softening to occur on the annealed grades or the solution treated grades but not on the aged or quenched and tempered grades of a particular material. Compare for example annealed versus quenched and tempered 4340 (Figure 142 versus Figures 143 and 144). Also compare the annealed versus tempered conditions of D2 tool steel (Figure 151 versus Figure 152). The surface softening may also be observed to exist in solution treated Rene' 41 (Figure 160) but absent in the fully aged material (Figure 161).

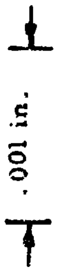
(a) Gentle Conditions - No visible surface distortion, although surface hardness loss was observed.
Surface Finish: 65 AA 1000X

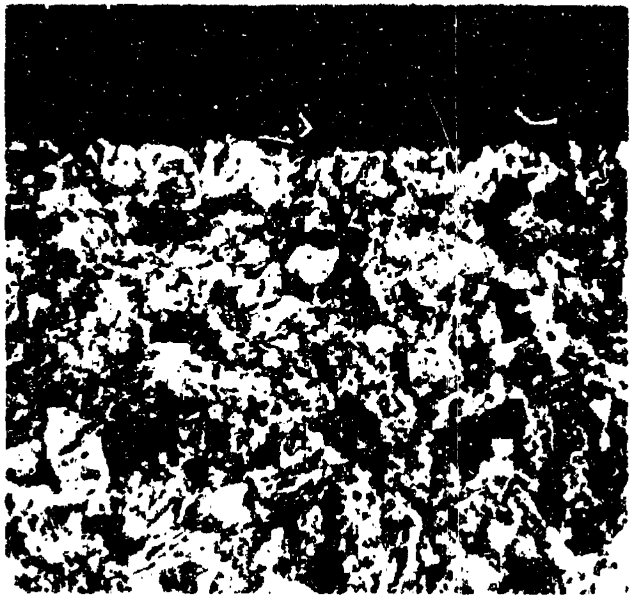
(b) Abusive Conditions - Slight roughening of surface without other evidence of disturbance except micro-hardness loss noted below.
Surface Finish: 140 AA 1000X



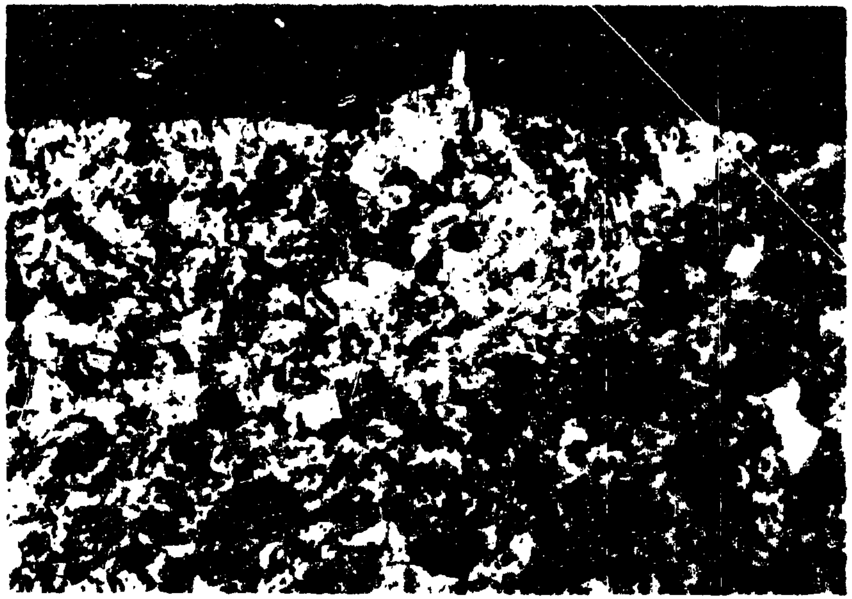
SURFACE CHARACTERISTICS OF
1018 STEEL (Hot Rolled, 87 R_B) PRODUCED
BY CHM

Figure 141

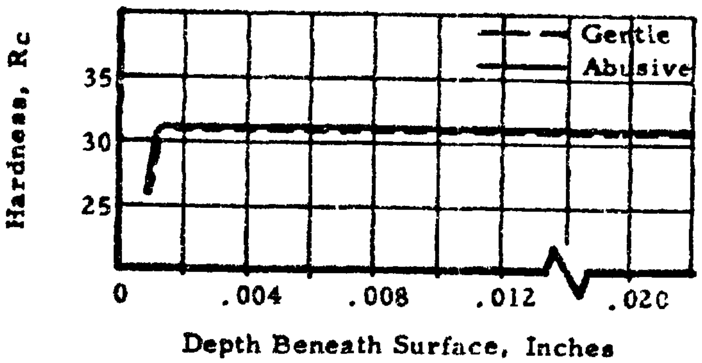




(a) Gentle Conditions - No visible surface effects other than shallow hardness loss.
Surface Finish: 35 AA 1000X

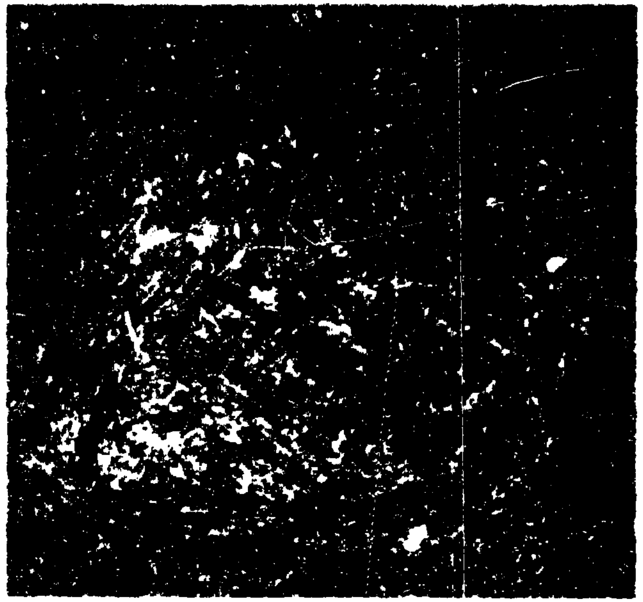


(b) Abusive Conditions - Slight surface roughening plus indicated hardness loss less than .002" deep.
Surface Finish: 120 AA 1000X

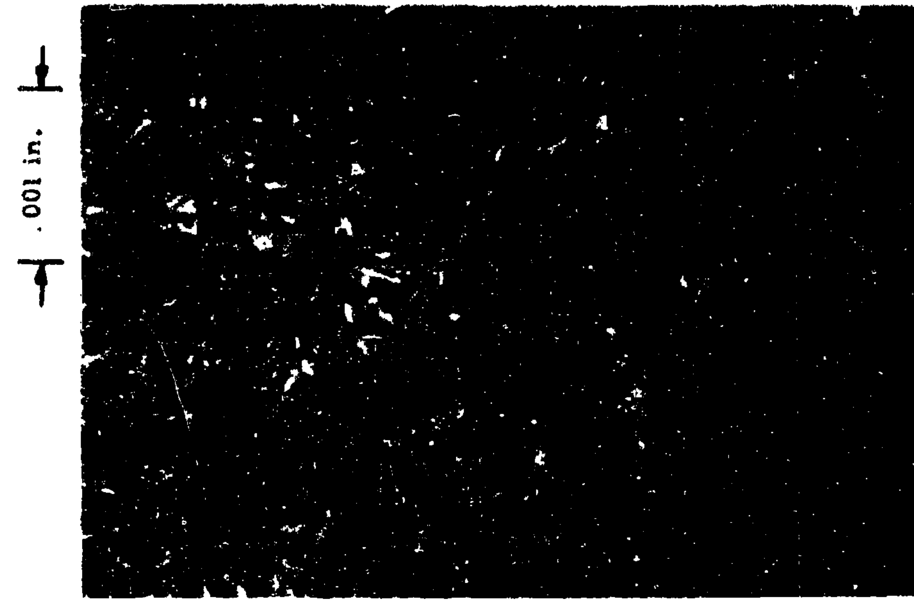


SURFACE CHARACTERISTICS OF 4340 STEEL (Annealed, 31-36 R_c) PRODUCED BY CHM

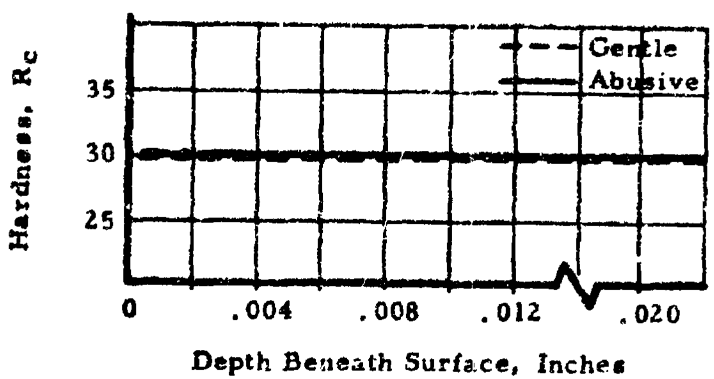
Figure 142



(a) Gentle Conditions - No visible surface effects.
Surface Finish: 35 AA 1000X

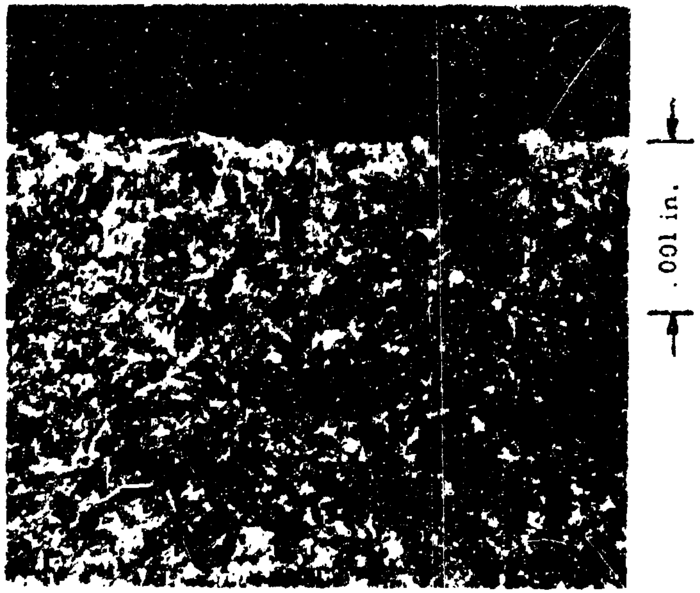


(b) Abusive Conditions - No visible surface effects.
Surface Finish: 230 AA 1000X



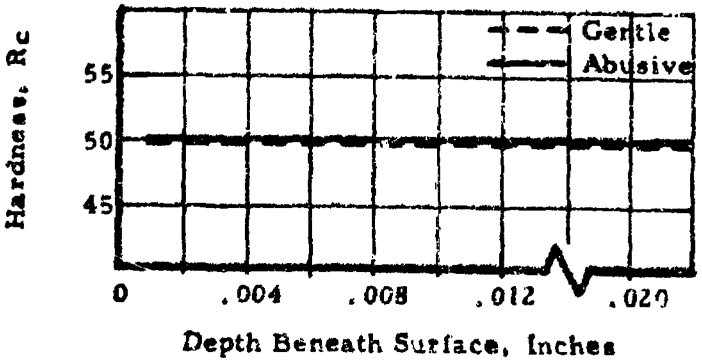
SURFACE CHARACTERISTICS OF
4340 STEEL (Quenched and Tempered, 30 R_c)
PRODUCED BY CHM

Figure 143



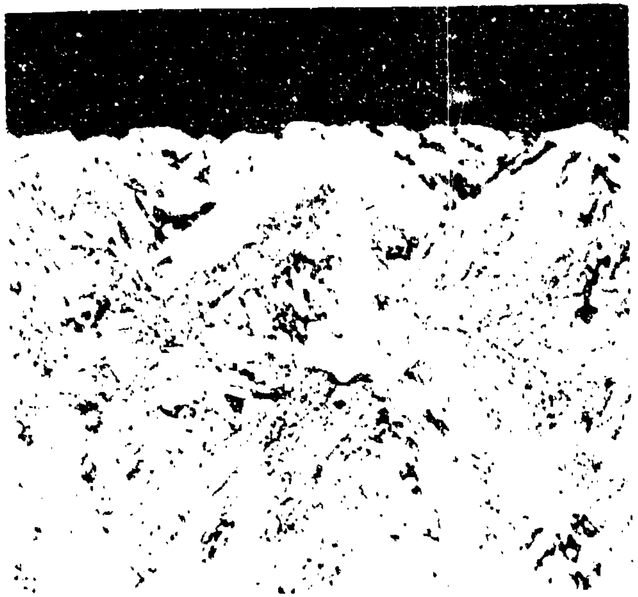
(a) Gentle Conditions - No visible surface effects.
Surface Finish: 25 AA 1000X

(b) Abusive Conditions - Somewhat irregular or unlevel surface but without microscopic roughness.
Surface Finish: 180 AA 1000X

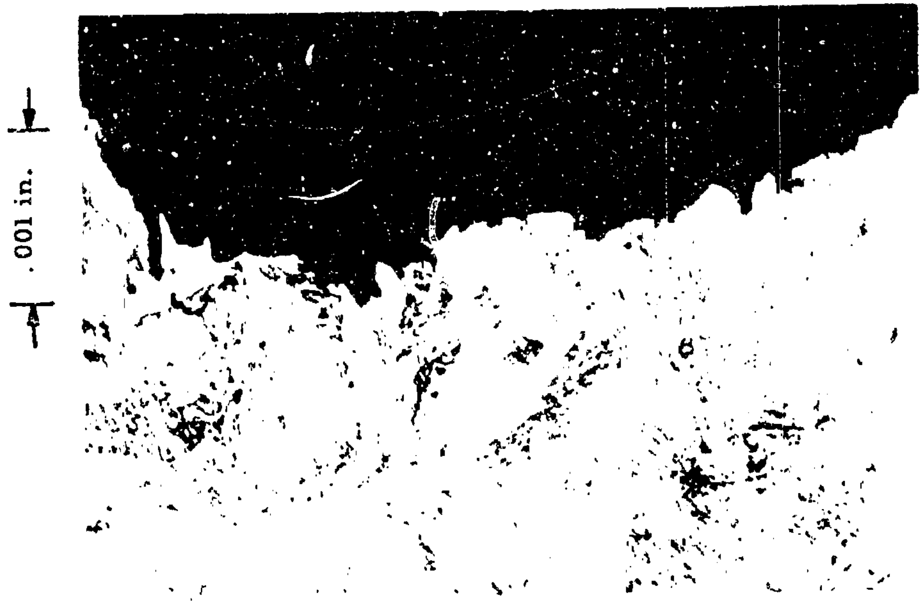


SURFACE CHARACTERISTICS OF
4340 STEEL (Quenched and Tempered, 50 R_c)
PRODUCED BY CHM

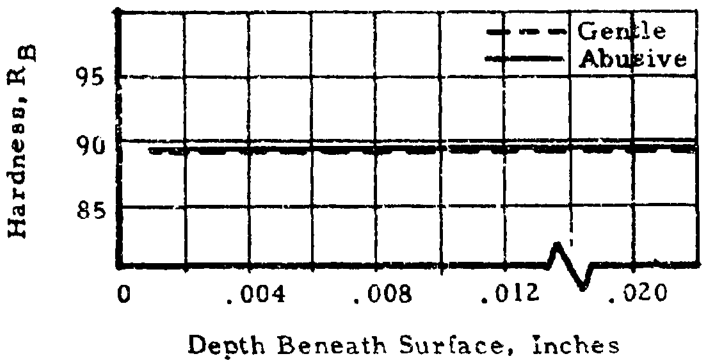
Figure 144



(a) Gentle Conditions - No visible surface effects.
Surface Finish: 25 AA 1000X

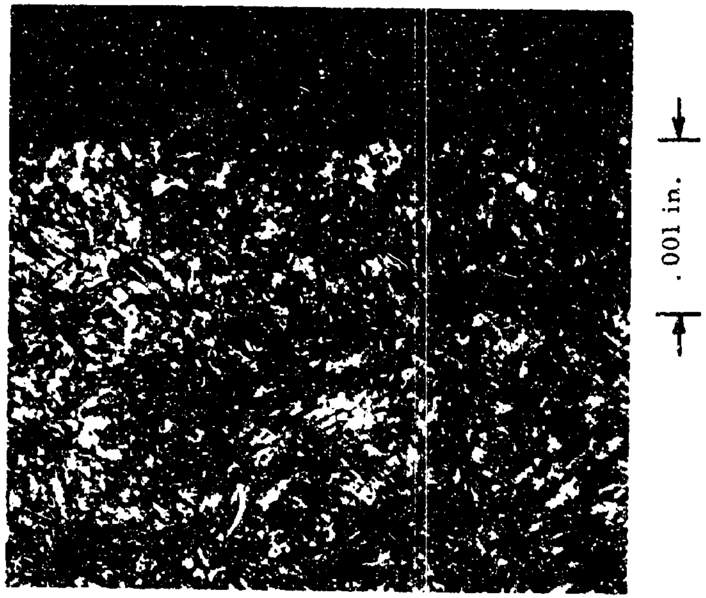


(b) Abusive Conditions - Marked surface roughening on both a micro and macro scale.
Surface Finish: 680 AA 1000X

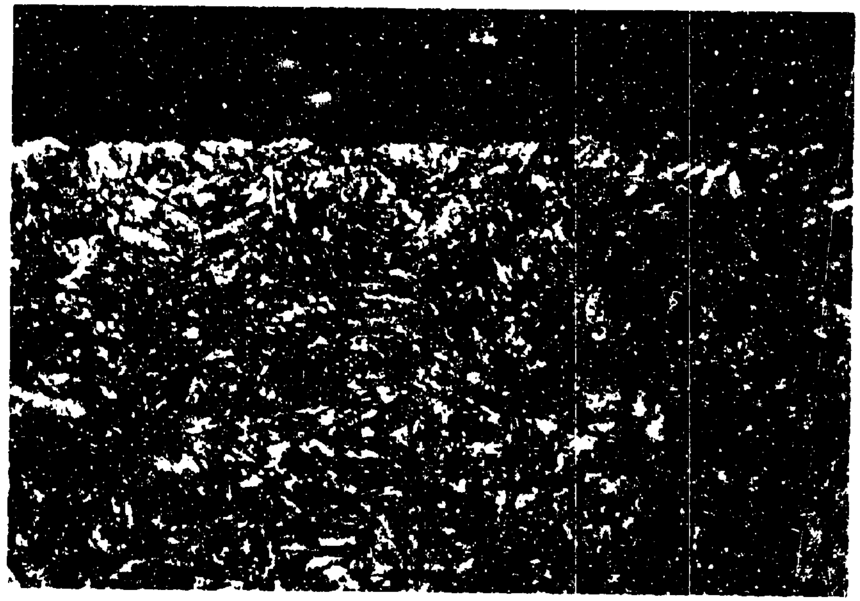


SURFACE CHARACTERISTICS OF
TYPE 410 STAINLESS STEEL (Annealed, 89 R_B)
PRODUCED BY CHM

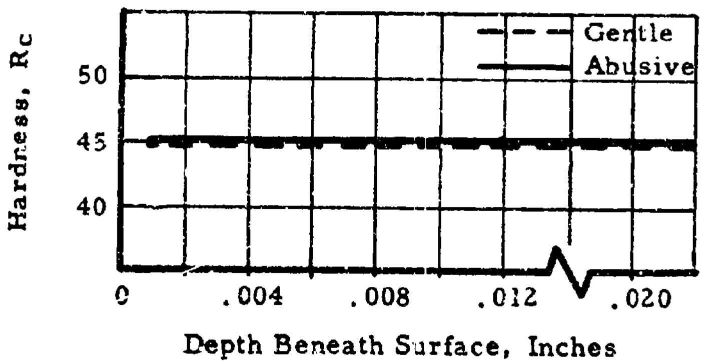
Figure 145



(a) Gentle Conditions - No visible surface effects.
Surface Finish: 25 AA 1000X

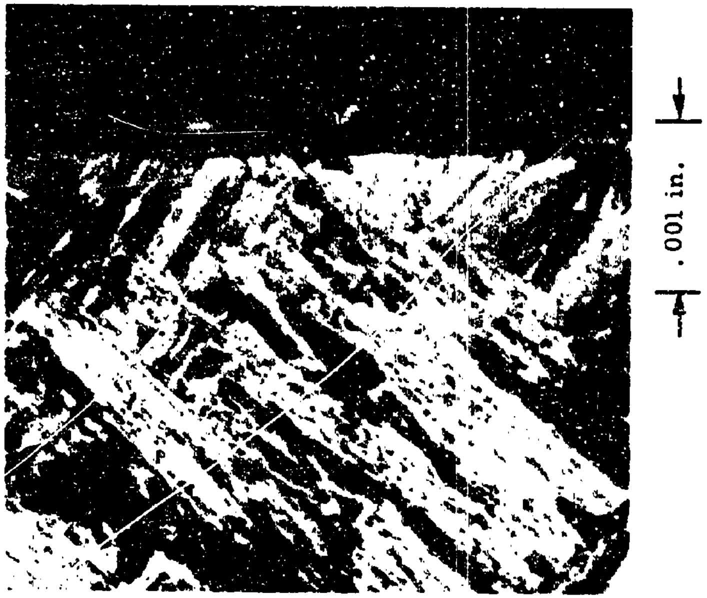


(b) Abusive Conditions - No visible surface effects.
Surface Finish: 25-55 AA 1000X



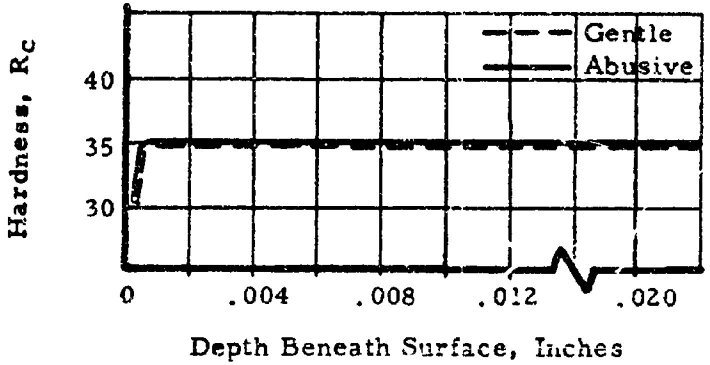
SURFACE CHARACTERISTICS OF
TYPE 410 STAINLESS STEEL (Quenched and
Tempered, 45 R_c) PRODUCED BY CHM

Figure 146



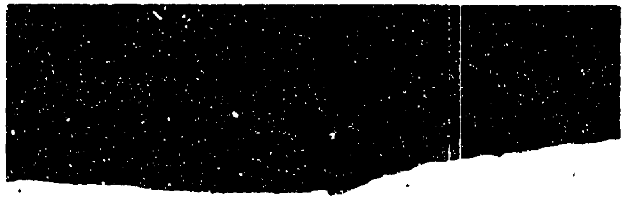
(a) Gentle Conditions - Slight evidence of microscopic surface roughening and subsurface hardness loss as noted below.
Surface Finish: 90 AA 1000X

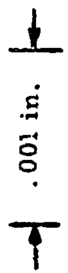
(b) Abusive Conditions - Somewhat irregular surface but without microscopic roughness.
Surface Finish: 550 AA 1000X



SURFACE CHARACTERISTICS OF
CAST TYPE 410 STAINLESS STEEL (Quenched and Tempered, 35 R_c) PRODUCED BY CHM

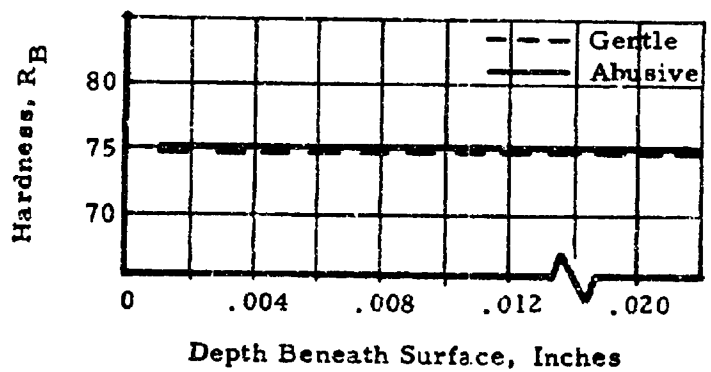
Figure 147





(a) Gentle Conditions - No visiLle surface effects.
Surface Finish: 65 AA 1000X

(b) Abusive Conditions - Microscopic s::rface roughening with tendency toward pitting.
Surface Finish: 140 AA 1000X

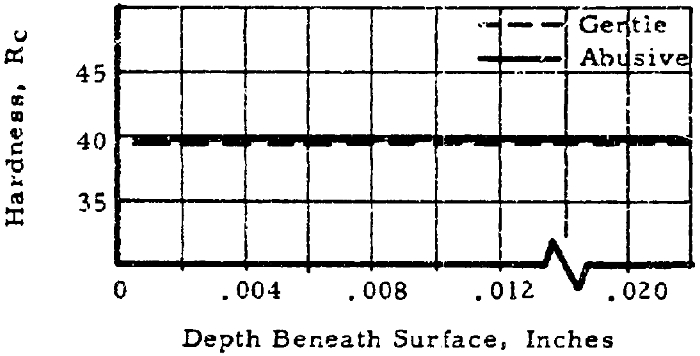


SURFACE CHARACTERISTICS OF
TYPE 302 STAINLESS STEEL (Annealed, 75 R_B)
PRODUCED BY CHM

Figure 148

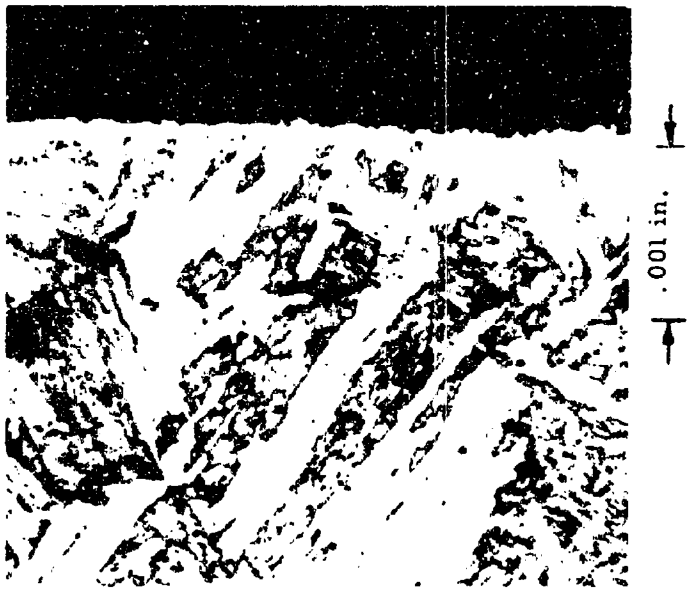
(a) Gentle Conditions - Slight tendency toward surface roughening.
Surface Finish: 50 AA 1000X

(b) Abusive Conditions - Slight tendency toward surface roughening.
Surface Finish: 270 AA 1000X



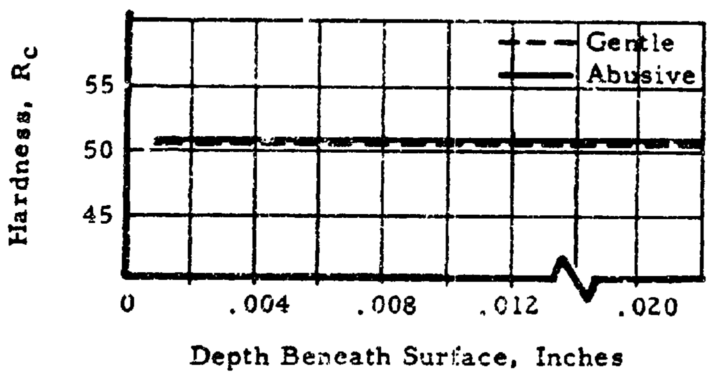
SURFACE CHARACTERISTICS OF
GRADE 250 MARAGING STEEL (Annealed, 39 R_c)
PRODUCED BY CHM

Figure 149



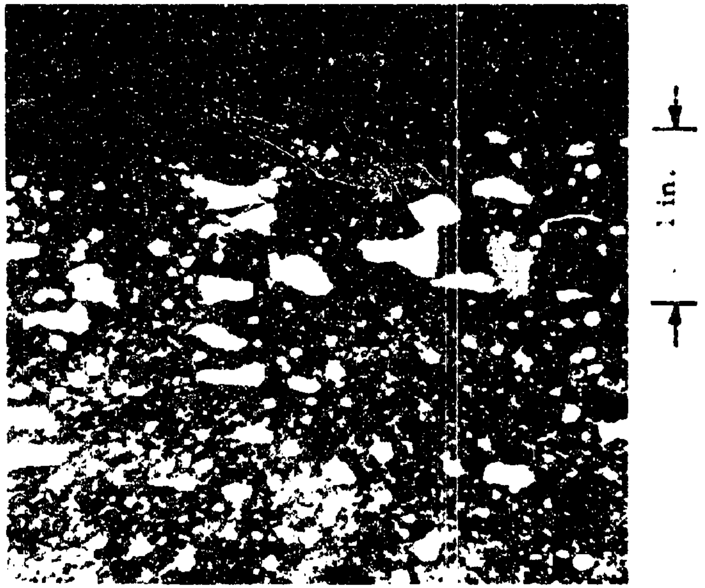
(a) Gentle Conditions - Very slight micro-scopic surface roughening.
Surface Finish: 20 AA 1000X

(b) Abusive Conditions - Very slight microscopic surface roughening.
Surface Finish: 140-180 AA 1000X

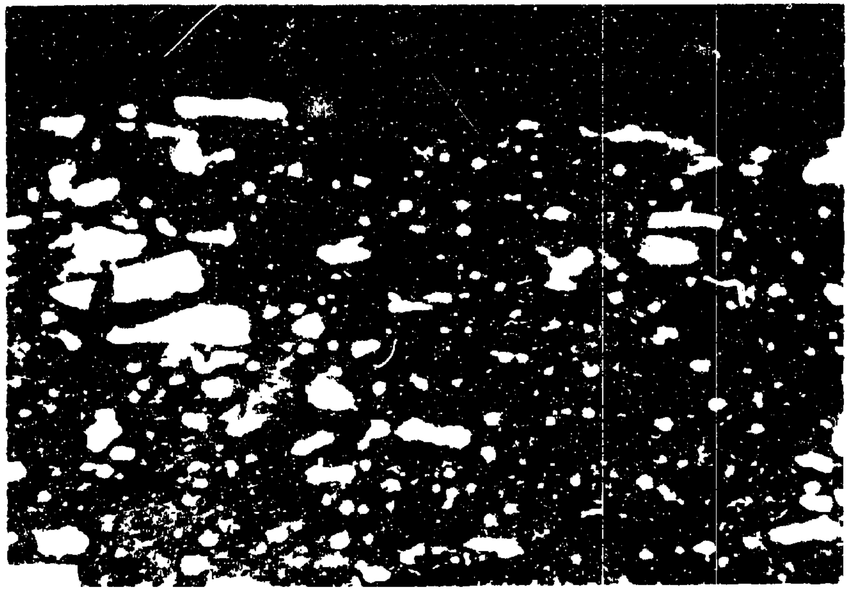


SURFACE CHARACTERISTICS OF
GRADE 250 MARAGING STEEL (Aged, 51 R_c)
PRODUCED BY CHM

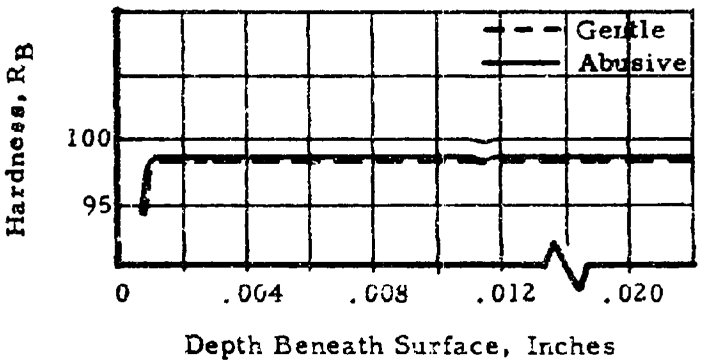
Figure 150



(a) Gentle Conditions - Moderate surface roughening and hardness loss as indicated below.
Surface Finish: 55 AA 1000X

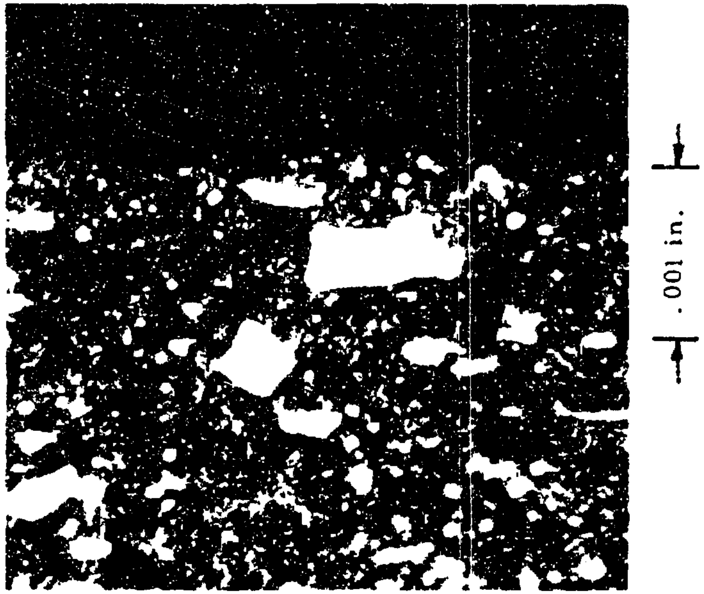


(b) Abusive Conditions - Moderate surface roughening and hardness loss as indicated below.
Surface Finish: 65 AA 1000X

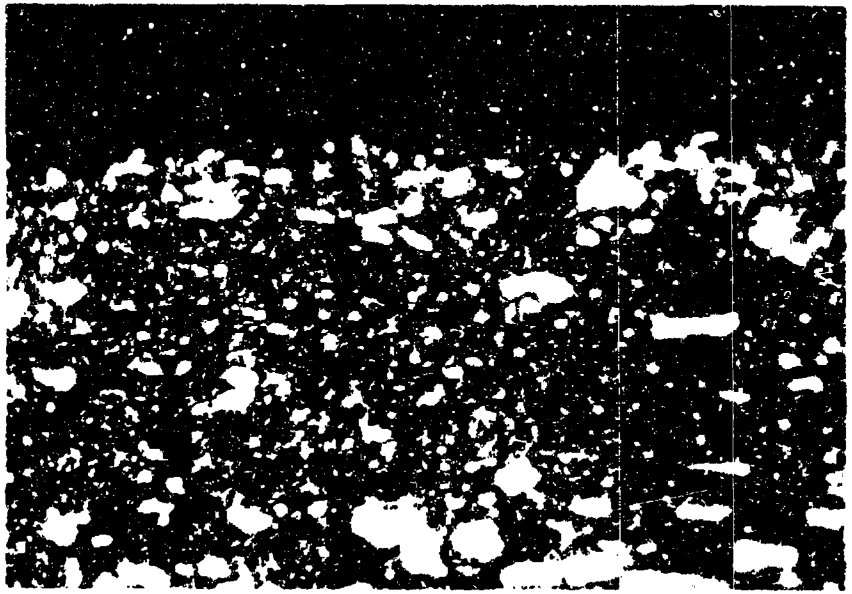


SURFACE CHARACTERISTICS OF
TYPE D2 TOOL STEEL (Annealed, 98 R_B)
PRODUCED BY CHM

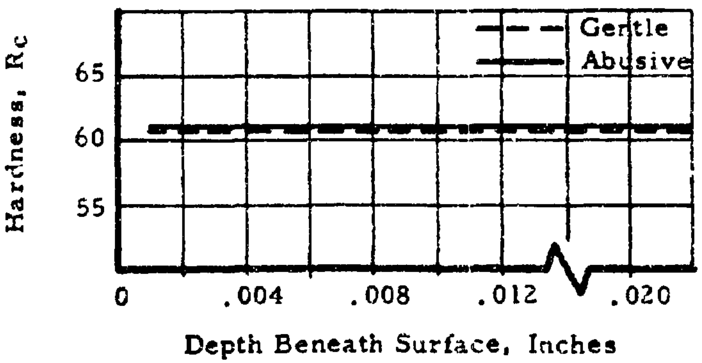
Figure 151



(a) Gentle Conditions - Slight surface roughening.
Surface Finish: 45 AA 1000X



(b) Abusive Conditions - Slight surface roughening.
Surface Finish: 75 AA 1000X

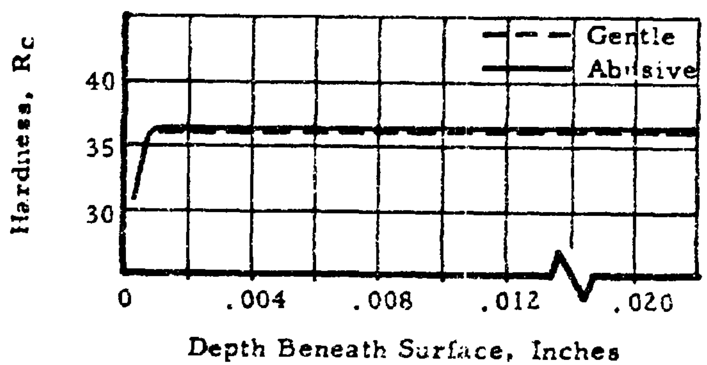


SURFACE CHARACTERISTICS OF
TYPE D2 TOOL STEEL (Quenched and Tempered, 61 R_c)
PRODUCED BY CHM

Figure 152

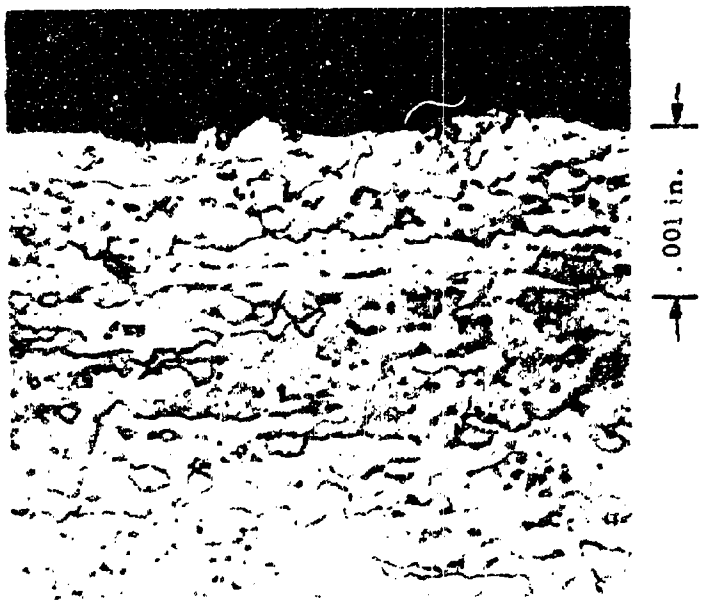
(a) Gentle Conditions - Very slight surface roughening.
Surface Finish: 45 AA 1000X

(b) Abusive Conditions - Moderate surface roughening with tendency toward unleveling.
Surface Finish: 65-80 AA 1000X

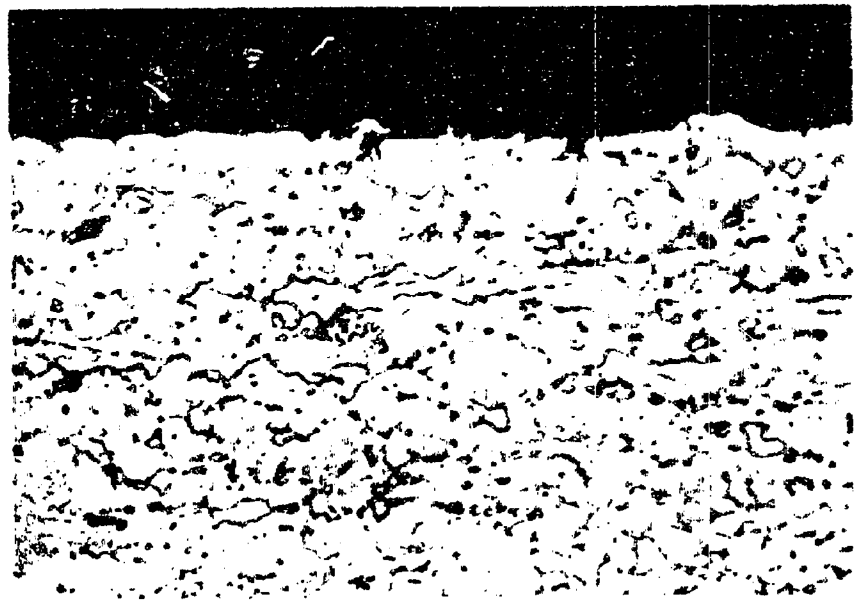


SURFACE CHARACTERISTICS OF
CAST 17-4PH STAINLESS STEEL (Aged, 37 R_c)
PRODUCED BY CHM

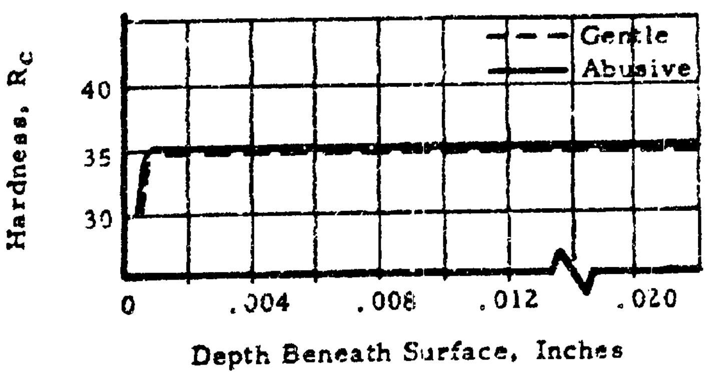
Figure 153



(a) Gentle Conditions - Slight surface irregularity but without evidence of distortion. Note microhardness loss below.
Surface Finish: 20 AA 1000X

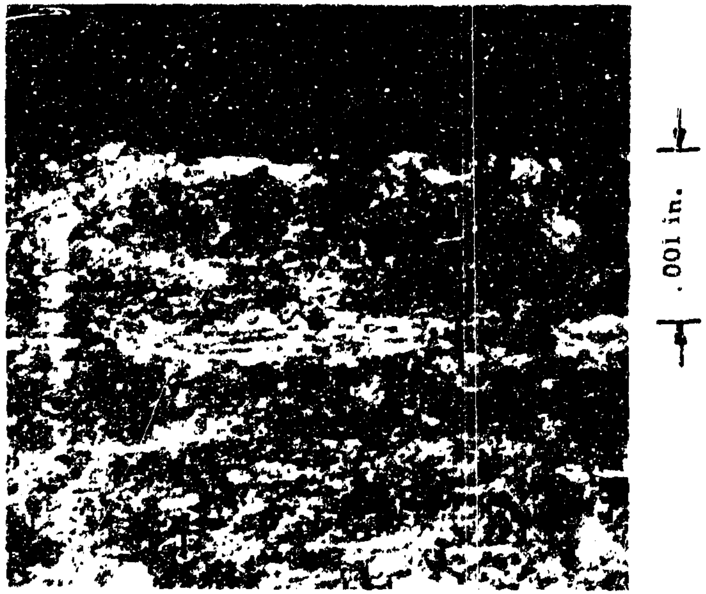


(b) Abusive Conditions - Same type of surface and extent of hardness loss as observed for gentle conditions.
Surface Finish: 25 AA 1000X

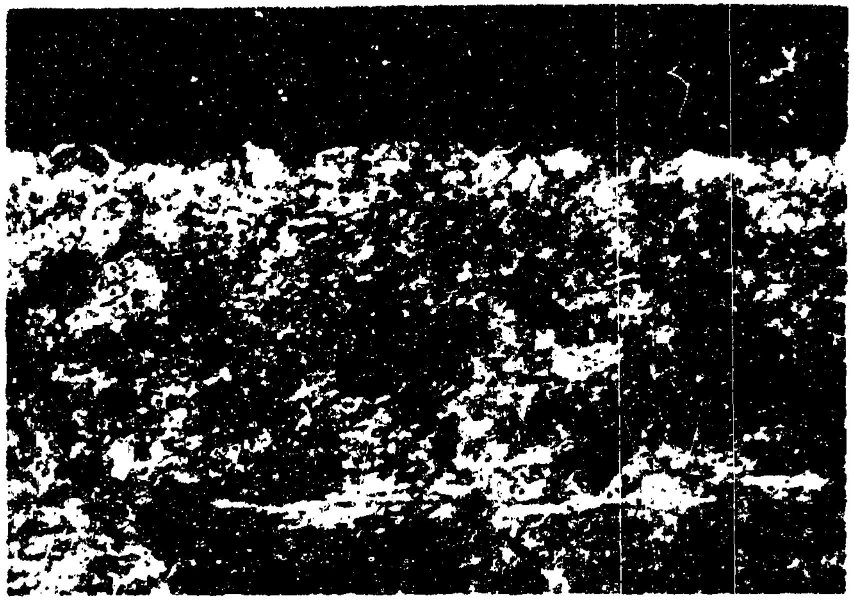


SURFACE CHARACTERISTICS OF TITANIUM 6Al-4V (Annealed, 35 R_c) PRODUCED BY CHM

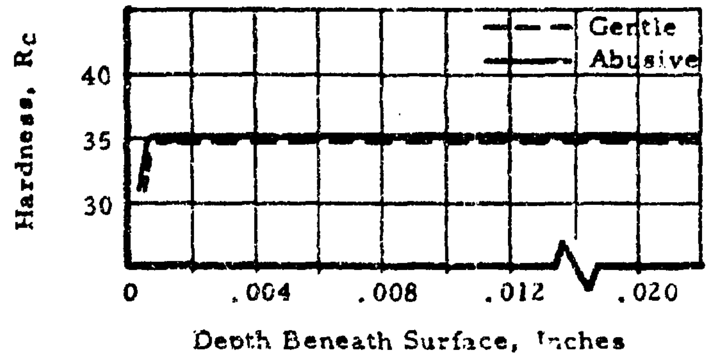
Figure 154



(a) Gentle Conditions - Very slight surface roughening plus slight drop in surface hardness.
Surface Finish: 20 AA 1000X

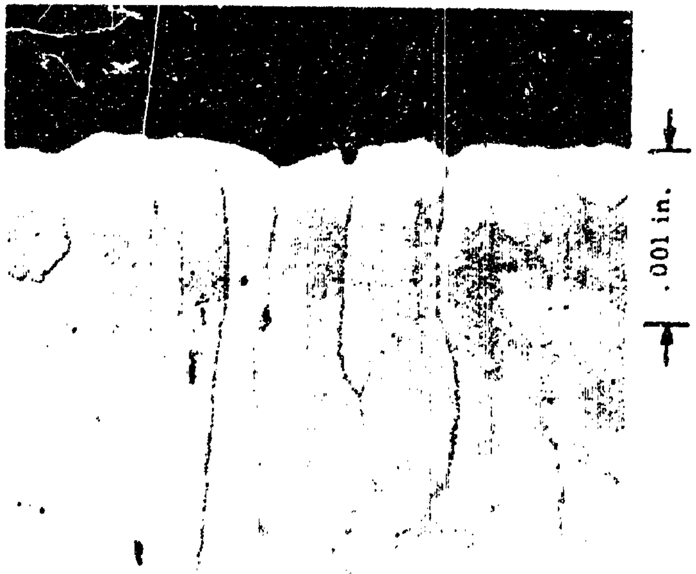


(b) Abusive Conditions - Moderate surface roughening plus slight drop in surface hardness.
Surface Finish: 25 AA 1000X

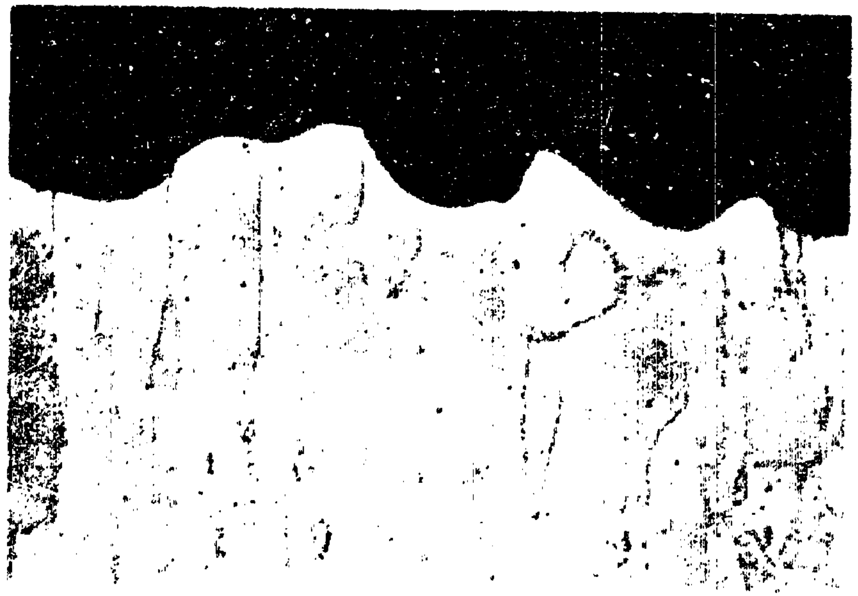


SURFACE CHARACTERISTICS OF TITANIUM 6Al-4V (Aged, 35 R_c) PRODUCED BY CHM

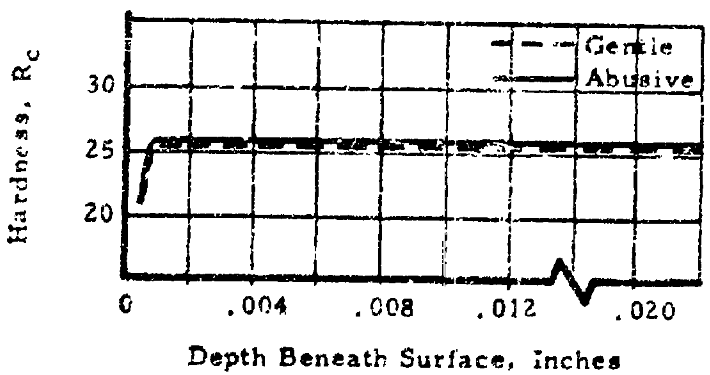
Figure 155



(a) Gentle Conditions - Slight microscopic surface roughening and hardness loss approximately .001" deep.
Surface Finish: 110 AA 250X

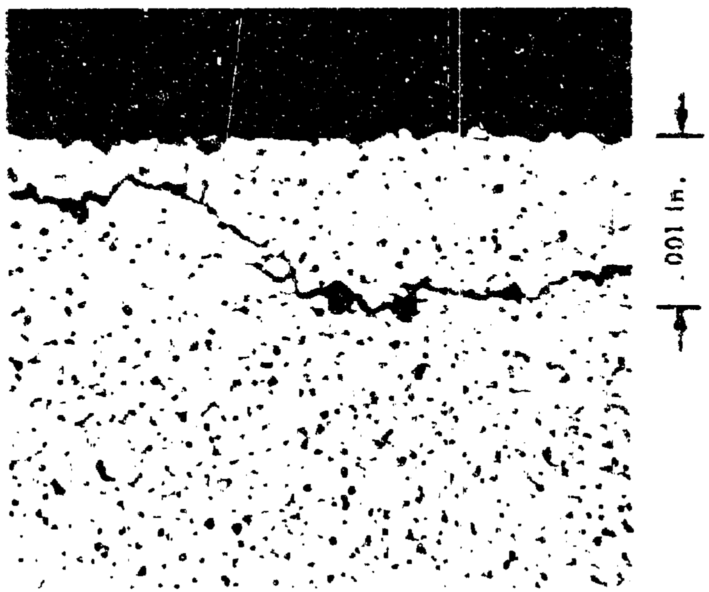


(b) Abusive Conditions - Moderate surface roughening and unleveling; plus hardness drop approximately .001" deep.
Surface Finish: 640 AA 250X

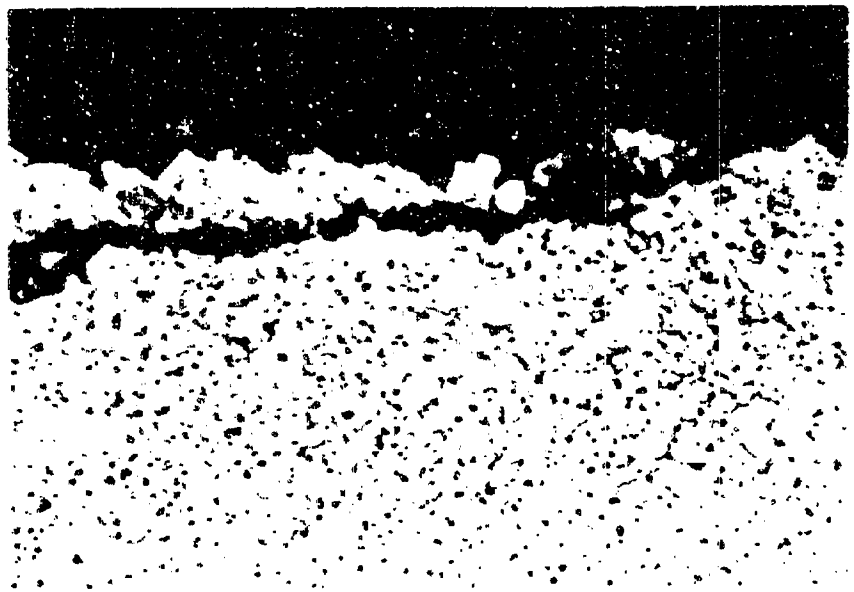


SURFACE CHARACTERISTICS OF MOLYBDENUM ALLOY TZM (Forged and Stress Relieved, 26 R_c) PRODUCED BY CHM

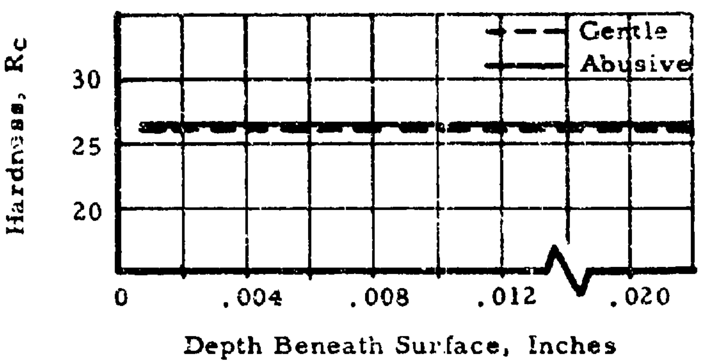
Figure 156



(a) Gentle Conditions - Subsurface intergranular cracking but without evidence of spalling.
Surface Finish: 80 AA 250X

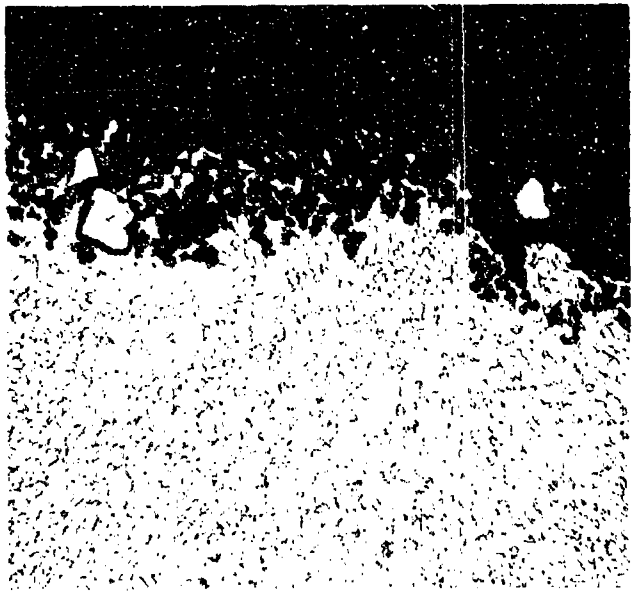


(b) Abusive Conditions - Microscopic surface roughness plus extensive intergranular cracking which produced some spalled areas.
Surface Finish: 110 AA 250X



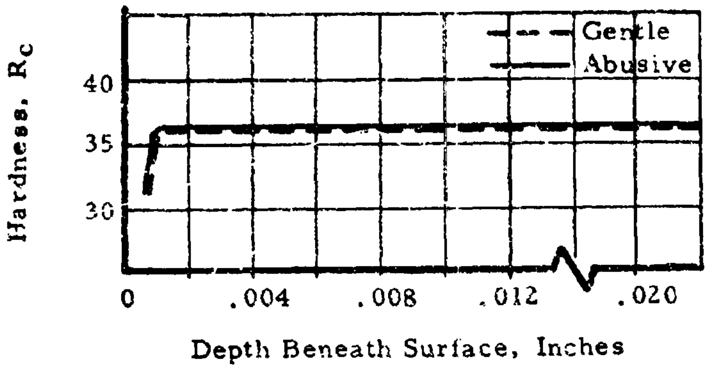
SURFACE CHARACTERISTICS OF
UNALLOYED TUNGSTEN (Pressed and Sintered, 93% Density, 27 R_c) PRODUCED BY CHM

Figure 157



(a) Gentle Conditions - Extensive matrix attack producing a porous or spongy layer approximately .001" deep. Surface Finish: 25 AA 1000X

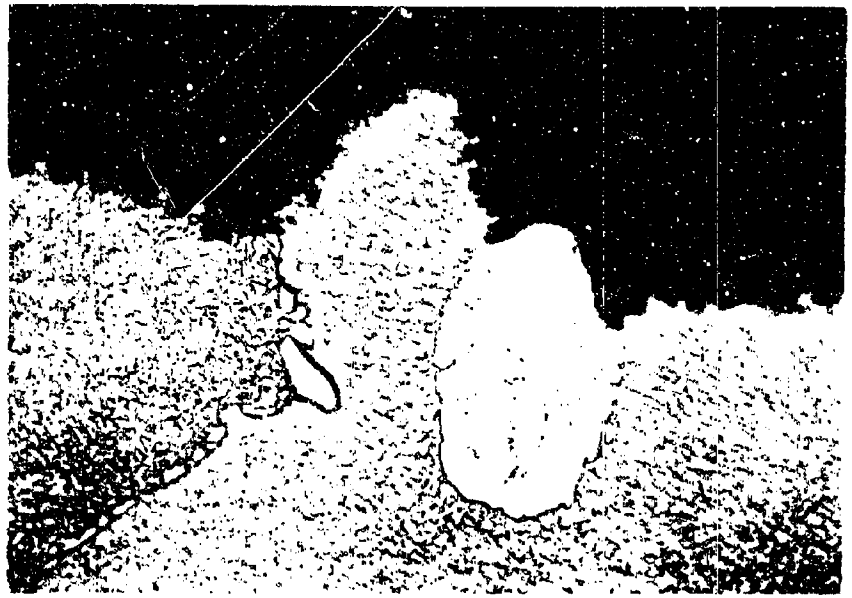
(b) Abusive Conditions - Intergranular and matrix attack producing spongy surface condition plus unleveling. Surface Finish: 230 AA 1000X



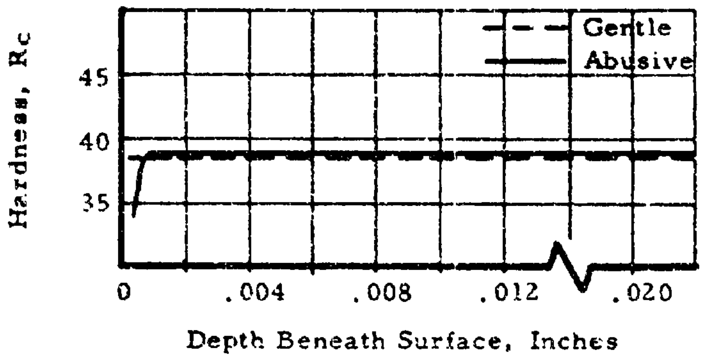
SURFACE CHARACTERISTICS OF CAST IN 100 (As Cast, 37 R_c) PRODUCED BY CHM

Figure 158

(a) Gentle Conditions - Intergranular and selective phase attack producing rough, spongy surface.
Surface Finish: 75 AA 1000X

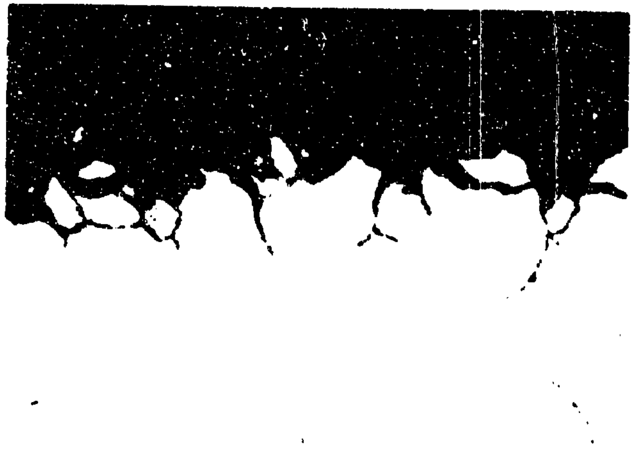


(b) Abusive Conditions - Intergranular and selective phase attack producing rough, spongy surface.
Surface Finish: 230 AA 1000X

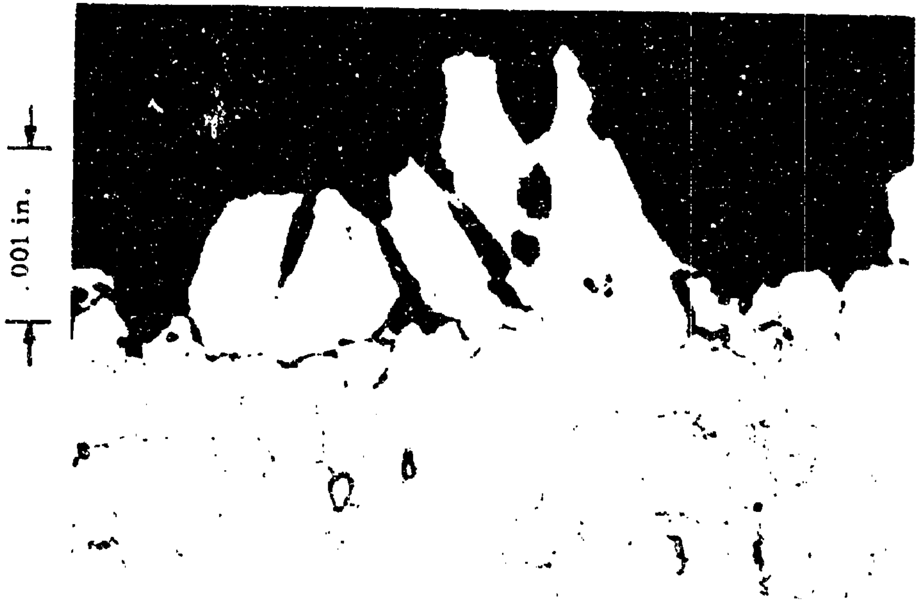


SURFACE CHARACTERISTICS OF
CAST IN 100 (Aged, 38 R_c) PRODUCED BY CHM

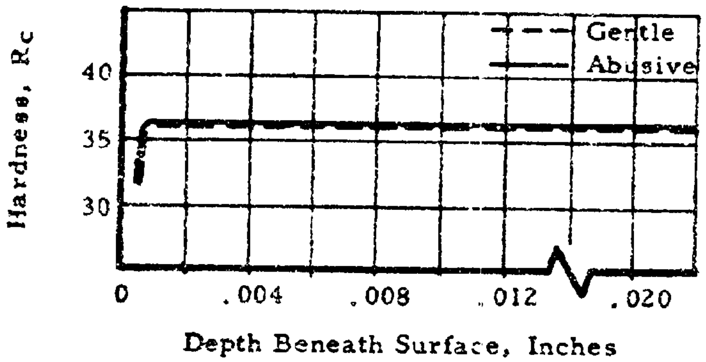
Figure 159



a) Gentle Conditions - Extensive intergranular attack up to .001" deep plus surface roughening.
Surface Finish: 75-110 AA 1000X



(b) Abusive Conditions - Intergranular attack plus preferential solutioning producing grossly irregular surface.
Surface Finish: 450 AA 1000X

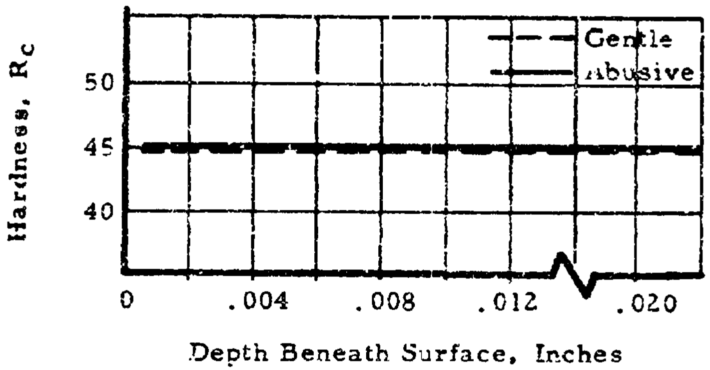


SURFACE CHARACTERISTICS OF RENE' 41 (Solution Treated, 37 R_c) PRODUCED BY CHM

Figure 160

(a) Gentle Conditions - Intergranular attack up to .001" deep plus pronounced surface roughening.
Surface Finish: 180 AA 1000X

(b) Abusive Conditions - Intergranular attack plus surface roughening and unleveling.
Surface Finish: 360 AA 1000X

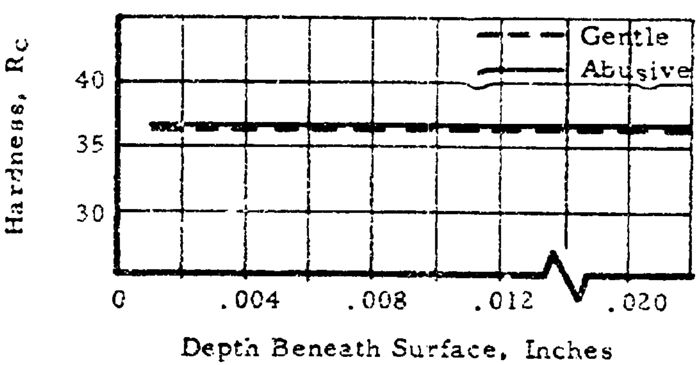


SURFACE CHARACTERISTICS OF RENE' 41 (Aged, 45 R_c) PRODUCED BY CHM

Figure 161

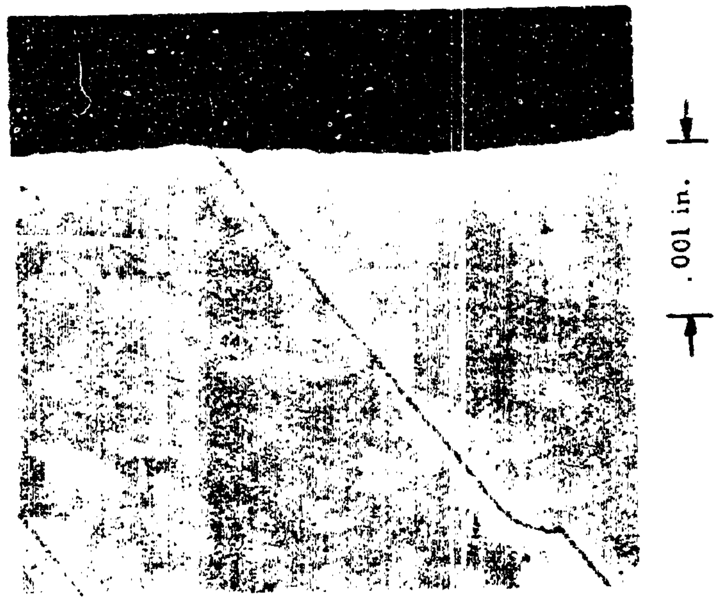
(a) Gentle Conditions - Surface unleveling and intergranular attack up to .002" deep.
Surface Finish: 160 AA   1000X

(b) Abusive Conditions - Surface unleveling and intergranular attack up to .002" deep.
Surface Finish: 550 AA   1000X

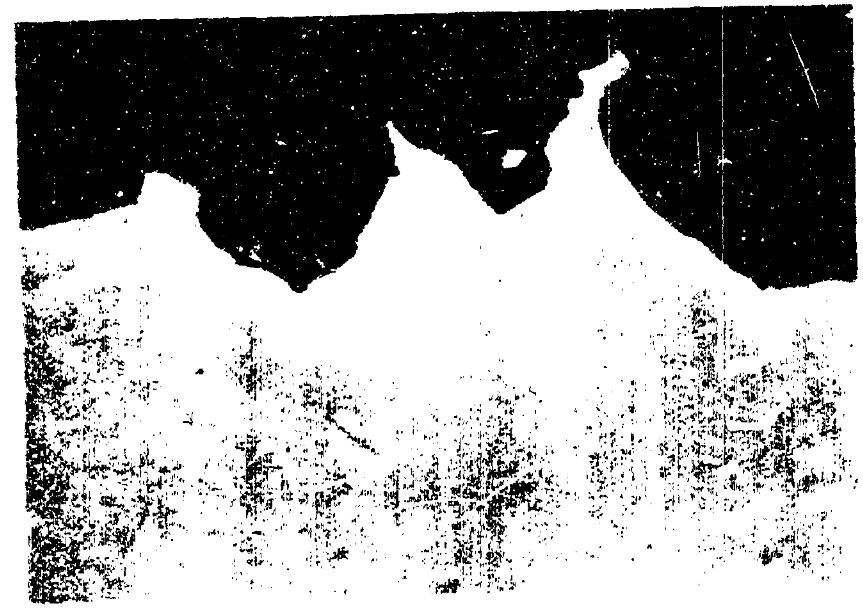


SURFACE CHARACTERISTICS OF
CAST RENE' 41 (Aged, 37 R_c) PRODUCED
BY CHM

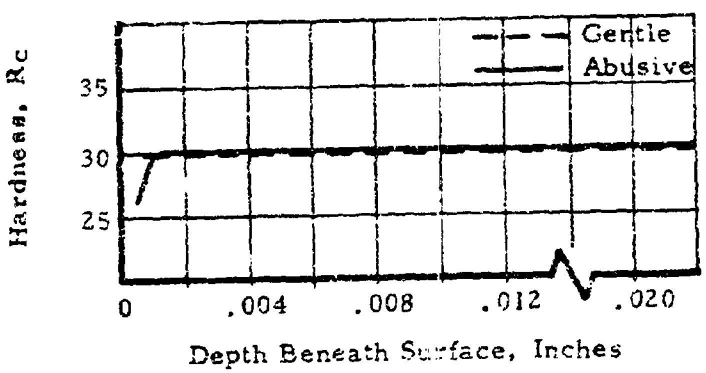
Figure 162



(a) Gentle Conditions - No significant effects.
Surface Finish: 55 AA   1000X

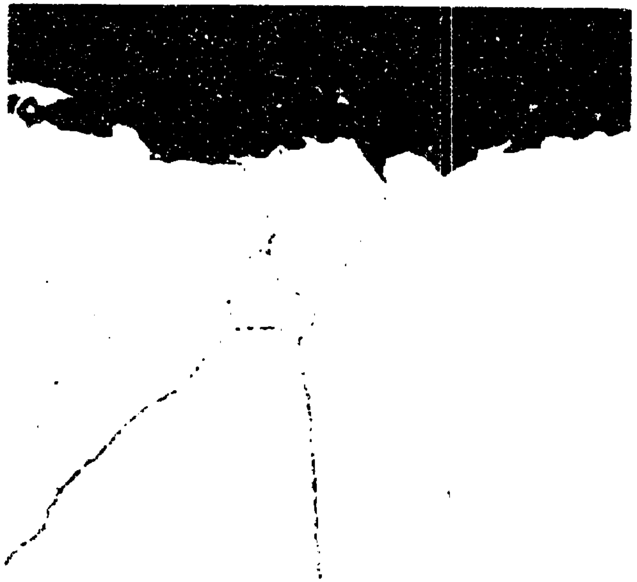


(b) Abusive Conditions - Irregular etching action related to differences in crystallographic orientation producing marked roughness. Slight hardness loss as noted below.
Surface Finish: 230-360 AA   1000X



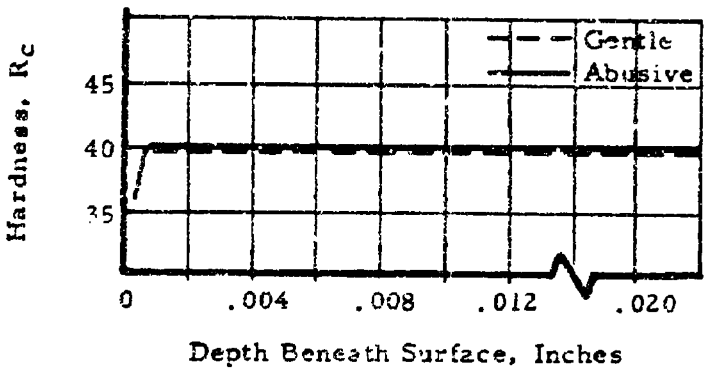
SURFACE CHARACTERISTICS OF WASPALOY (Solution Treated, 30 R_c) PRODUCED BY CHM

Figure 163



(a) Gentle Conditions - Moderate surface roughening.
Surface Finish: 100 AA 1000X

(b) Abusive Conditions - Moderate surface roughening, preferential attack, plus slight loss in surface hardness.
Surface Finish: 180 AA 1000X

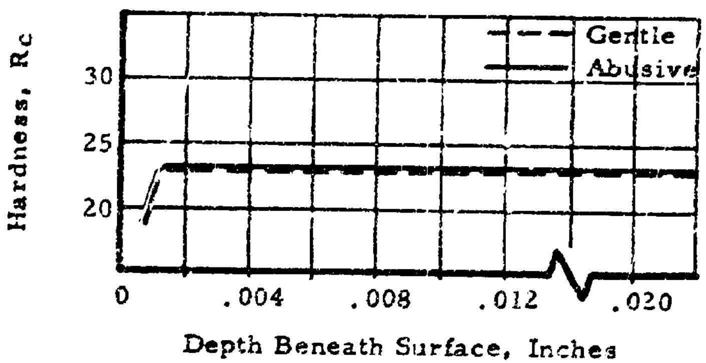


SURFACE CHARACTERISTICS OF WASPALOY (Aged, 40 R_c) PRODUCED BY CHM

Figure 164

(a) Gentle Conditions - Attack of carbide phase plus surface roughening or unleveling.
Surface Finish: 150 AA 1000X

(b) Abusive Conditions - Attack of carbide phase plus surface roughening or unleveling.
Surface Finish: 270 AA 1000X

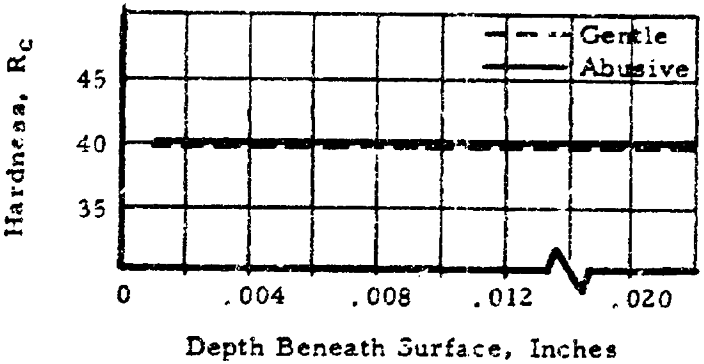


SURFACE CHARACTERISTICS OF
HAYNES ALLOY NO. 31 (Cast, 23 R_c)
PRODUCED BY CHM

Figure 165

(a) Gentle Conditions - Pronounced surface roughening and unleveling.
Surface Finish: 410 AA 1000X

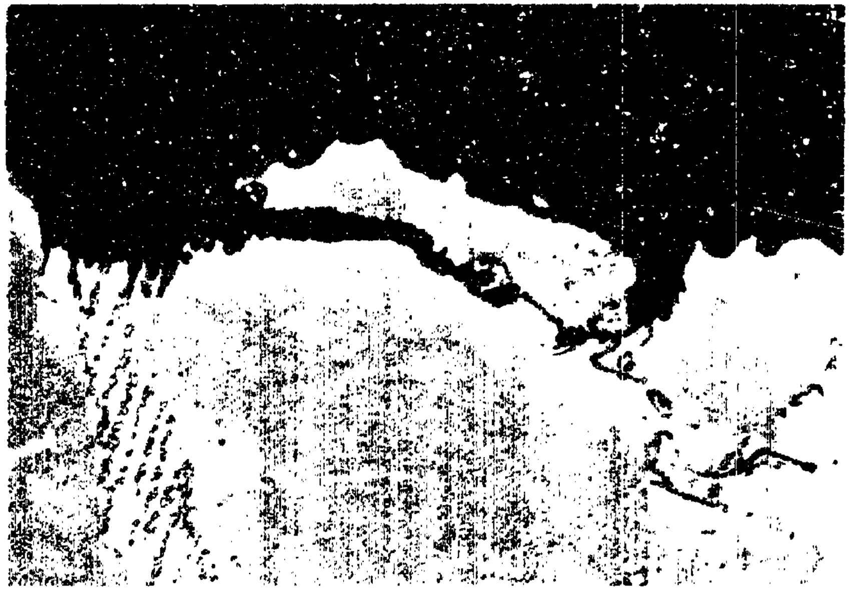
(b) Abusive Conditions - Pronounced surface roughening and unleveling.
Surface Finish: 450 AA 1000X



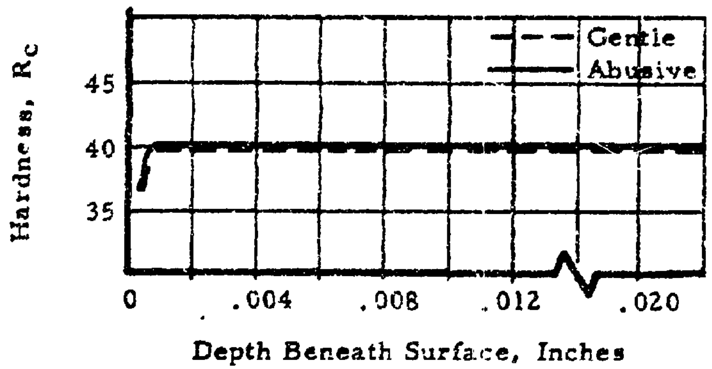
SURFACE CHARACTERISTICS OF
CAST INCONEL 718 (Aged, 40 R_c) PRODUCED
BY CHM

Figure 166

(a) Gentle Conditions - Intergranular attack and preferential solutioning at grain boundaries.
Surface Finish: 55 AA 1000X



(b) Abusive Conditions - Extensive attack of grain boundaries and carbide phase.
Surface Finish: 270 AA 1000X



SURFACE CHARACTERISTICS OF CAST UDIMET 700 (Aged, 40 R_c) PRODUCED BY CHM

Figure 167

TABLES OF DATA

(Tables I through XVII)

TABLE 5

GENERAL MACHINING CONDITIONS USED FOR MANUFACTURING SPECIMENS OR OTHER THAN TEST CUT SURFACES

Milling	Ti-6Al-4V	AISI 4340	Inconel 718
Cutter Diameter, in.	1-1/4"	2-1/2	1-3/4
Tool Material	[illegible] Carbide	M2	M42
Feed, in./tooth	.005	.004	.002
Cutting Speed, ft./min.	400	33	15
Tool Wear (maximum)	.010	.015	.015
Cutter	Single Tooth Fly	10 tooth shell mill	10 tooth shell mill
Fluid	Dry	Chlorinated Oil	Chlorinated Oil

Grinding	Ti-6Al-4V	AISI 4340 and Inconel 718
Grinding Wheel	[illegible]	32A46C10LV
Wheel Speed, ft./min.	3000	3100
Depth of Grind, in.	.011	.010
Down Feed, in./pass	First .008 in. at .0005 in./pass Next .0004 in. at .0004 in./pass Last .0012 in. at .0002 in./pass	Same as Ti-6Al-4V
Cross Feed, in./pass	.050	.050
Table Speed, ft./min.	40	40
Grinding Fluid	KNO_2 (1:250)	Highly Sulfurized Oil

TABLE II

MILLING CONDITIONS USED FOR MAKING TEST CUTS ON AISI 4340 AND INCONEL 718 SPECIMENS

END MILLING - END CUTTING*

	4340, 50 R_c		Inconel 718	
	Gentle	Abusive	Gentle	Abusive
Axial Rake, deg.	0	0	0	0
Radial Rake, deg.	-7	-7	30	30
Tool Material	C-2	C-2	T15	T15
Feed, in /tooth	.006	.006	.006	.006
Cutting Speed, ft./min	120	120	20	20
Tool Wear, in.	0-.004	.060	0-.006	.060
Cutting Fluid	Dry	Dry	Chlor. Oil	Chlor. Oil

Cutter: 4 in. dia., Single Tooth, 45° Corner Angle, 5° Clearance
Depth of Cut: .030 in.
Width of Cut: .75 in.

END MILLING - PERIPHERAL CUTTING*

	4340, 50 R_c		Inconel 718	
	Gentle	Abusive	Gentle	Abusive
Axial Rake, deg	30	30	30	30
Radial Rake, deg	10	10	10	10
Tool Material	T15	T15	T15	T15
Feed, in./tooth	.001	.001	.002	.002
Cutting Speed, ft./min.	35	35	20	20
Tool Wear, in.	0-.004	.012	0-.004	.012
Cutting Fluid	Sol. 1:20	Sol. 1:20	Chlor. Oil	Chlor. Oil

Cutter: 1 in. dia., 4 Flute, 7° Clearance
Depth of Cut: .030 in.
Width of Cut: .75 in.

*Milling Technique
End Milling - End Cutting: Mill on Center
End Milling - Peripheral Cutting: Climb Mill

TABLE III

MILLING CONDITIONS USED FOR MAKING TEST CUTS ON Ti-6Al-4V SPECIMENS

Cond. No.	Type* Cut	Cutting Speed ft./min.	Feed (in./tooth)	Cutting Fluid	Tool Wearland (in.)	Depth of Finish Cut (in.)
1	End	100	.004	Hocut	.003 max.	.030
2	End	100	.004	Dry	.018-.020	.005
3	End	100	.004	Hocut	.018-.020	.005
4	End	100	.008	Dry	.003 max.	.030
5	End	100	.008	Hocut	.003 max.	.005
6	End	100	.008	Dry	.018-.020	.030
7	End	150	.008	Dry	.003 max.	.005
8	End	150	.008	Hocut	.018-.020	.030
9	End	150	.008	Dry	.018-.020	.005
10	Peripheral	100	.004	Hocut	.018-.020	.030
11	Peripheral	100	.004	Dry	.003 max.	.005
12	Peripheral	100	.004	Dry	.018-.020	.030
13	Peripheral	100	.008	Hocut	.003 max.	.005
14	Peripheral	100	.008	Dry	.003 max.	.030
15	Peripheral	100	.008	Hocut	.018-.020	.005
16	Peripheral	150	.008	Dry	.018-.020	.030
17	Peripheral	150	.008	Hocut	.003 max.	.005
18	Peripheral	150	.008	Hocut	.018-.020	.030
X1	End	100	.004	Hocut	.018-.020	.030
X2	Peripheral	100	.004	Hocut	.003 max.	.030

Cutter Geometry - End Cutting:

4 in. diameter, 1-1/2 in. long, 10 teeth, 45° corner angle, C-2 carbide, 0° radial rake, 10° clearance, 5° end cutting edge angle, +5° axial rake

* Milling Technique: Mill on center

Cutter Geometry - Peripheral Cutting:

4 in. diameter, 6 in. long, 12 teeth, C-2 carbide, 0° radial rake, 10° clearance, +15° axial rake

* Milling Technique: Climb mill

TABLE IV

SURFACE GRINDING CONDITIONS USED FOR MAKING TEST CUTS ON SPECIMENS

	Ti-6Al-4V			4340, 50 R_c			Inconel 718		
	Gentle	Conven.	Abusive	Gentle	Conven.	Abusive	Gentle	Conven.	Abusive
Grinding Wheel	C60HV	C60KV	A46MV	A46HV	A46KV	A46MV	A46HV	A46KV	A46MV
Wheel Speed, ft./min.	2000	6000	6000	2000	6000	6000	2000	6000	6000
Down Feed in./pass	"LS"*	.001	.002	"LS"	.001	.002	"LS"	.001	.002
Cross Feed in./pass	.050	.050	.050	.050	.050	.050	.050	.050	.050
Table Speed ft./min.	40	40	40	40	40	40	40	40	40
Grinding Fluid	KNO_2 (1:20)	Chem. Emul.	Dry	Sulf. Oil	Sol. Oil (1:20)	Dry	Sulf. Oil	Sol. Oil (1:20)	Dry

Depth of Grind = .010 in.

* "LS" = Low Stress Down Feed: First .008 in. at .0005 in./pass
Next .0008 in. at .0004 in./pass
Last .0012 in. at .0002 in./pass

Grinding Equipment: Norton 8 in. by 24 in. hydraulic surface grinder

TABLE V

ELECTRICAL DISCHARGE MACHINING (EDM) CONDITIONS FOR MAKING TEST CUTS ON SPECIMENS

	Ti-6Al-4V		4340, 50 R_c		Inconel 718	
	Finishing	Roughing	Finishing	Roughing	Finishing	Roughing
Frequency	250 kc	8 kc	250 kc	8 kc	250 kc	4-8 kc
Amperes	2	3	1	5	2	3-6
Capacitance	2.8	4.2	.05	3	.05-1	1-4.5
Voltage	60	70	60	70	35	40-70

TABLE VI

ELECTROCHEMICAL MACHINING (ECM) CONDITIONS USED FOR MAKING TEST CUTS ON SPECIMENS

	Ti-6Al-4V		4340, 50 R_c		Inconel 718	
	Gentle	Abusive	Gentle	Abusive	Gentle	Abusive
Voltage Applied						
To Final Surface	20	20-0	26	2	17-20	2-20
Current (amps)						
Start	90	90	27	0.3	900-1300	900-1750
Finish	90	0	27	0.3	1600-2500	15-1750
Feed Rate (in./min.)	.050	dwell	.020	dwell	.045-.060	.060-dwell
Electrolyte Pressure						
Inlet	140	140	160	40	175-230	175-220
Outlet	40	40	40	35	30-70	30-90
Electrolyte Temp. (°F)	80	80	80	75	100-105	100-110
Bottom Cap (inches)	.010	.300	.008	.130	---	.050

TABLE VII

ELECTROPOLISHING (ELP) CONDITIONS

	AISI 4340	Inconel 718
Solution	Globe Electropolish #4	Ethylene glycol-75% (by vol.) Sulfuric acid-25% (by vol.) Hydrofluoric acid-1% (by vol.) of total volume
Temperature	150 ± 3°F	180 ± 3°F
Current Density	5 amps/sq. in.	5-6 amps/sq. in.
Agitation	Continuous mechanical	Continuous mechanical
Material Removed	.003-.004 in./side	.003-.004 in./side
Starting Surface Finish	5-15 AA	5-15 AA
ELP Surface Finish	10-13 AA	8-11 AA

TABLE VIII

CHEMICAL MACHINING (CHM) CONDITIONS USED FOR MAKING TEST CUTS ON SPECIMENS

	Ti-6Al-4V		AISI 4340		Inconel 718	
	Gentle	Abusive	Gentle	Abusive	Gentle	Abusive
Solution	HF - 3.0N H_2CrO_4-0.8N Ti - 15 gm/l Wetting agent .24 gm/l	HF - 1.5N H_2CrO_4 Ti - 1.0 gm/l Wetting agent 0	Free acid-3.5N NO_3-3.0N PO_4 - 1.5N Metal 100 gm/l	Free acid-6.0N NO_3-1.0N PO_4 - 5.0N Metal 100 gm/l	Free acid-4.0N NO_3 - 3.0N HF - 0.5N Metal 150 gm/l	Free acid 8.5N NO_3-1.0N PO_4 - 1.5N Metal 10 gm/l
Temperature	115 ± 3°F	140 ± 3°F	140 ± 3°F	0 ± 3°F	140 ± 3°F	160 ± 3°F
Material Removed	.019 - .021 in./side	.019 - .021 in./side	.019 - .022 in./side	.019 - .022 in./side	.020 - .030 in./side	.020 - .030 in./side
Starting Surface Finish	30 - 40 AA	30 - 40 AA	5 - 15 AA	5 - 15 AA	5 - 15 AA	5 - 15 AA
Chem Milled Surface Finish	13 - 17 AA	100 - 200 AA	35 - 48 AA	170 - 220 AA	40 - 130 AA*	130 - 220 AA*

* Values of surface finish on Inconel 718 varied with material heat treat conditions. The specimens machined in the aged condition had a surface finish of 40-50 AA under gentle conditions and a surface finish of 130-210AA under abusive conditions. Specimens machined in the solution heat treat condition had a surface finish of 105-130 AA under gentle conditions and a 140-220 AA surface finish after abusive machining.

TABLE IX

HAND GRINDING CONDITIONS USED FOR MAKING TEST CUTS ON SPECIMENS

	Ti-6Al-4V		4340, 50 R_c		Inconel 718	
	Gentle	Abusive	Gentle	Abusive	Gentle	Abusive
Abrasive	SiC	SiC	Al_2O_3	Al_2O_3	Al_2O_3	Al_2O_3
Grit Size	80	80	80	80	80	80
Belt Speed, ft./min.	2000	6000	2000	6000	2000	6000
Belt Backing	Rubber	Cast Iron	Rubber	Cast Iron	Rubber	Cast Iron
Grinding Fluid	Dry	Dry	Dry	Dry	Dry	Dry
Belt Condition	New	Worn	New	Worn	New	Worn
Nominal Depth of Cut (in.)	.0001	.001	.0001	.001	.0001	.001

Total Material Removed: 0.005 in.

TABLE X

DRILLING CONDITIONS
USED FOR MAKING TEST CUTS ON SPECIMENS

	Ti-6Al-4V		4340, 50 R_c		Inconel 718	
	Gentle	Abusive	Gentle	Abusive	Gentle	Abusive
Drill Speed, ft./min.	30	75	30	60	25	35
Feed, in./rev.	.005	.005	.001	.005	.005	.005
Drill Material	T15	T15	T15	T15	T15	T15
Cutting Fluid	Chem. Emul. (1:10)	Dry	Sulf. Oil	Dry	Chlor. Oil	Dry
Wearland on Margin, in.	0	.015	0	.015	0	.015

Drill: 1/4 in. dia; 118° Point Angle, Crankshaft Point, 7° Lip Relief

TABLE XI

SUMMARY OF PEENING CONDITIONS

AISI 4340

Steel Shot Peening

	Level 1	Level 2
Shot Size	S110	S110
Intensity	.006-.008A	.006-.008A
Coverage	300%	300%
Shot Hardness	50-55	55-60

Inconel 718

Steel Shot Peening

Shot Size	S110	S110
Intensity	.006-.008A	.006-.008A
Coverage	300%	125%
Shot Hardness	50-55	50-55

Glass Bead Peening

Bead Size: .005-.008" Bead

Intensity: .007-.011N

Coverage: 300%

TABLE XII

SUMMARY OF FATIGUE TEST DATA FOR TITANIUM 6AL-4V (BETA ROLLED)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE SURFACE GRINDING			
A226	75.0	106	Failure
A227	70.0	147	Failure
A180	67.5	180	Failure
A225	65.0	9,594	Runout
A176	65.0	209	Failure
A178	65.0	173	Failure
A179	65.0	170	Failure
A224	62.5	10,964	Runout
A177	62.5	10,018	Runout
A175	62.5	11,422	Runout
ABUSIVE SURFACE GRINDING			
A79	60.0	29	Failure
A80	50.0	36	Failure
A81	35.0	155	Failure
A82	25.0	326	Failure
A83	15.0	1,375	Failure
A86	15.0	1,153	Failure
A88	15.0	1[illegible],790	Runout
A85	12.5	10,308	Runout
A87	12.5	10,573	Runout
A84	10.0	10,4[illegible]3	Runout
GENTLE CHM			
A89	59.5	281	Failure
A96	58.4	157	Failure
A93	55.4	179	Failure
A95	55.0	13,171	Runout
A97	53.9	299	Failure
A98	52.6	271	Failure
A92	52.5	12,203	Runout
A94	52.5	10,335	Runout
A90	50.0	10,582	Runout
A91	48.4	405	Failure

TABLE XII (continued)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
ABUSIVE CHM			
A103	51.3	172	Failure
A99	50.7	278	Failure
A106	48.0	303	Failure
A102	47.5	10,532	Runout
A108	47.5	163	Failure
A101	45.0	14,890	Runout
A105	45.0	10,367	Runout
A107	45.0	10,500	Runout
A100	45.0	12,533	Runout
A104	44.5	365	Failure
MILLING: CONDITION 1			
A111	75.2	216	Failure
A112	70.6	237	Failure
A113	67.5	10,005	Runout
A115	67.5	7,586	Failure
A109	67.5	10,078	Runout
A110	65.0	10,000	Runout
A118	65.0	10,00[illegible]	Runout
A116	64.0	4,072	Failure
A117	62.5	10,026	Runout
A114	61.2	493	Failure
MILLING: CONDITION 2			
A260	80.0	142	Failure
A267	75.0	1,295	Failure
A264	72.5	454	Failure
A266	72.5	10,021	Runout
A268	72.5	896	Failure
A261	70.0	2,875	Failure
A263	70.0	10,400	Runout
A265	70.0	10,137	Runout
A269	70.0	10,242	Runout
A262	67.5	10,156	Runout

TABLE XII (continued)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
MILLING: CONDITION 3			
A317	75.0	1,250	Failure
A321	75.0	10,119	Runout
A323	75.0	833	Failure
A322	73.1	1,299	Failure
A315	72.9	169	Failure
A318	72.5	366	Failure
A319	72.5	10,357	Runout
A320	72.5	10,262	Runout
A324	72.5	283	Failure
A316	70.0	10,000	Runout
MILLING: CONDITION 4			
A135	85.0	91	Failure
A130	79.7	6,705	Failure
A131	75.0	9,369	Failure
A133	75.0	676	Failure
A136	75.0	8,149	Failure
A132	72.5	10,385	Runout
A134	72.5	10,000	Runout
A137	72.5	1,951	Failure
A139	72.5	185	Failure
A138	70.0	10,101	Runout
MILLING: CONDITION 5			
A240	80.0	185	Failure
A248	70.0	10,085	Runout
A242	67.5	890	Failure
A246	67.5	12,847	Runout
A249	67.2	367	Failure
A247	66.8	13,089	Runout
A241	65.0	5,368	Failure
A243	65.0	1,877	Failure
A245	65.0	10,455	Runout
A244	62.5	10,220	Runout

TABLE XII (continued)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
MILLING: CONDITION 6			
A172	80.0	221	Failure
A183	77.5	736	Failure
A170	75.0	284	Failure
A182	75.0	10,701	Runout
A184	75.0	1,417	Failure
A181	72.5	10,396	Runout
A171	70.0	1,736	Failure
A174	70.0	16,050	Runout
A173	67.5	9,766	Failure-under grips
A169	65.0	10,365	Runout
MILLING: CONDITION 7			
A223	80.0	518	Failure
A229	75.0	127	Failure
A250	75.0	2,384	Failure
A252	72.5	6,943	Failure
A271	72.5	10,400	Runout
A251	71.6	10,846	Runout
A228	70.0	10,443	Runout
A258	70.0	7,432	Failure
A270	70.0	10,368	Runout
A259	67.5	10,277	Runout
MILLING: CONDITION 8			
A148	90.0	78	Failure
A141	85.0	138	Failure
A143	80.0	351	Failure
A144	77.5	155	Failure
A146	77.5	623	Failure
A140	75.0	1,936	Failure
A142	75.0	10,358	Runout
A149	75.0	10,039	Runout
A145	75.0	10,064	Runout
A147	72.5	10,118	Runout

TABLE XII (continued)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
MILLING: CONDITION 9			
A325	75.0	133	Failure
A327	67.5	983	Failure
A332	67.5	863	Failure
A326	67.0	770	Failure
A328	65.0	10,207	Runout
A329	65.0	1,413	Failure
A331	65.0	10,257	Runout
A333	65.0	10,392	Runout
A334	63.0	1,073	Failure
A330	62.5	10,000	Runout
MILLING: CONDITION 10			
A160	80.0	127	Failure
A166	66.4	408	Failure
A159	66.4	2,139	Failure
A161	63.4	428	Failure
A167	62.9	10,168	Failure
A162	62.5	470	Failure
A158	60.9	369	Failure
A163	58.0	590	Failure
A165	55.0	10,133	Runout
A164	50.0	10,213	Runout
MILLING: CONDITION 11			
A185	78.5	66	Failure
A186	70.5	2,180	Failure
A194	67.5	182	Failure
A199	67.5	3,048	Failure
A187	66.9	6,556	Failure
A188	65.0	10,479	Runout
A197	65.0	10,012	Runout
A220	62.9	7,975	Failure
A221	62.5	8,711	Failure
A222	60.9	173	Failure

TABLE XII (continued)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
MILLING: CONDITION 12			
A291	82.2	114	Failure
A292	72.2	168	Failure
A293	70.0	153	Failure
A294	60.0	772	Failure
A295	52.2	485	Failure
A297	51.4	9,176	Failure
A298	47.5	693	Failure
A299	45.0	10,200	Runout
A300	40.4	768	Failure
A296	40.0	10,100	Runout
MILLING: CONDITION 13			
A200	80.0	66	Failure
A209	70.0	10,042	Runout
A207	69.0	212	Failure
A201	67.8	158	Failure
A208	67.5	10,206	Runout
A206	67.5	10,032	Runout
A205	65.0	10,020	Runout
A204	62.5	10,076	Runout
A202	61.8	7,968	Failure
A203	60.0	10,058	Runout
MILLING: CONDITION 14			
A278	77.4	85	Failure
A279	70.0	1,322	Failure
A288	68.5	184	Failure
A280	65.6	202	Failure
A282	65.0	327	Failure
A287	65.0	10,345	Runout
A285	62.5	10,565	Runout
A283	60.0	523	Failure
A286	60.0	10,045	Runout
A284	55.0	10,000	Runout

TABLE XII (continued)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
MILLING: CONDITION 15			
A230	78.1	92	Failure
A231	68.7	167	Failure
A232	60.0	353	Failure
A233	51.2	7,387	Failure
A239	50.0	12,892	Runout
A234	47.5	12,564	Runout
A236	47.5	8,455	Failure
A238	47.5	10,358	Runout
A237	45.0	10,200	Runout
A235	42.2	7,337	Failure
MILLING: CONDITION 16			
A275	70.9	67	Failure
A276	63.5	85	Failure
A277	55.0	226	Failure
A289	45.0	452	Failure
A314	37.5	1,642	Failure
A290	35.9	1,355	Failure
A313	35.0	10,094	Runout
A312	32.5	10,105	Runout
A281	30.0	11,215	Runout
A311	25.0	10,327	Runout
MILLING: CONDITION 17			
A216	71.5	10,104	Runout
A217	70.8	5,273	Failure
A210	70.0	244	Failure
A218	68.1	6,097	Failure
A219	67.5	291	Failure
A211	65.0	5,062	Failure
A213	65.0	10,234	Runout
A215	65.0	10,169	Runout
A214	62.6	6,944	Failure
A212	62.5	10,258	Runout

TABLE XII (continued)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
MILLING: CONDITION 18			
A301	63.5	177	Failure
A302	58.3	179	Failure
A308	45.2	595	Failure
A307	45.0	413	Failure
A306	42.5	10,045	Runout
A305	41.6	365	Failure
A304	40.0	10,315	Runout
A309	40.0	514	Failure
A310	37.5	10,505	Runout
MILLING: CONDITION X1			
A122	85.0	582	Failure
A120	80.0	2,283	Failure
A126	80.0	10,208	Runout
A123	77.5	2,120	Failure
A125	77.5	12,553	Runout
A121	75.0	10,180	Runout
A124	75.0	10,086	Runout
MILLING: CONDITION X2			
A154	80.0	79	Failure
A150	75.0	4,481	Failure
A152	75.0	102	Failure
A151	72.5	10,470	Runout
A153	72.5	120	Failure
A156	72.5	275	Failure
A149	70.0	10,371	Runout
A155	70.0	10,132	Runout
GENTLE HAND GRINDING			
A335	70.0	105	Failure
A336	60.0	266	Failure
A340	60.0	264	Failure
A339	57.5	10,450	Runout
A338	55.0	10,115	Runout
A337	50.0	12,343	Runout

TABLE XII (continued)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
ABUSIVE HAND GRINDING			
A341	70.0	44	Failure
A342	59.0	69	Failure
A343	40.0	326	Failure
A346	34.4	304	Failure
A345	30.0	10,115	Runout
A344	25.0	12,106	Runout

TABLE XIII

SUMMARY OF FATIGUE TEST DATA FOR AISI 4340 ALLOY QUENCHED AND TEMPERED (50 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{3})	Status
GENTLE SURFACE GRINDING			
B92	120.0	69	Failure
B57	115.0	94	Failure
B91	105.0	501	Failure
B167	100.0	17,361	Runout
B58	95.0	18,914	Runout
B162	94.3	269(a)	Failure
CONVENTIONAL SURFACE GRINDING			
B96	90.0	96	Failure
B165	84.3	2,801	Failure
B164	80.8	558	Failure
B59	75.0	735	Failure
B163	74.5	84(a)	Failure
B95	70.0	20,653	Runout
ABUSIVE SURFACE GRINDING			
B60	83.3	78	Failure
B168	75.0	101	Failure
B130	69.3	167	Failure
B98	65.0	10,747	Runout
B131	65.0	211	Failure
B97	60.0	9,414	Runout
ELECTROPOLISHING			
B127	100.0	170	Failure
B123	93.0	224	Failure
B122	91.5	332	Failure
B90	90.0	10,961	Runout
B126	90.0	10,135	Runout
B128	85.0	11,553	Runout

(a) Failure through surface pit.

TABLE XIII (continued)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^3)	Status
GENTLE SURFACE GRINDING + SHOT PEENING (LEVEL 1)			
B169	133.0	102	Failure
B170	125.0	96	Failure
B172	115.0	261	Failure
B174	116.0	32,011	Runout
B173	107.5	15,664	Runout
B171	100.6	14,493	Runout
ABUSIVE SURFACE GRINDING + SHOT PEENING (LEVEL 1)			
B135	120.0	50	Failure
B124	100.0	97	Failure
B93	95.0	327	Failure
B94	94.0	616	Failure
B132	92.5	13,675	Runout
B99	90.0	12,760	Runout
ABUSIVE SURFACE GRINDING + SHOT PEENING (LEVEL 2)			
B134	120.0	31	Failure
B155	110.0	76	Failure
B136	100.5	200	Failure
B137	95.0	133	Failure
B133	90.0	1,523	Failure
B166	85.0	10,938	Runout
ELECTROPOLISHING + SHOT PEENING (LEVEL 1)			
B61	132.0	54	Failure
B63	121.0	93	Failure
B86	[illegible]	[illegible]	Failure
B102	95.0	13,470	Runout
B88	92.5	19,585	Runout
B87	80.0	10,695	Runout
GENTLE HAND GRINDING			
B183	110.0	133	Failure
B184	105.0	182	Failure
B182	100.0	13,583	Runout
B185	95.0	130	Failure
B189	90.0	10,511	Runout
B186	85.0	10,622	Runout

TABLE XIII (continued)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
ABUSIVE HAND GRINDING			
B199	105.0	104	Failure
B198	100.0	190	Failure
B202	99.0	13,095	Runout
B201	96.0	11,250	Runout
B200	92.5	10,251	Runout
B197	85.0	12,768	Runout
ABUSIVE HAND GRINDING + SHOT PEENING (LEVEL 1)			
B206	122.5	97	Failure
B205	118.0	10,225	Runout
B204	115.0	10,699	Runout
B203	110.0	15,722	Runout

TABLE XIV

SUMMARY OF FATIGUE TEST DATA FOR INCONEL 718 ALLOY SOLUTION TREATED AND AGED PRIOR TO MACHINING

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE SURFACE GRINDING CONDITIONS			
C52	84.8	271	Failure
C88	78.2	458	Failure
C89	67.6	1,013	Failure
C51	64.9	3,171	Failure
C99	60.8	3,538	Failure
C90	60.0	11,620	Runout
GENTLE EDM CONDITIONS			
C165	43.7	763	Failure
C164	41.5	2,329	Failure
C143	33.0	906	Failure
C105	30.0	2,892	Failure
C104	24.7	5,272	Failure
C141	22.5	10,980	Runout
ABUSIVE EDM CONDITIONS			
C145	35.0	1,124	Failure
C107	30.4	1,168	Failure
C106	24.9	5,390	Failure
C146	23.5	4,477	Failure
C144	22.5	10,967	Runout
C108	20.0	17,650	Runout
GENTLE ECM CONDITIONS			
C109	50.0	1,179	Failure
C114	47.5	2,416	Failure
C112	45.0	2,286	Failure
C113	43.5	2,899	Failure
C110	42.5	13,495	Runout
C111	40.0	12,140	Runout

TABLE XIV (continued)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
ABUSIVE ECM CONDITIONS			
C154	50.0	1,195	Failure
C149	45.0	2,811	Failure
C150	41.0	4,622	Failure
C153	40.0	5,475	Failure
C151	39.0	10,695	Runout
C152	39.0	3,526	Failure
ELECTROPOLISHING			
C54	50.0	2,831	Failure
C97	47.5	1,971	Failure
C96	44.9	7,207	Failure
C55	43.3	3,532	Failure
C95	42.5	10,500	Runout
C56	42.5	11,218	Runout
GENTLE EDM + SHOT PEENING (LEVEL 1)			
C221	80.0	7,989	Failure
C214	74.8	5,218	Failure
C220	72.3	6,328	Failure
C219	70.0	9,314	Failure
C213	67.3	9,534	Failure
C208	65.6	11,972	Failure
ABUSIVE EDM + SHOT PEENING (LEVEL 1)			
C169	77.0	2,211	Failure
C168	76.8	2,891	Failure
C171	76.5	1,579	Failure
C170	75.2	10,802	Failure
C166	74.0	11,233	Failure
C165	70.0	9,080	Runout
ABUSIVE EDM+ FULL REHEAT TREATMENT (IN VACUUM)			
C173	50.0	1,190	Failure
C184	45.0	1,640	Failure
C183	42.5	3,171	Failure
C172	40.0	9,202	Failure
C185	39.4	4,885	Failure
C186	37.5	14,142	Runout

TABLE XIV (continued)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{3})	Status
ABUSIVE EDM + STRESS RELIEF (1150°F/4 hrs.) IN AIR			
C190	40.0	3, 358	Failure
C187	35.0	170	Failure
C189	30.0	3, 986	Failure
C192	27.5	3, 260	Failure
C188	25.0	11, 130	Failure
C191	25.0	11, 215	Runout
GENTLE ECM + SHOT PEENING (LEVEL 1)			
C204	90.0	957	Failure
C209	84.6	1, 822	Failure
C205	81.7	1, 956	Failure
C207	79.9	7, 105	Failure
C206	77.5	11, 040	Runout
C203	75.0	10, 451	Runout
GENTLE ECM + GLASS BEAD PEENING			
C202	94.9	622	Failure
C196	90.0	6, 531	Failure
C194	84.1	4, 195	Failure
C87	80.0	6, 854	Failure
C195	78.0	14, 139	Runout
C201	77.5	11, 107	Failure
ABUSIVE ECM + SHOT PEENING (LEVEL 1)			
C210	89.0	887	Failure
C212	85.0	788	Failure
C217	79.1	1, 310	Failure
C215	75.0	1, 172	Failure
C216	69.7	7, 398	Failure
C211	65.1	1, 608	Failure, outside test section
ABUSIVE ECM + SHOT PEENING (LEVEL 2)			
C226	90.0	1, 352	Failure
C237	83.3	4, 311	Failure
C239	81.6	6, 313	Failure
C222	78.2	5, 372	Failure
C223	75.7	2, 177	Failure
C224	75.0	10, 818	Runout

TABLE XIV (continued)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
ELP + SHOT PEENING (LEVEL 1)			
C233	99.5	432	Failure
C234	90.0	1,200	Failure
C230	85.0	1,941	Failure
C231	82.5	5,921	Failure
C229	80.0	8,851	Failure
C232	78.0	10,341	Failure
CONVENTIONAL SURFACE GRINDING + FULL REHEAT TREATMENT (IN VACUUM)			
C103	66.0	740	Failure
C101	63.0	1,211	Failure
C104	57.6	1,364	Failure
C100	56.9	1,516	Failure
C228	51.7	1,898	Failure
C102	50.0	33,038	Runout

TABLE XV

SUMMARY OF FATIGUE TEST DATA FOR INCONEL 718 ALLOY SOLUTION TREATED BEFORE MACHINING, VACUUM AGED AFTER MACHINING

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE SURFACE GRINDING CONDITIONS			
D93	82.5	456	Failure
D92	77.5	11,850	Runout
D57	75.7(a)	2,214	Failure
D94	75.0	1,413	Failure
D91	75.0	10,710	Runout
D58	73.7(a)	6,453	Failure
D58	65.0	12,326	Runout
D57	55.0	11,214	Runout
GENTLE EDM CONDITIONS			
D156	49.9	855	Failure
D115	45.0	961	Failure
D174	37.5	1,770	Failure
D175	35.0	11,706	Runout
D116	32.0	17,884	Runout
D157	30.0	10,574	Runout
ABUSIVE EDM CONDITIONS			
D176	50.0	886	Failure
D159	37.5	1,980	Failure
D117	31.9	4,345	Failure
D177	30.0	5,132	Failure
D158	28.0	10,430	Runout
D118	26.0	10,461	Runout

(a) Specimen step loaded to this stress after runout at lower stress level.

TABLE XV (continued)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE ECM CONDITIONS			
D199	55.0	2,048	Failure
D178	50.0	2,961	Failure
D179	45.0	4,564	Failure
D119	43.0	2,686	Failure
D161	42.5	11,195	Runout
D160	40.0	11,095	Runout
ABUSIVE ECM CONDITIONS			
D162	55.0	878	Failure
D181	50.0	2,698	Failure
D163	45.0	3,327	Failure
D139	43.5	11,308	Runout
D200	43.0	3,341	Failure
D180	42.5	11,174	Runout
GENTLE ELP CONDITIONS			
D122	50.0	825	Failure
D123	45.0	2,394	Failure
D61	40.0	3,487	Failure
D124	37.8	3,454	Failure
D59	37.5	2,777	Failure
D60	32.5	5,385	Failure
D126	27.5	10,000	Runout

TABLE XVI

STRESS CORROSION DATA ON Ti 6Al-4V

Machining Condition	Test Condition	U. T. S. (ksi)	0.2% Y. S. (ksi)	Elong. (%)	Avg. Elong.
Milling-Cond. 1	Unexposed	138	129	9.5	
	Unexposed	139	129	10.5	10.0
	Exposed	134	130	2	
	Exposed	133	129	1.5	
	Exposed	140	130	3.5	2.3
Milling-Cond. 4	Unexposed	139	130	10.5	
	Unexposed	139	129	11.5	11.0
	Exposed	141	130	3.5	
	Exposed	137	129	4	
	Exposed	140	131	5.5	4.3
Milling-Cond. 6	Unexposed	141	127	10	
	Unexposed	140	127	12	11.0
	Exposed	140	130	5	
	Exposed	139	129	4.5	
	Exposed	142	131	7.5	5.7
Milling-Cond. 8	Unexposed	140	126	10	
	Unexposed	139	125	8.5	9.2
	Exposed	142	131	7	
	Exposed	140	127	5	
	Exposed	138	129	2	4.7
Milling-Cond. 10	Unexposed	140	129	7.5	
	Unexposed	138	127	4.5	6.0
	Exposed	143	132	6.5	
	Exposed	147	138	4.5	
	Exposed	146	136	3.5	4.8

TABLE XVI (continued)

Machining Condition	Test Condition	U. T. S. (ksi)	0.2% Y. S. (ksi)	Elong. (%)	Avg. Elong.
Milling-Cond. 12	Unexposed	138	125	4.5	
	Unexposed	136	125	3.5	4.0
	Exposed	141	130	4	
	Exposed	139	131	2	
	Exposed	144	132	4	3.3
Milling-Cond. 14	Unexposed	139	129	8	
	Unexposed	138	130	7.5	7.8
	Exposed	142	132	5.5	
	Exposed	141	131	4	
	Exposed	141	131	5.5	5.0
Milling-Cond. 16	Unexposed	134	125	3.5	
	Unexposed	135	123	4	3.8
	Exposed	142	133	2	
	Exposed	146	1[illegible]7	2	
	Exposed	144	142	1.5	1.8
Milling-Cond. 18	Unexposed	135	125	4	
	Unexposed	133	124	4	4.0
	Exposed	149	141	3	
	Exposed	150	141	5	
	Exposed	121	(a)	1	3.0
Gentle Surface Grind	Unexposed	141	132	9.5	
	Unexposed	142	133	11.5	10.5
	Exposed	135	127	2.5	
	Exposed	138	128	3.5	2.0

(a) Failed before 0.2% Y. S. was obtained

TABLE XVI (continued)

Machining Condition	Test Condition	U. T. S. (ksi)	0.2% Y. S. (ksi)	Elong. (%)	Avg. Elong.
Abusive Surface	Unexposed	142	134	9.5	
Grind	Unexposed	144	135	7.5	8.5
	Exposed	141	129	3	
	Exposed	140	127	5	
	Exposed	142	129	4	4.0
Gentle CHM	Unexposed	141	132	9	
	Unexposed	140	131	9	9.0
	Exposed	141	131	4	
	Exposed	135	126	3	
	Exposed	136	127	1.5	2.8
Abusive CHM	Unexposed	139	131	8	
	Unexposed	140	133	9.5	8.8
	Exposed	140	130	5	
	Exposed	138	130	4.5	
	Exposed	141	133	5	4.8

TABLE XVII

STRESS CORROSION DATA ON AISI 4340

Machining Condition	Failure Observed After (hours)	Previously Examined At (hours)	Failure Location (inches from end) (b)
Gentle Surface Grind	147	126	5.0
	239	216	4.0
	249	239	3.8
	1,000 (a)	---	---
Conventional Surface Grind	147	126	4.2
	147	126	3.8
	177	171	6.0
	1,000 (a)	---	---
Abusive Surface Grind	163	153	5.2
	163	153	5.0
	239	216	---
	249	239	4.0
Gentle Surface Grind + Shot Peen (Level 1)	484	479	6.0
	1,000 (a)	---	---
	1,000 (a)	---	---
	1,000 (a)	---	---
Abusive Surface Grind + Shot Peen (Level 1)	1,000 (a)	---	---
	1,000 (a)	---	---
	1,000 (a)	---	---
	1,000 (a)	---	---
Abusive Surface Grind + Shot Peen (Level 2)	91	83	3.2
	153	147	3.2
	193	191	5.5
	197	195	4.1

(a) Samples removed after 1,000 hours without failure

(b) Measured from end of specimen. Distance from opposite fixture edge is 6 inches.

TABLE XVII (continued)

Machining Condition	Failure Observed After (hours)	Previously Examined At (hours)	Failure Location (inches from end) (b)
Gentle Hand Grind	126	117	4.9
	193	191	4.2
	216	213	4.5
	908	891	---
Abusive Hand Grind	83	81	4.8
	163	153	5.2
	197	195	3.5
	216	213	3.6
Abusive Hand Grind + Shot Peen (Level 1)	147	126	3.8
	249	239	5.0
	315	313	5.2
	479	454	4.0
Electropolish	31	29	---
	44	36	5.5
	68	60	---
	1,000 (a)	---	---
Electropolish + Shot Peen (Level 1)	313	290	3.5
	331	315	4.1
	454	434	---
	631	603	3.5

(a) Samples removed after 1,000 hours without failure

(b) Measured from end of specimen. Distance from opposite fixture edge is 6 inches.

APPENDIX I

DETAILED MANUFACTURE OF TEST SPECIMENS

I-1 General Preparation of Specimens

I-2 Test Cuts - Surface Grinding

I-3 Test Cuts - Milling

I-4 Test Cuts - Hand Grinding

I-5 Test Cuts - Drilling

I-6 Test Cuts - Electrical Discharge Machining (EDM)

I-7 Test Cuts - Electrochemical Machining (ECM)

I-8 Test Cuts - Electropolishing (ELP)

I-9 Test Cuts - Chemical Machining (CHM)

APPENDIX I-1

General Preparation of Specimens

The general procedure used was to saw blanks, perform any necessary heat treatment and then reduce blanks to a size suitable for producing the various test cuts or test surfaces which were to be studied. After these test cuts were made, the specimens were finish manufactured, making them ready for testing. The following table summarizes the amount of metal which was removed in taking the test cuts on the various types of specimens and using the various metal removal processes.

	Depth of Test Cut (in.)			
Machining Process	Metallography	Residual Stress	Fatigue	Stress Corrosion
Milling	0.030	0.005 and 0.030	0.005 and 0.030	0.030
Surface Grinding	0.010	0.010	0.010	0.010
EDM	0.125	0.080	0.043	-
ECM	0.125	0.080	0.043	-
Chemical Milling	0.020	0.020	0.020	0.020
ELP	0.003	0.003	0.003	0.003
Hand Grinding	0.005	0.005	0.005	0.005

Specimens for residual stress, stress corrosion and fatigue tests were prepared in accordance with Figures 1 through 5 of the main report (Section 5). Whenever residual stress or fatigue specimens were made using a particular set of metal removal variables, the coupons required for metallographic studies were cut from these specimens. In several instances, however, combinations of cutting parameters were subjected to metallographic evaluation only. In those instances, metallographic coupons as shown in Figure 168 were specifically prepared for that purpose.

General Preparation of Specimens (continued)

Metallographic Coupons

Metallographic coupons were, in general, prepared for the test cut by removing .010 in. or more by low stress grinding from the original plate thickness. Grinding conditions were as outlined in Table I. The specimens were then given the test cuts as outlined in the various tables (II through X). After the test cuts were completed, these coupons were sectioned, metallographically mounted in accordance with specific procedures intended to retain edge characteristics and etched for examination (Appendix II-1).

Metallographic coupons for milling and grinding conditions where residual stress or fatigue tests were not run were taken from the same type specimens as had been used for residual stress studies (Figure 1). This was done since the cutting of a reasonably large surface area was required in order to obtain a representative test cut surface.

In all cases, metallographic coupons were sectioned using a silicon carbide slitting saw. Mounting and polishing were accomplished as previously noted.

Residual Stress Specimens

Residual stress specimens per Figure 1 were prepared from blanks described in Figure 169. The initial milling procedures on the blanks were as noted in Table I. The blanks were reduced from the rough milled size using low stress grinding (Table I) to a thickness which allowed stock for the test cut, also noted in Figure 169. Additional grinding stock (.010 in.) was left on the backs of the ECM and EDM specimens to compensate for excessive warpage of the specimen during the test cuts, should it occur. Low stress grinding per Table I was used on the back surface of these specimens after the test cut was completed in order to reduce the specimen to the final dimensions shown in Figure 1. As indicated in Figure 169, the CHM and ELP specimens were low stress ground essentially to the finished thickness prior to taking the test cuts. A stop-off procedure was used to prevent stock removal from all surfaces other than the test cut surface.

Fatigue Specimens

The fatigue specimens used to develop data in this report are shown in Figures 2 and 3. The specimen shown in Figure 2 was used

General Preparation of Specimens (continued)

for all tests on Inconel 718 and 4340 as well as on the CHM abusive grinding and some milling conditions on the titanium alloy. As initial fatigue work on titanium was being carried out, the desirability of having a larger surface area under test became apparent. In order to accomplish this, the specimen design was modified to provide a constant stress gage section. After the design was balanced in terms of load and deflection characteristics, the design was finalized as shown in Figure 3.

In checking out the tapered section specimen (Figure 3), fatigue behavior of gently ground samples was found to be equal to that exhibited by the initially selected hourglass specimen (Figure 2). Thereafter, all milling data developed under this contract on titanium were produced with the constant stress specimen shown in Figure 3.

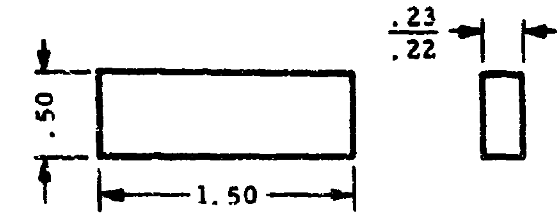
Test Cuts

At the appropriate point in specimen manufacture, test cuts were made on the gage section of specimens using the variety of metal removal methods and variables being studied by this effort. A summary of the specific cutting conditions used to manufacture test specimens is as follows:

Metal Removal Method	Table No.
Milling, Inconel 718 and 4340	II
Milling, Titanium Alloys	III
Surface Grinding	IV
Electrical Discharge Machining (EDM)	V
Electrochemical Machining (ECM)	VI
Chemical Milling (CHM)	VII
Electropolishing	VIII
Hand Grinding	IX
Drilling	X

Surface Finish

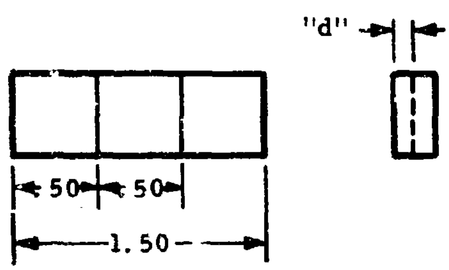
Surface finish measurements were made on each specimen after manufacturing. A stylus type instrument, a Model BL-185 Surfindicator, was used. All surface finish readings contained in this report are average values taken perpendicular to the lay of the surface (when present). A cutoff of .030" was used for surfaces of 30 microinches or greater. A cutoff of .010" was used for surfaces less than 30 microinches.



a) <u>Blank Prior to Test Cut</u>

EDM and ECM:
"LS" Grind cleanup
(.010" min. per side)

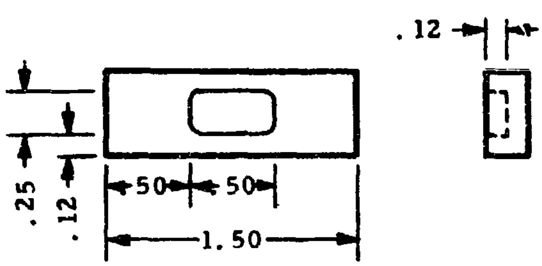
CHM:
"LS" Grind plus hand
polish (240, 400, 600
grit papers)



b) <u>Finished EDM and CHM Coupon</u>

EDM: "d" = 0.12"

CHM: "d" = 0.020"

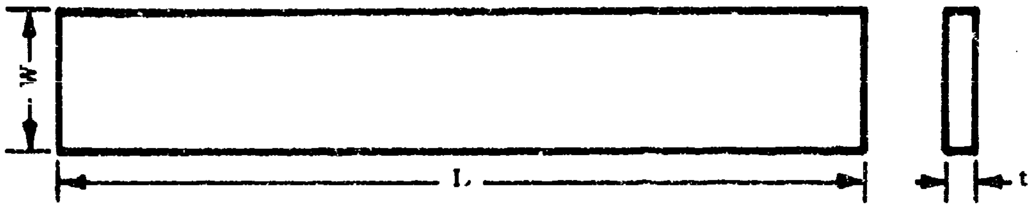


c) <u>Finished ECM Coupon</u>

METALLOGRAPHIC COUPONS

Figure 168

a) Blank Prior to Test Cut

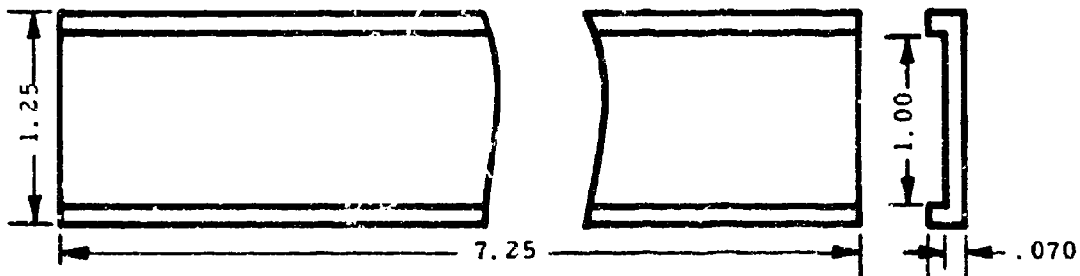


Test Cut Operation	Mill to these dimensions L	W	t	LS Grind to this "t" dimension
Milling (.030" test cut)	4.75	.82	.11	.090*
Milling (.005" test cut)	4.75	.82	.09	.065*
Surface Grinding	4.75	.82	.09	.070*
EDM or ECM	7.25	1.25	.1[illegible]	.150
ELP	4.75	.82	.09	.063**
CHM	4.75	.82	.10	.080**
Hand Grinding	4.75	.82	.08	--

* Final test cut, .005" or .030" milling or .010" grinding is made on finished specimen configuration shown in Figure 2.

** After grinding, specimen is longitudinally hand polished on successively finer silicon carbide papers (240, 400, 600).

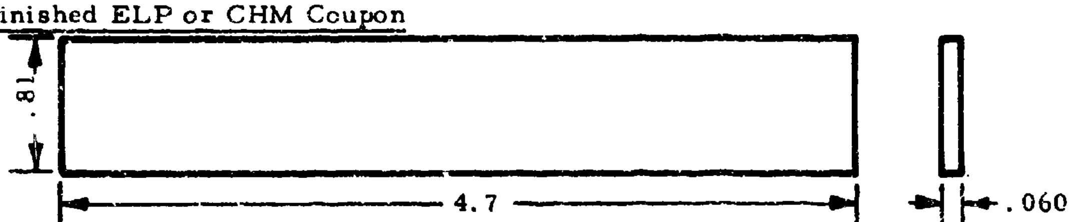
b) Finished EDM or ECM



EDM is through-slot, test machining conditions per Table V.

ECM is pocket, test machining conditions per Table VI.

c) Finished ELP or CHM Coupon

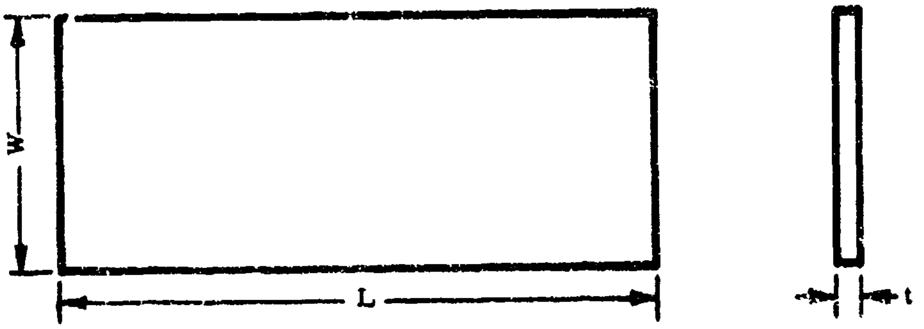


Electropolished per conditions listed in Table VIII.
Chemical machined per conditions listed in Table VII.

RESIDUAL STRESS BLANKS

Figure 169

a) Blank Prior to Test Cut

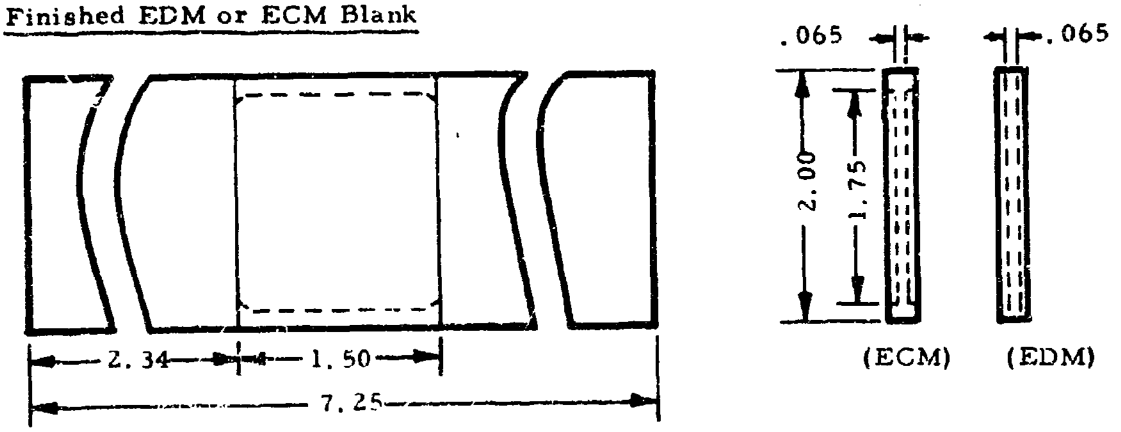


Test Cut Operation	Mill to these dimensions L	W	t	LS Grind to this "t" dimension
Milling (test cut .030")	4.63	2.00	.15	.125*
Milling (test cut .005")	4.63	2.00	.10	.075*
Surface Grinding	4.63	2.00	.11	.065*
EDM and ECM	7.25	2.00	.17	.150
ELP	4.63	2.00	.09	.071**
CHM	4.63	2.00	.13	.015**
Hand Grinding	4.63	2.00	.08	--

*Blank is subsequently milled or surface ground using test conditions shown in Tables II and III, then gage section is reduced to dimension shown in Figures 4 and 5.

**Blank is further machined in gage section to approximately finish dimensions (allowing for ELP or CHM stock removal), then longitudinally polished in gage section using successively finer silicon carbide papers (240, 400, 600).

b) Finished EDM or ECM Blank



EDM cut is through-slot located as shown above.

ECM cut is pocket (shown by dashed lines in above sketch).

FATIGUE SPECIMEN BLANKS

Figure 170

APPENDIX I-2

Test Cuts - Surface Grinding

All test surfaces were ground on a Norton 8 in. x 24 in. hydraulic surface grinder. The 4340 specimens were held in place by a magnetic chuck. The titanium and Inconel 718 specimens were mechanically clamped to a table of the grinder.

Specimens were positioned on the table so that the grinding marks or "lay" of the ground surface was parallel to the longitudinal axis of the test specimen. The specific machining conditions used are listed in Table IV.

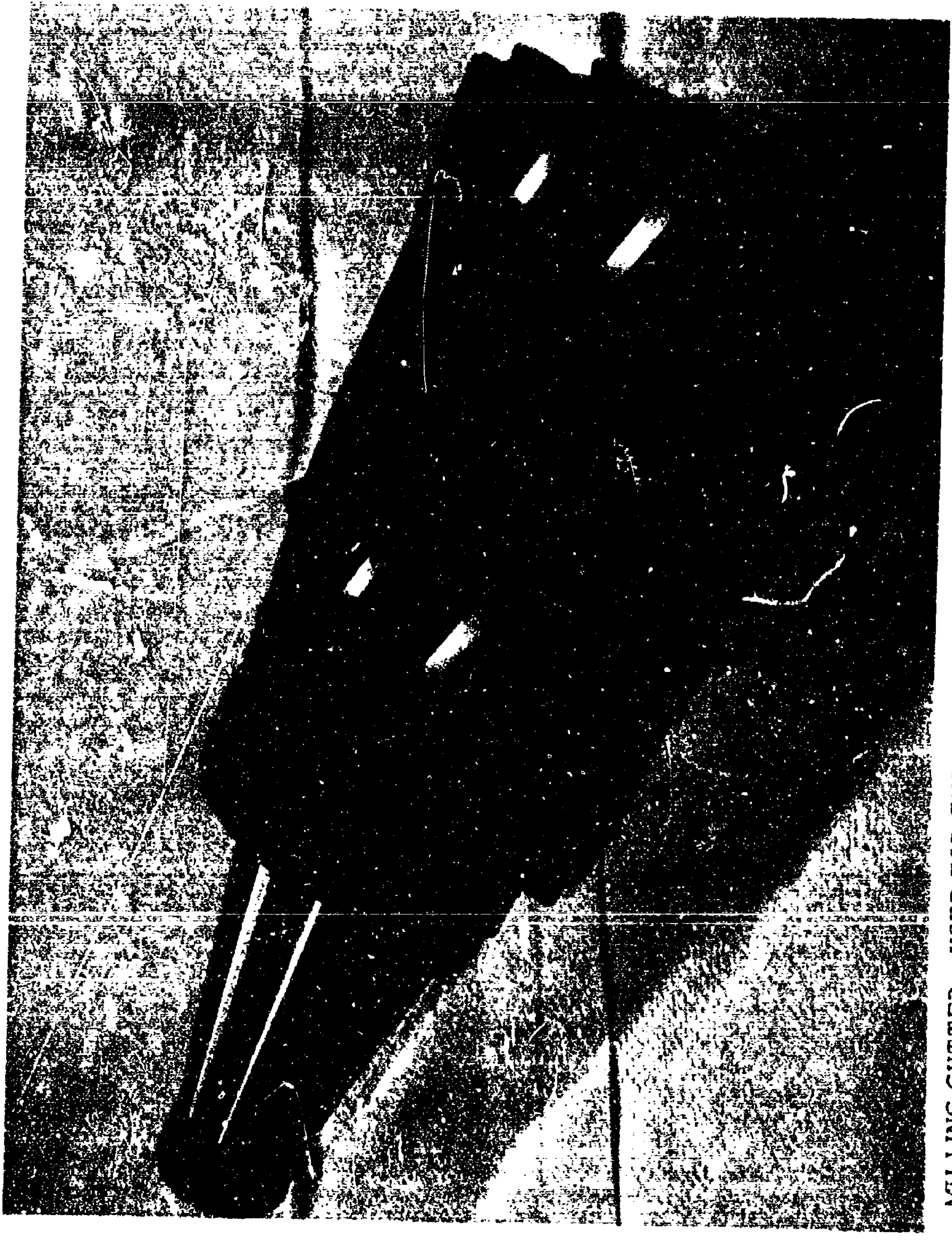
APPENDIX I-3

Test Cuts - Milling

Test cuts on Ti-6Al-4V were made on a Cincinnati No. 3 Dial-Type Horizontal Milling Machine. The cutters used for the titanium milling program were manufactured by Boeing/Seattle and loaned to Metcut for this particular project. These are shown in Figures 171 and 172. For the end cutting operation, a heavy vertical end milling attachment was used to adapt the milling machine for this particular cutting condition. The schematic drawing, Figure 173, shows the position of cutting and resulting "lay" orientation produced on the test surface of the specimens.

Specimens were bolted down to a base plate in making the test cuts. Use was made of loading holes in the specimens plus additional holes outside the test area of the blank. These additional holes were subsequently cut from the specimen prior to testing. The complete list of cutting conditions for Ti-6Al-4V are given in Table III.

Test cuts on AISI 4340 and Inconel 718 were performed on the same machine as noted above. Conventional end milling cutters were used for the finished cuts on these materials. Geometry of these cutters is described in Table II.



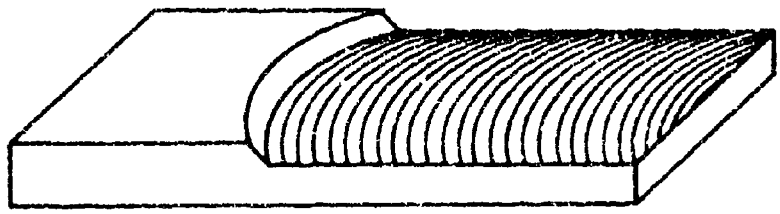
MILLING CUTTER - USED FOR END MILLING, PERIPHERAL CUTTING OF Ti-6Al-4V

Figure 171

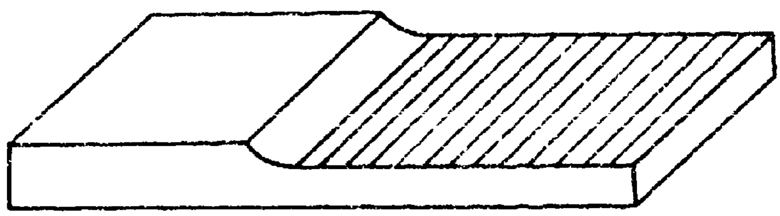
MILLING CUTTER - USED FOR END MILLING, END CUTTING OF Ti-6Al-4V

Figure 172

CHARACTERISTIC SURFACES PRODUCED
IN END MILLING



END MILLING - END CUTTING



END MILLING - PERIPHERAL CUTTING

Figure 173

APPENDIX I-4

Test Cuts - Hand Grinding

A belt grinding or sanding operation was chosen to provide representative grinding conditions. Freehand sanding or the use of vibratory-type sanders could have been employed. It was believed, however, that the method chosen would provide representative results and at the same time, lend itself to reasonable control and duplication.

A setup was made in which a cloth abrasive belt was driven by a 10" diameter pulley coupled to a variable speed drive. The belt in turn, 4" wide x 54" long, ran between a drive pulley and a 4" idler pulley. In the hand grinding operation, the test specimens were bolted to an aluminum plate. This was done to simplify handling of the specimens. Using this device, each specimen was drawn back and forth across the belt, thereby exposing the test surface to the abrasive surface of the belt.

Gentle conditions were produced using a rubber covered 10" diameter drive pulley. Abusive conditions were produced using a cast iron pulley of the same size. Other variables included changes in belt speed, work piece pressure, and belt condition.

A complete list of the machining variables used in hand grinding is summarized in Table IX.

APPENDIX I-5

Test Cuts - Drilling

Test cuts were made in small coupons on a Cincinnati 16" Sliding Head Box Column Drill. The coupons were fixed in a small table vise. Positive feed was used on all drilling operations. A summary of the gentle and abusive conditions used in all three of the test materials is presented in Table X.

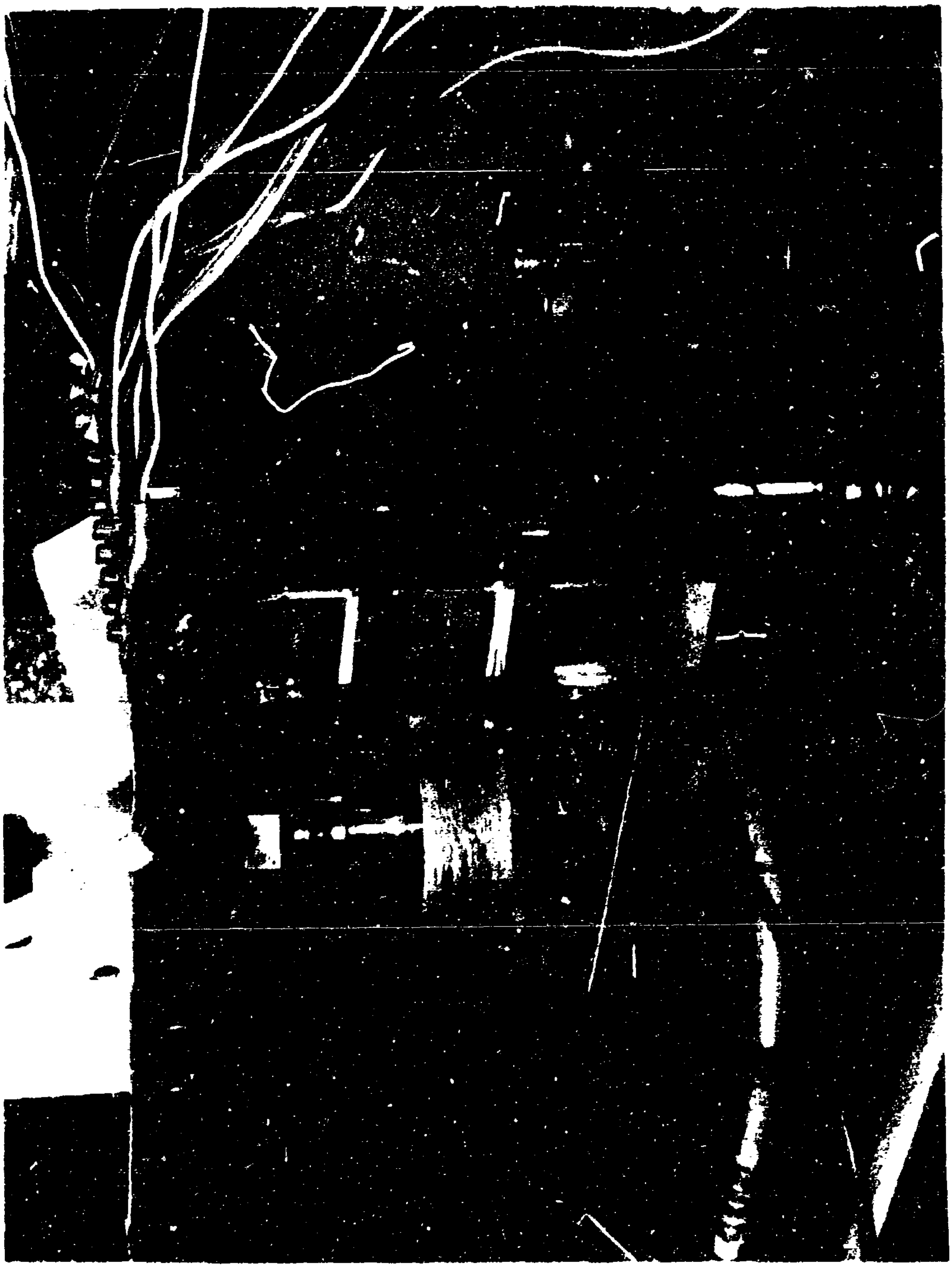
APPENDIX I-6

Test Cuts - Electrical Discharge Machining (EDM)

The electrical discharge machining of AISI 4340 and Inconel 718 specimens was carried out by GE/Evendale using an Elox HRP-104 EDM machine with an NPS-D100B power supply. Photographs of the physical setup for making the fatigue specimens and the resulting test specimens are shown in Figures 174 and 175. The EDM setup and photographs of resulting residual stress specimens are shown in Figures 176 and 177.

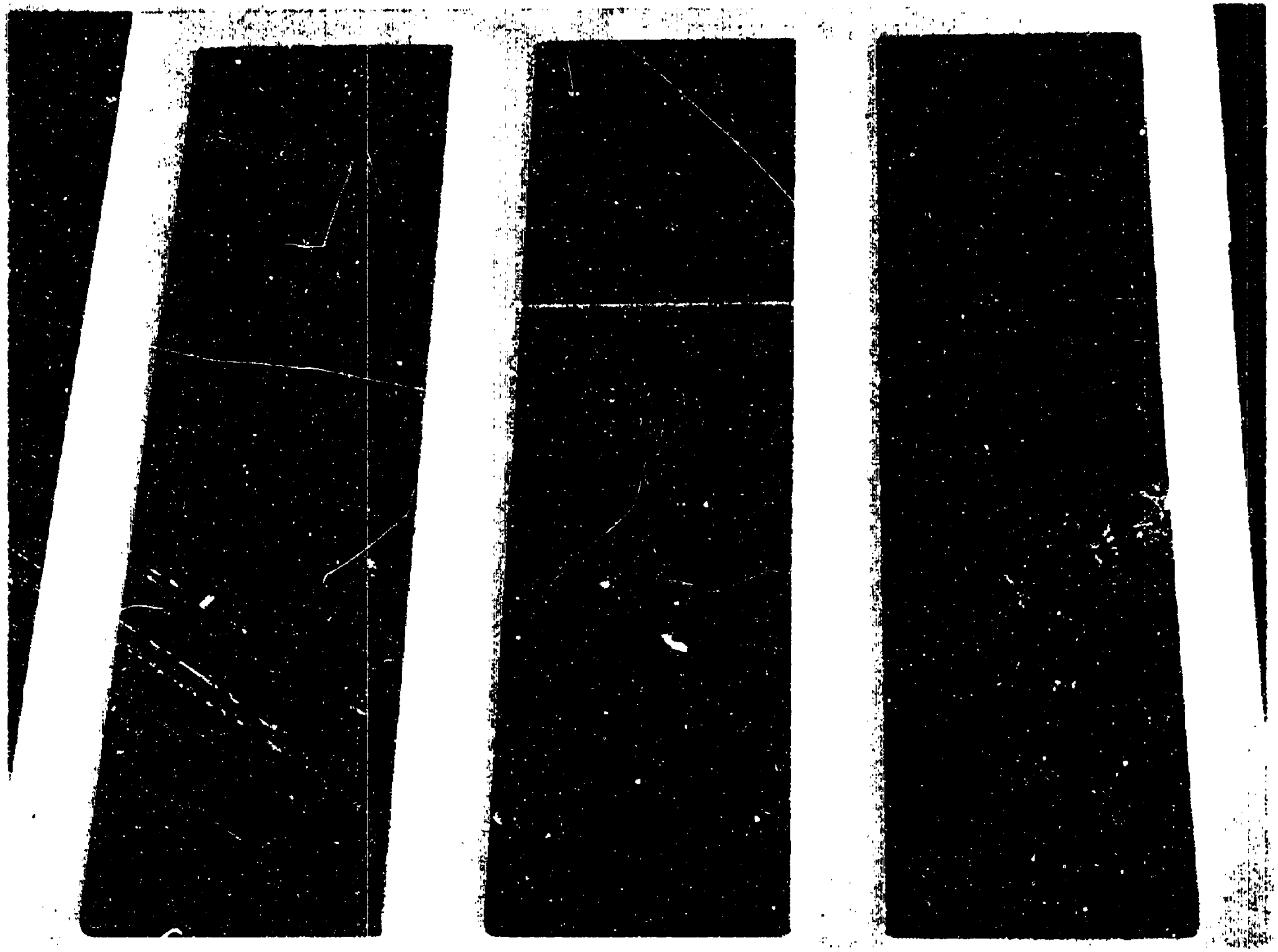
As may be seen in the photographs of the fixturing, the metal removal was accomplished with the use of rotating brass electrodes which produced through-slots on the specimen blanks. The workpiece (4340 or Inconel 718) had a positive polarity and was submerged in Elox 13 dielectric oil during the cutting process. The EDM machine was equipped with a retract system to guard against shorting in the event of excess material buildup on the electrode. The roughing cuts were made on the test coupons by removing approximately .020 in./pass and were continued to within .010 in. of the final specimen surface. On the roughing EDM condition this last .010 in. was removed in a single pass. Under finishing EDM conditions the last .010 in. was removed in successive passes of .005, .003 and .002 in.

Various operating conditions used to achieve the required surfaces for the test specimens are tabulated in Table V.



TOOLING SETUP FOR MAKING EDM TEST CUTS ON FATIGUE SPECIMEN COUPONS.

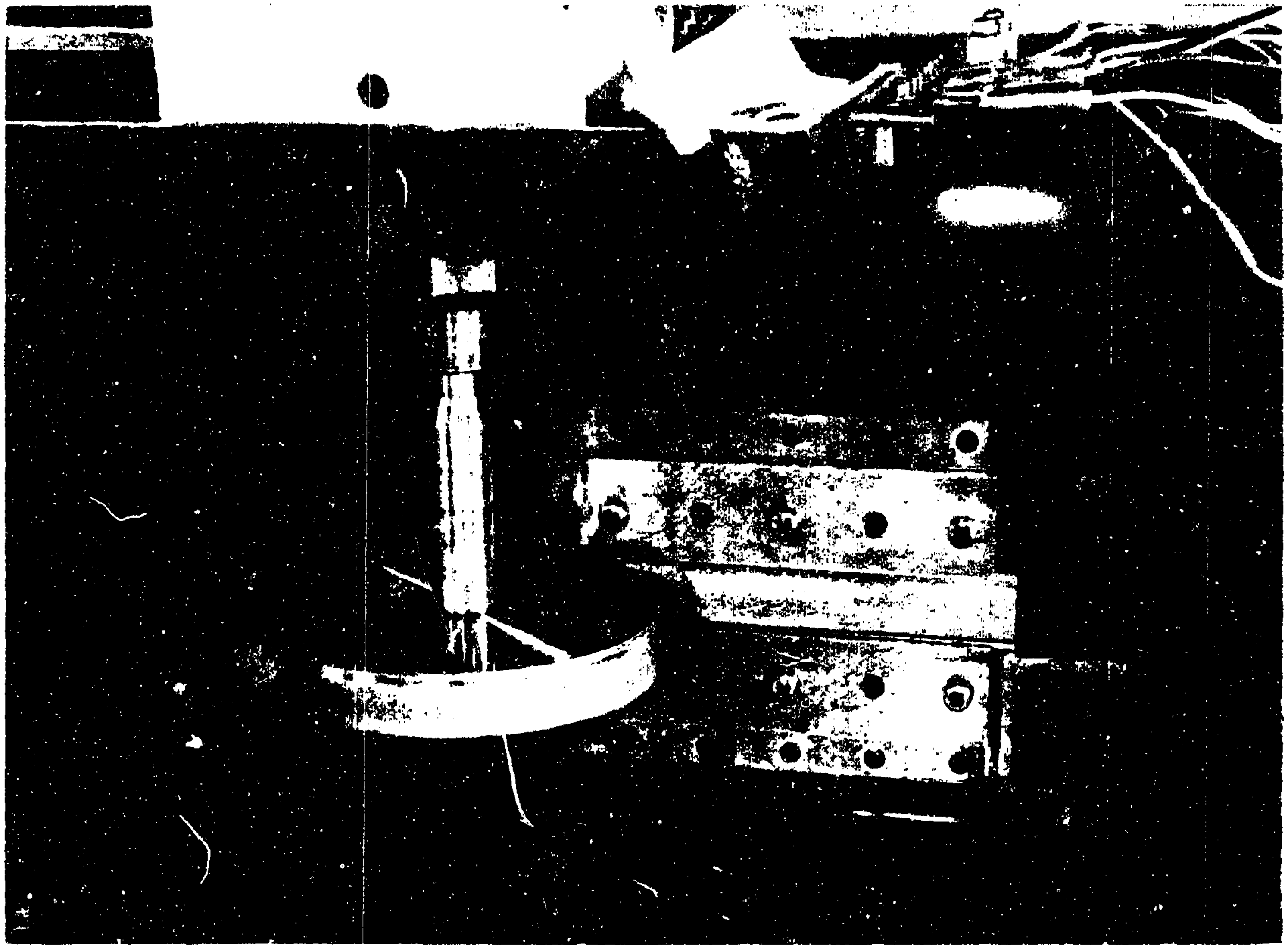
Figure 174



AS GROUND GENTLE ABUSIVE

INCONEL 718 FATIGUE SPECIMEN COUPONS PROCESSED BY EDM

Figure 175



TOOLING SETUP FOR MAKING EDM TEST CUTS ON RESIDUAL STRESS COUPONS.

Figure 176

GENTLE ABUSIVE AS GROUND

INCONEL 718 RESIDUAL STRESS SPECIMEN COUPONS
PROCESSED BY EDM

Figure 177

APPENDIX I-7

Test Cuts - Electrochemical Machining (ECM)

The electrochemical machining of fatigue and residual stress specimens was carried out on a Cincinnati Milling Machine Company Triplex system using a 30 volt - 10,000 amp rapid electric power supply. The metallurgical specimens were made on a small laboratory unit constructed by G. E. equipped with a 50 volt - 500 amp power supply.

The ECM tooling for fatigue specimens and the resulting specimens are illustrated in Figures 178 through 181. The electrolyte flow was down one side of the electrode, across the gap between the specimen and the electrode, and out the opposite side of the tooling. This is most easily seen in the schematic drawing, Figure 178. The electrolyte used for the Inconel 718 and Ti-6Al-4V fatigue specimens was 1 lb. /gal. NaCl, while 1/2 and 1/4 lb. /gal. NaCl was used on AISI 4340. Dimensions of the electrodes were as follows:

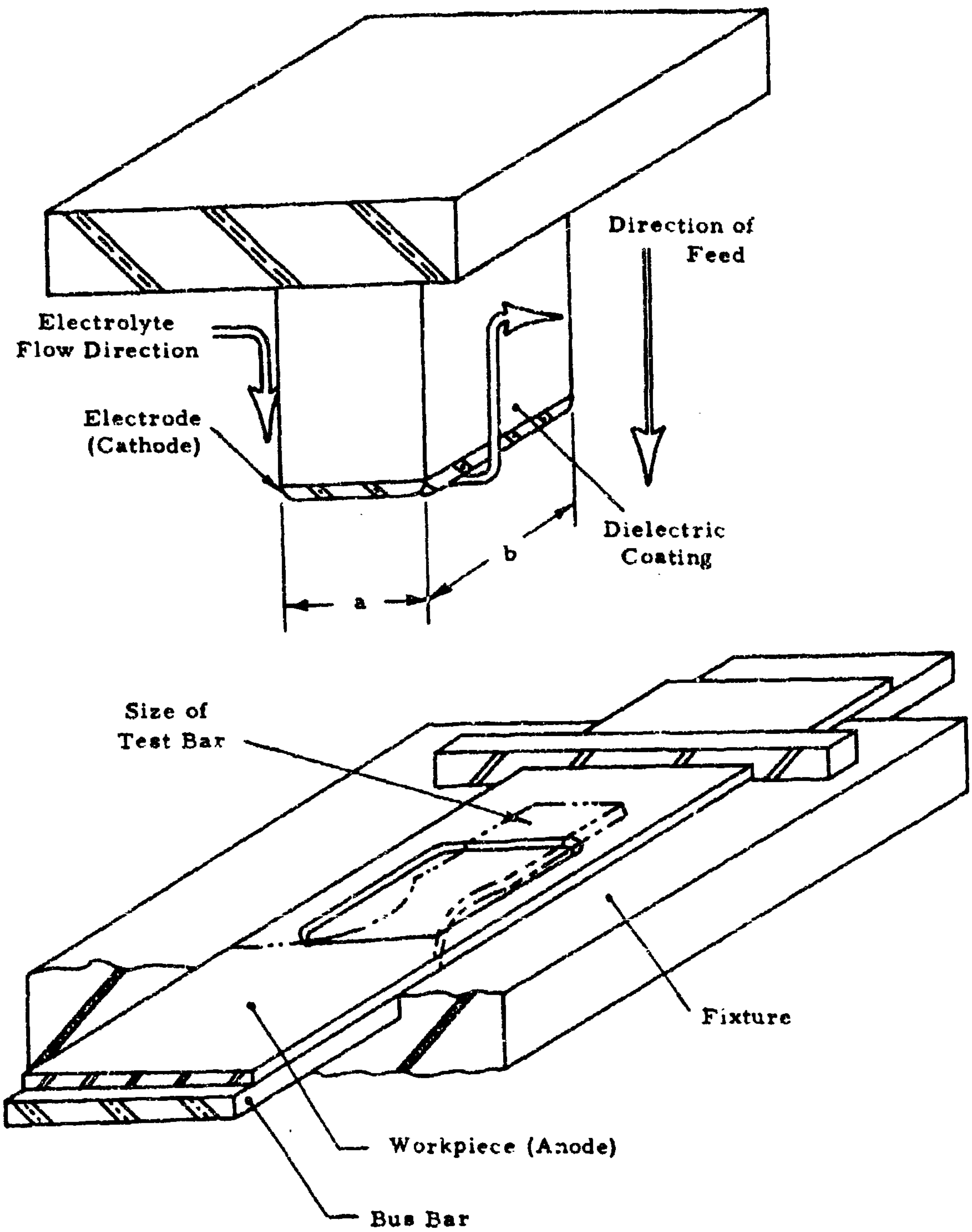
Fatigue Specimen Blanks: rectangular, 1.5 x 1.75 in.
Metallurgical Coupon Blanks: rectangular, .25 x .50 in.

The various metal removal conditions used for the fatigue and metallurgical specimens are shown in Table VI.

In preparing the ECM specimens a consistent pattern of lines or striations appeared on the surface of the specimens. This can be seen in Figures 180 and 181. The reason for this surface marking was not understood, but it appeared to be attributable to one of three things:

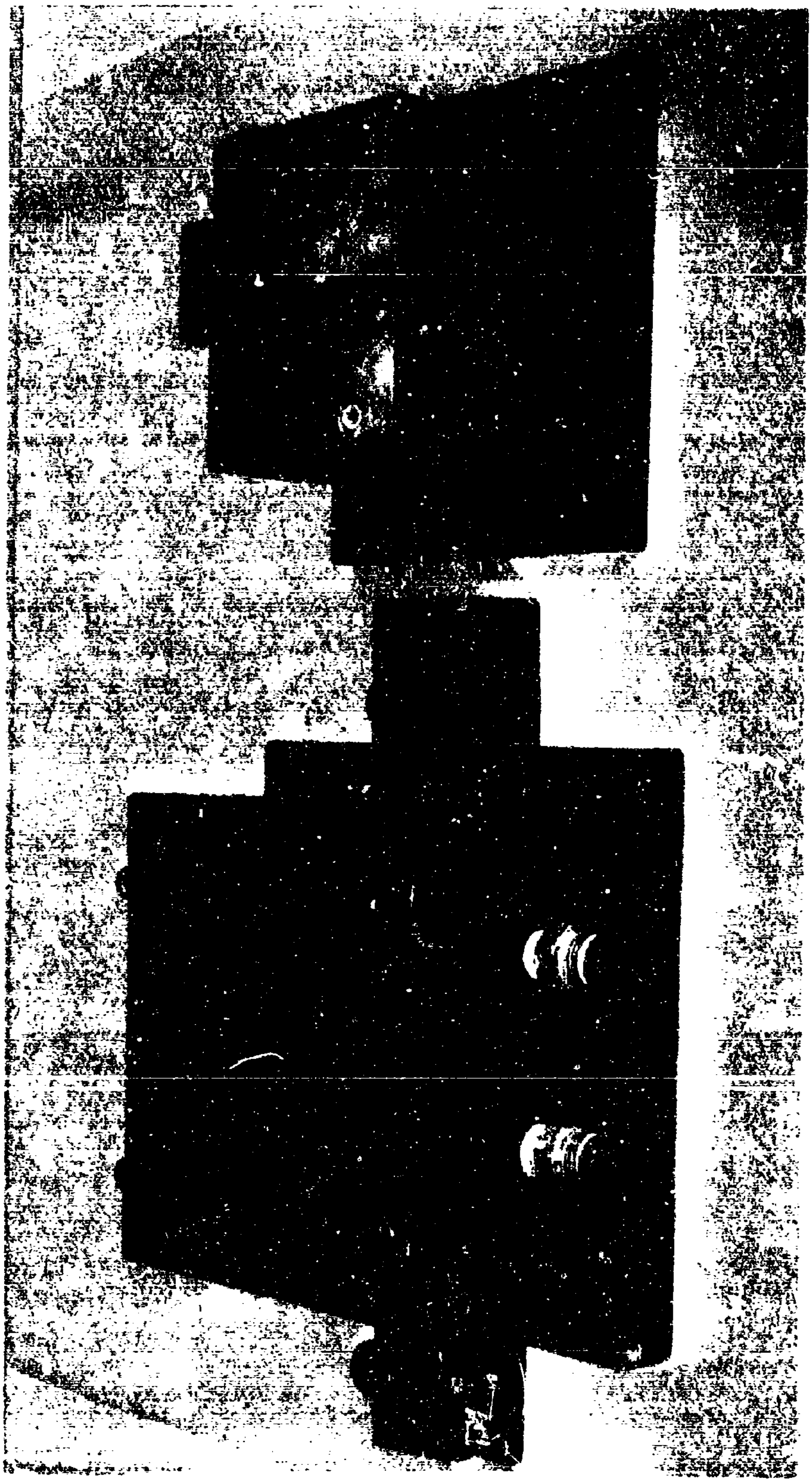
1) Ghost imaging from the prior machined finish.
2) Caused by direction of flow of the electrolyte.
3) Caused by alloy segregation of some other characteristic of the workpiece.

A series of experiments were subsequently run by G. E. in which the grinding finishing direction, direction of the electrolyte flow, and orientation of the workpiece were all interchanged in various combinations. This effort showed conclusively that the surface markings produced by chemical milling could be attributable to characteristics of the workpiece, most probably due to alloy segregation in the material.



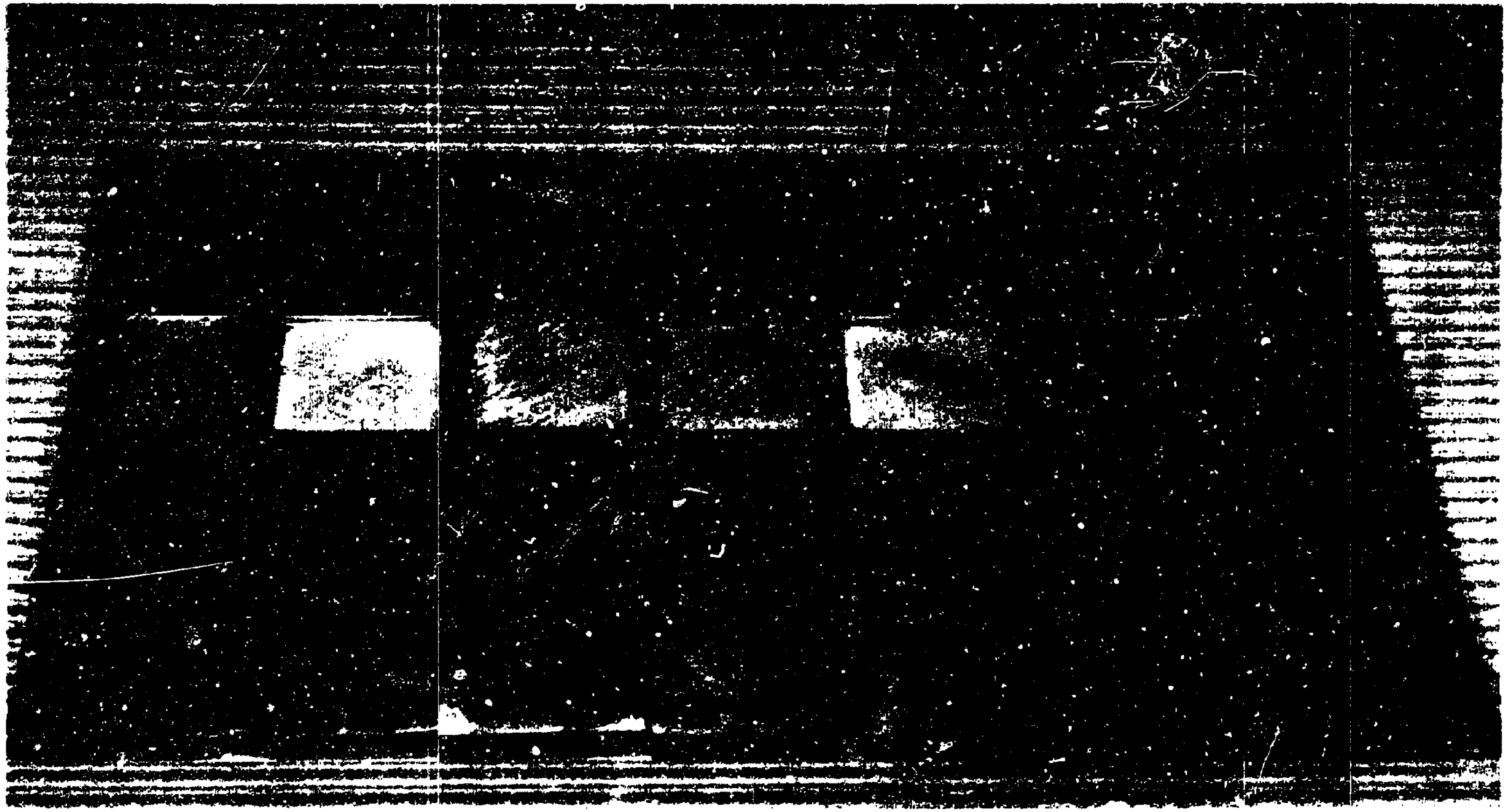
ELECTROCHEMICAL MACHINING - FRONTAL FIXTURING

Figure 178



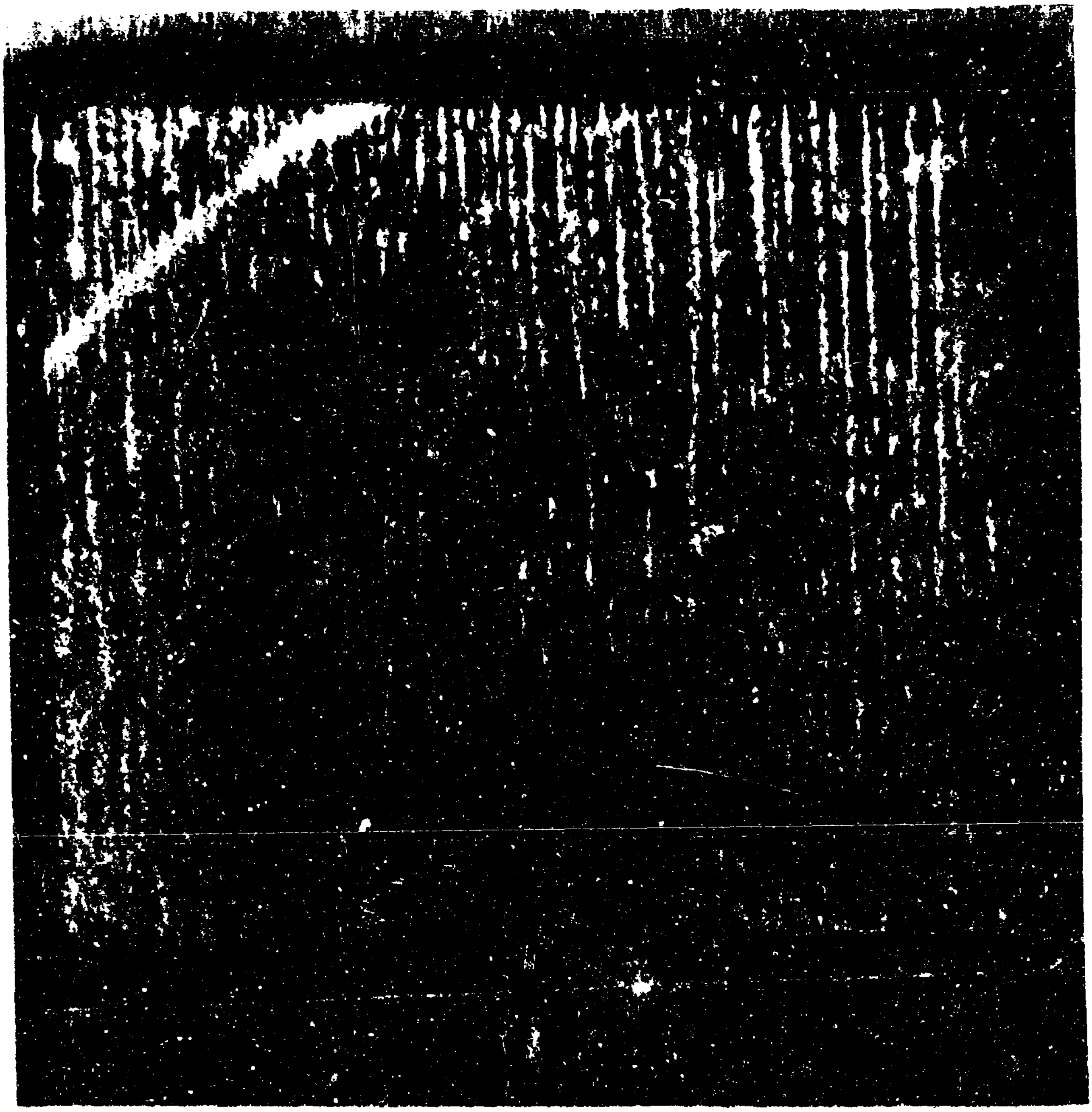
FIXTURING USED FOR ECM POCKETING OF FATIGUE SPECIMENS.

Figure 179



INCONEL 718 FATIGUE SPECIMEN COUPONS AFTER ECM POCKETING.

Figure 180



CLOSEUP VIEW OF INCONEL 718 FATIGUE SPECIMEN COUPON
AFTER ECM POCKETING.

Figure 181

APPENDIX I-8

Test Cuts - Electropolishing (ELP)

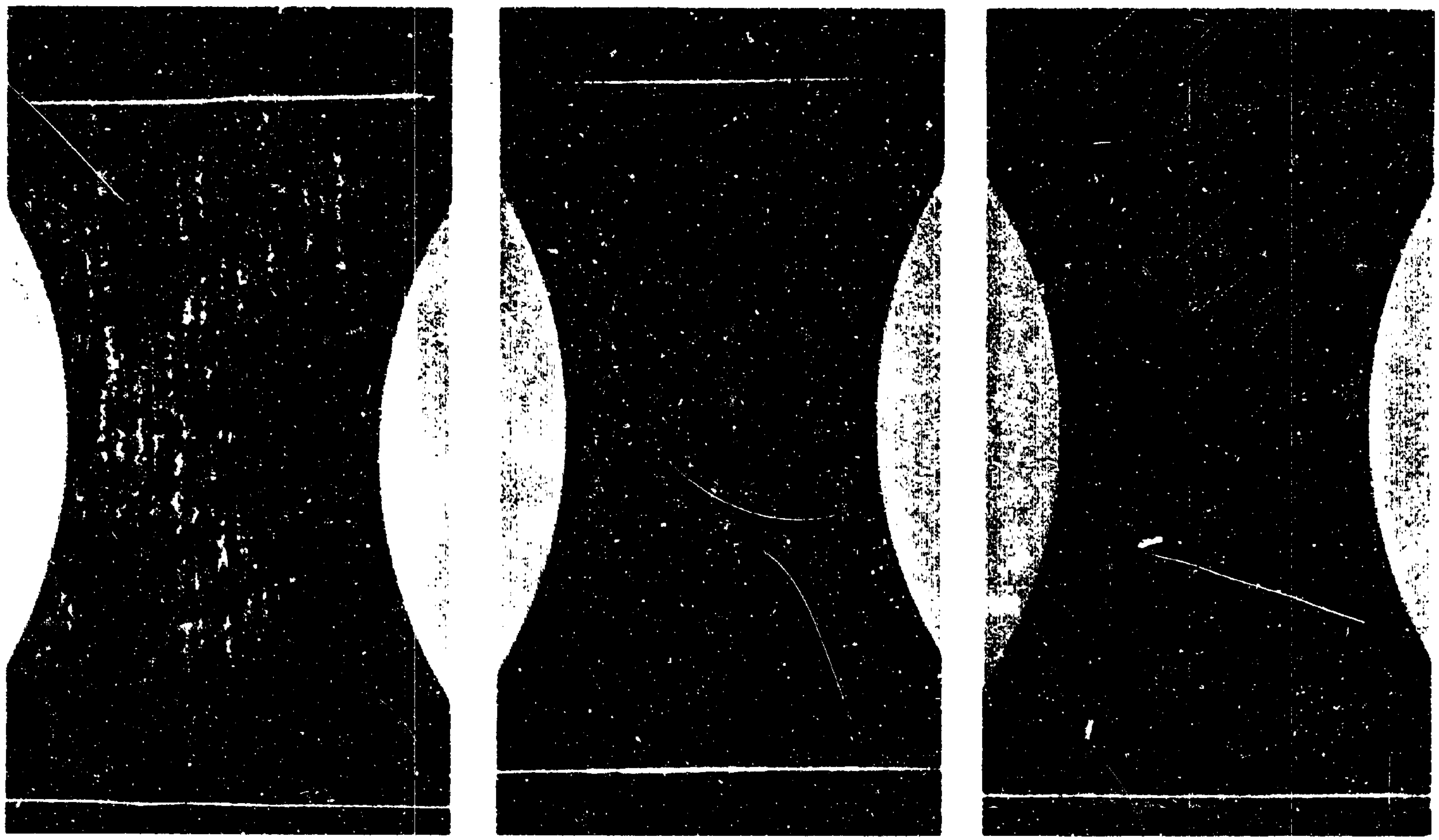
AISI 4340 was successfully electropolished in several solutions by exercising careful control of the operating parameters. Solutions which were successful in electropolishing 4340 gave good results only in specific ranges of temperature and current density. The solution selected for electropolishing all the 4340 samples in this study was Globe Electropolish #4. This solution is a mixture of heavy mineral acids. During electropolishing, the solution had about a 10°F temperature range in which polishing occurred. Above or below the correct temperature range, the polishing effect ceased and the surface finish became worse. A list of operating conditions and results is shown in Table VII. The 4340 material (Figure 182) gave a bright, polished appearance upon being removed from the solution, but this appearance was difficult to maintain through the rinsing and drying cycle.

The electropolishing of Inconel 718 proved to be a difficult job. Commercial electrolytes as well as those made using many published formulations were tried unsuccessfully. The surface finish and appearance of electropolished Inconel 718 degenerated very rapidly with these solutions. Mixtures of acetic-perchloric acid showed some promise, however, the perchloric acid solutions were extremely slow (.0001 in/30 min.) and also dangerous to use because of their explosive nature. Ultimately, reasonable success was achieved using an ethylene glycol - sulfuric acid - hydrofluoric acid under the conditions described in Table VII. The operating temperature required for this solution was not quite as critical as had been experienced in the 4340 electropolishing operation, but the overall process does require good control of all of the operating conditions. The surface lines or markings which appear on the polished specimens, as shown in Figure 182, became evident shortly after the electropolishing was started. They consistently re-established the same pattern regardless of agitation, method of running, or additional mechanical polishing of the surface. It is presumed that these surface markings are attributable to the normal alloy segregation in the material. A similar reaction was observed with ECM finishing, as discussed at a greater length in Section I-7.

The setup used in the electropolishing of samples is shown in Figure 183. The setup consists of the polishing solution, lead cathodes, a mechanical stirrer, a hot plate and a 15 volt, 30 amp DC power supply. The steps in the electropolishing of samples were as follows:

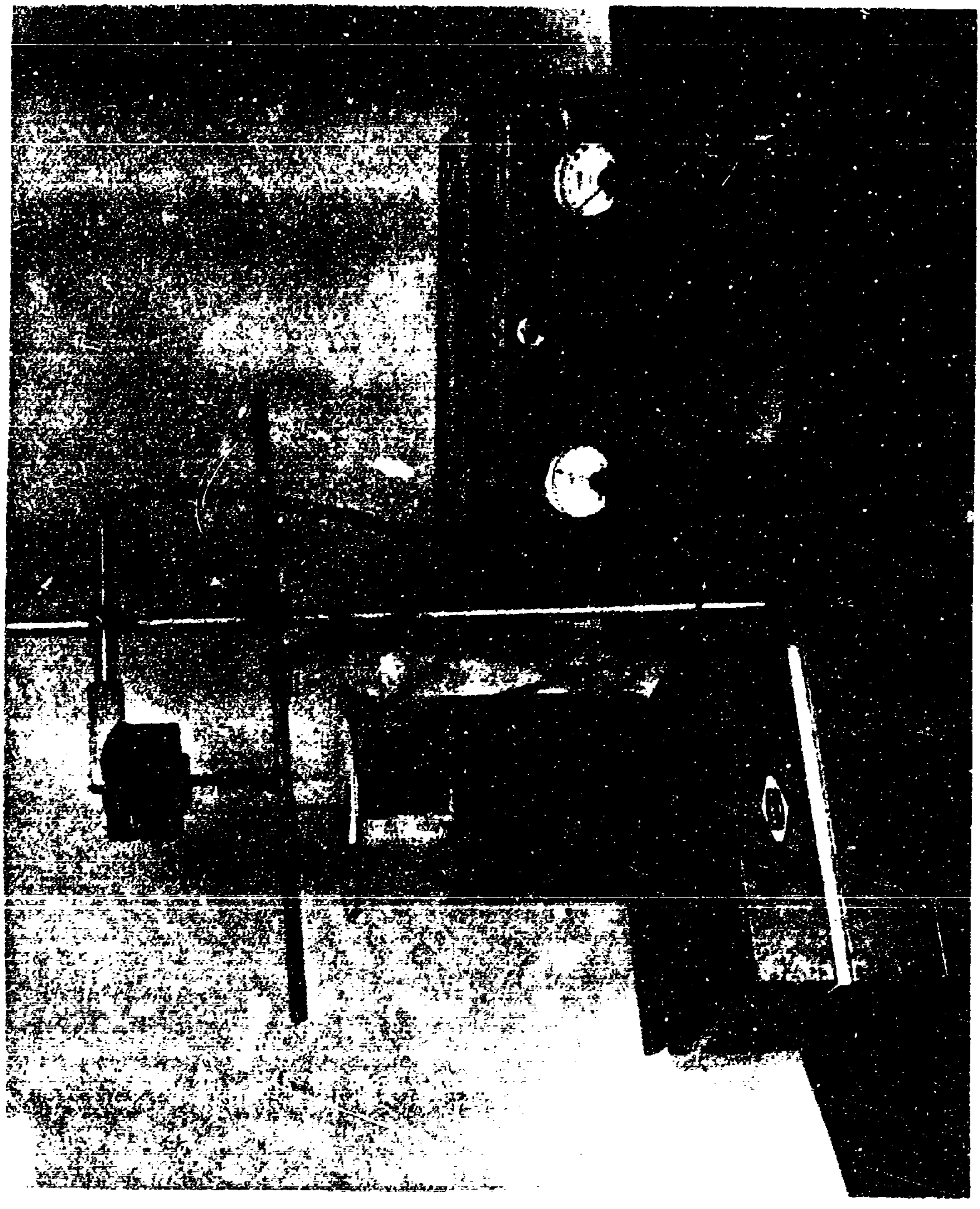
Test Cuts - Electropolishing (ELP) (continued)

1. Wipe clean with acetone.
2. Mask with Turcoform Maskant #522.
3. Trim area to be polished (Figure 184).
4. Rack parts to ensure good electrical contact.
5. Electropolish.
6. Rinse and dry immediately.
7. Strip masking.

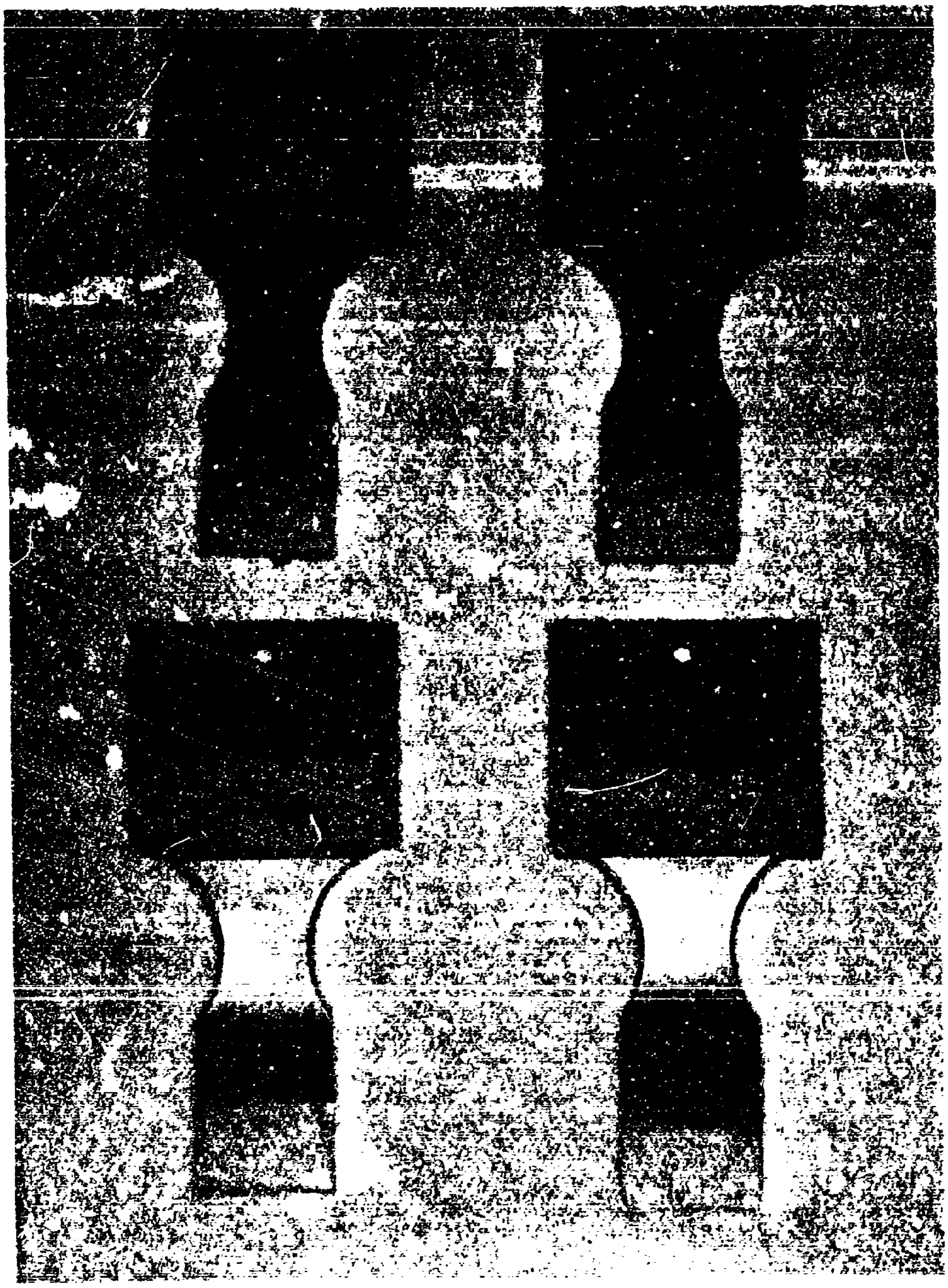


Inconel 718 Solution Treated Only — Inconel 718 Solution Treated and Aged — AISI 4340

ELECTROPOLISHED FATIGUE SAMPLES



SETUP USED FOR ELECTROLYTIC POLISHING OF COUPONS.



ELECTROLYTICALLY POLISHED INCONEL 718 FATIGUE SPECIMENS PRIOR TO REMOVAL OF STOPOFF MATERIALS.

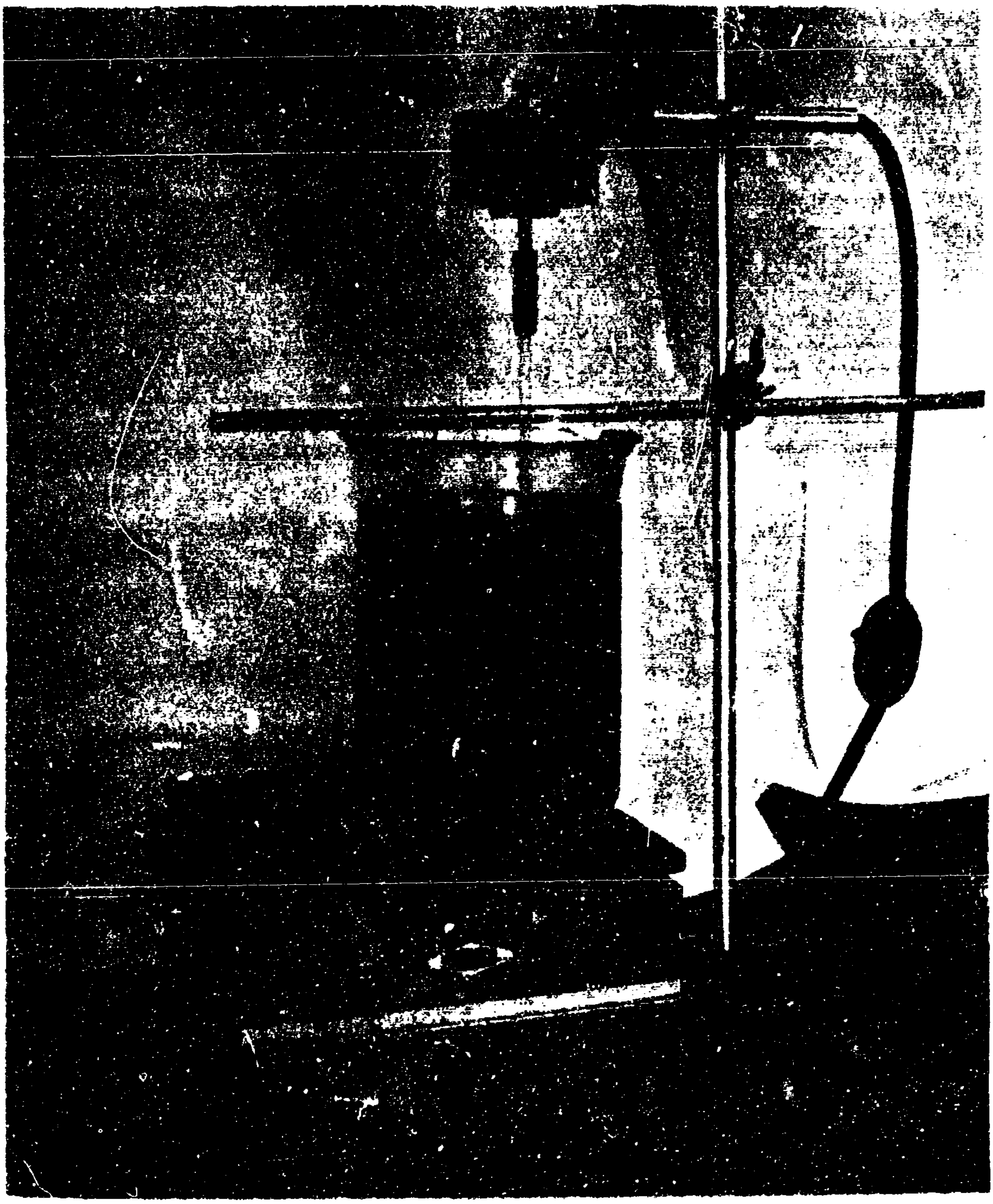
Figure 184

APPENDIX I-9

Test Cuts - Chemical Machining (CHM)

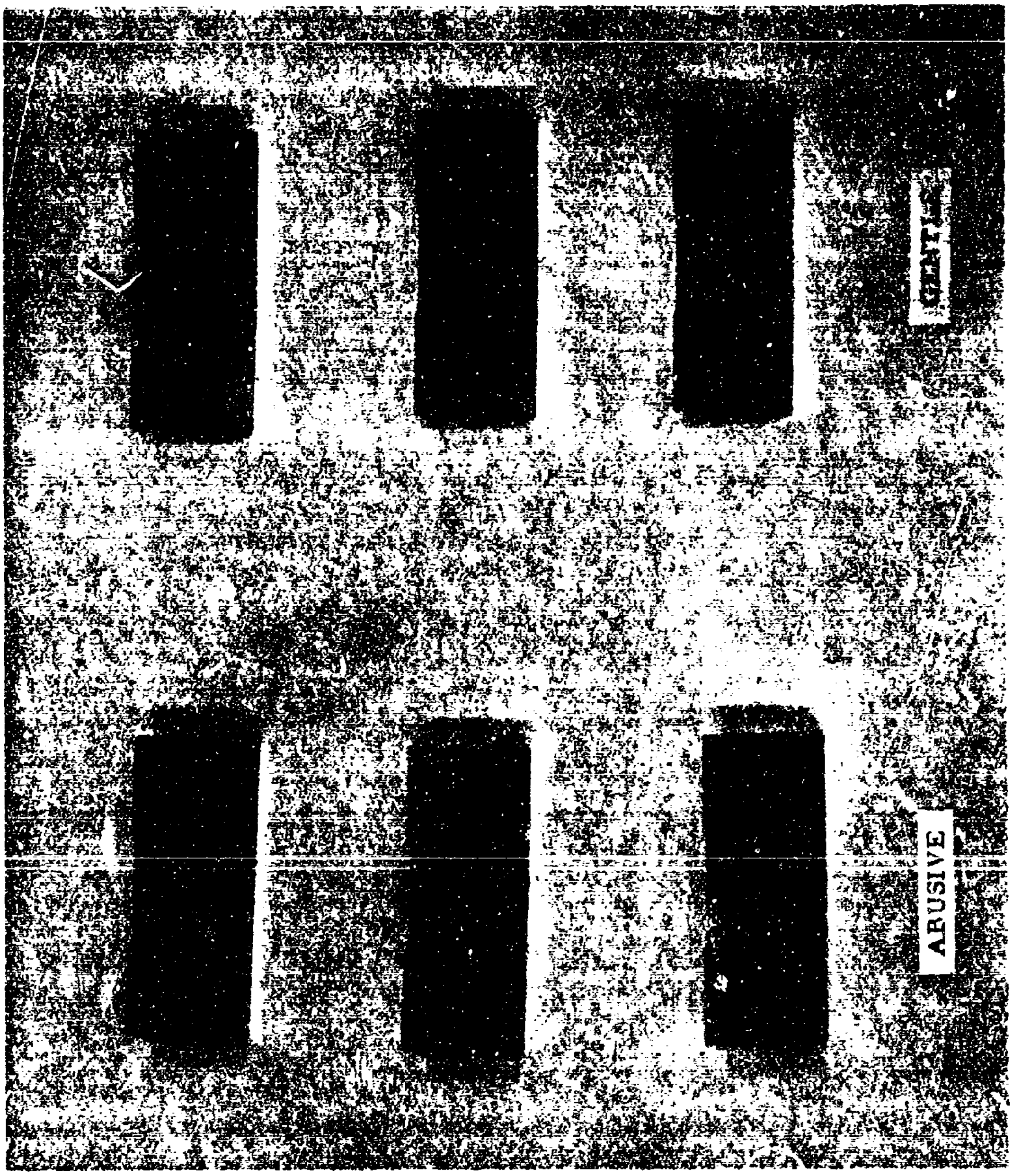
The chemical milling of 4340, Inconel 718, and Ti-6Al-4V were not as difficult as electropolishing, although the chemical milling operation required close control of both the solution composition and operating conditions. The surface finish of all three materials deteriorated rapidly in uncontrolled or badly contaminated solutions. The titanium chemical milling solution was particularly susceptible to some metallic contaminants. The chemical milling of samples was generally faster than electropolishing because of the faster metal removal rates. In all three metals, the chemical milling solutions remove material at approximately .75 mil/min. The chemical milling was done with the setup shown in Figure 185. The setup consists of the milling solution, a stirrer for agitation, and a hot plate for maintaining the correct temperature. The factors having the greatest influence on the chemical milled surface were solution composition and contamination. Figure 186 shows an example of abusive and gentle chemical milled 4340. Figures 187 and 188 are pictures of gentle and abusive chemical milled Ti-6Al-4V. The steps involved in the chemical milling of samples are as follows:

1. Wipe clean with acetone.
2. Mask with Turcoform Maskant #522.
3. Trim area to be milled.
4. Chemical mill.
5. Rinse and dry immediately.
6. Strip masking.



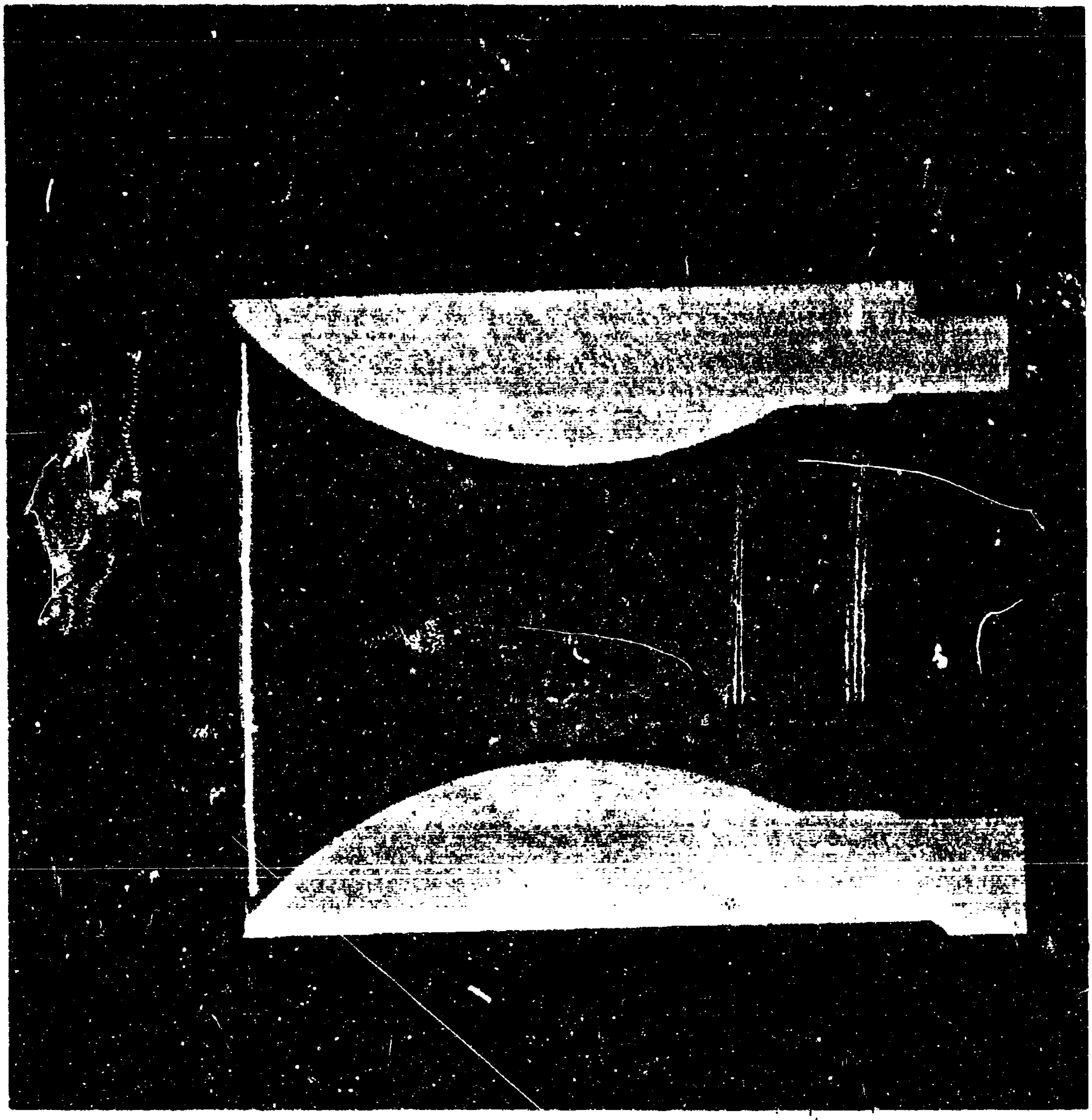
SETUP USED FOR CHEMICAL MACHINING OF COUPONS.

Figure 185



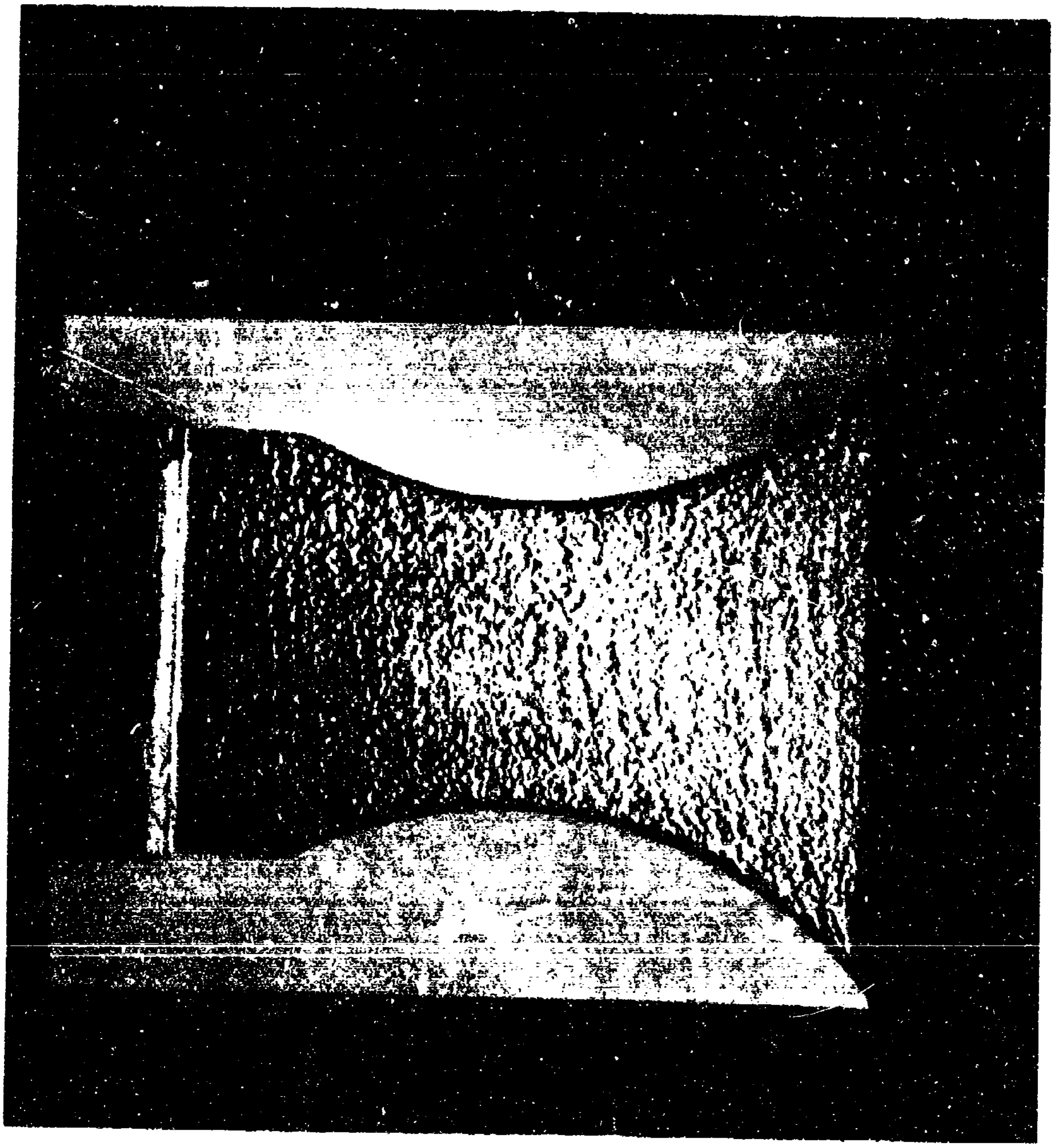
METALLOGRAPHIC COUPONS OF AISI 4340 WHICH HAVE BEEN PROCESSED BY CHM.

Figure 186



TITANIUM 6Al-4V - GENTLE CHM

Figure 187



TITANIUM 6Al-4V - ABUSIVE CHM

Figure 188

APPENDIX II

DETAILED PROCEDURES

II-1 Metallurgical Procedures

II-2 Procedures for Measurement of Residual Stress

II-3 Fatigue Testing Procedures

II-4 Statistical Analysis of Titanium Fatigue Data

II-5 Procedures for Stress Corrosion Evaluation

II-6 Fractographic Procedures

APPENDIX II-1

Metallurgical Procedures

Specimens used for metallographic studies were obtained from portions of fatigue or residual stress coupons or from specifically prepared metallographic coupons. All samples were sectioned by standard metallographic techniques using a silicon carbide cutoff disk flooded with a water-base coolant to prevent overheating. Samples were then ground back using an abrasive belt plus coolant. At this point, they were mounted using a special procedure which was developed in order to provide maximum edge retention during the metallographic polishing operation. An outline of this procedure is as follows:

- Cast samples in a 1-1/4 in. diameter mold with a mixture of an epoxy resin and a suitable hardener plus a fine grit pellitized aluminum oxide filler.

- Place mounts in a vacuum chamber during the initial setting period. (This step facilitates air removal, minimizes the possibility of voids between the metal sample and the mounting plastic, and also improves the adherence of the mounting compound to the surface of the sample.)

- Cure mounts at a temperature not exceeding 70°F for approximately 12 hours.

- Grind and polish specimens metallographically using an automatic mechanically driven polishing unit of the positive positioning type. Successively finer silicon carbide papers, to 600 grit, followed by diamond paste on suitable cloths are used to achieve the final metallographic polish.

After polishing, samples were etched using reagents suitable for the alloy involved. Etchants used for the current test materials were as follows:

Titanium 6Al-4V: HF, HNO_3, H_2O
AISI 4340: Nital, 2%
Inconel 718: Kalling's

In order to characterize surface hardness gradients, Knoop microhardness readings were taken using a Tukon machine. One hundred gram and five hundred gram load ranges were generally used at depths greater than .005 in. from the surface of the specimen. In order to obtain valid readings

Metallurgical Procedures (continued)

and to minimize the possibility of edge yielding under these loads, series of 10 and 25-gram Knoop readings were taken on most specimens in the first .002 to .005 in. from the surface.

Direct Rockwell readings were also taken on all samples to determine the base hardness.

All data presented in this report have been normalized and converted from Knoop values to Rockwell values using standard calibration and conversion procedures.

APPENDIX II-2

Procedures for Measurement of Residual Stress

A surface layer removal technique was used to determine the residual stress data presented in this report. The procedure using the specimen shown in Figure 3 of this report consists of successively etching off thin layers of the stressed surface of the specimen and determining the corresponding change in specimen curvature. The actual curvature measurement is made by measuring change in deflection over a fixed span of 3.5 in. The fixture used for making these measurements is shown in Figures 189 and 190.

Successive layer removal was accomplished on titanium and 4340 by etching, which consisted of total immersion of the samples for short intervals of time in an acid bath. The backs of the sample were "stopped-off" with a lacquer so that the etching action would be confined to the test surface only. Twenty percent HF was used on the titanium specimens; 10 to 15 percent HNO_3 was used on the 4340 specimens.

In working with the Inconel 718 specimens, an electrolytic swabbing method was used to remove controlled amounts from the test surface. The electrolyte consisted of 25 percent HCl. The setup for this electrolytic etching technique is shown in Figure 191.

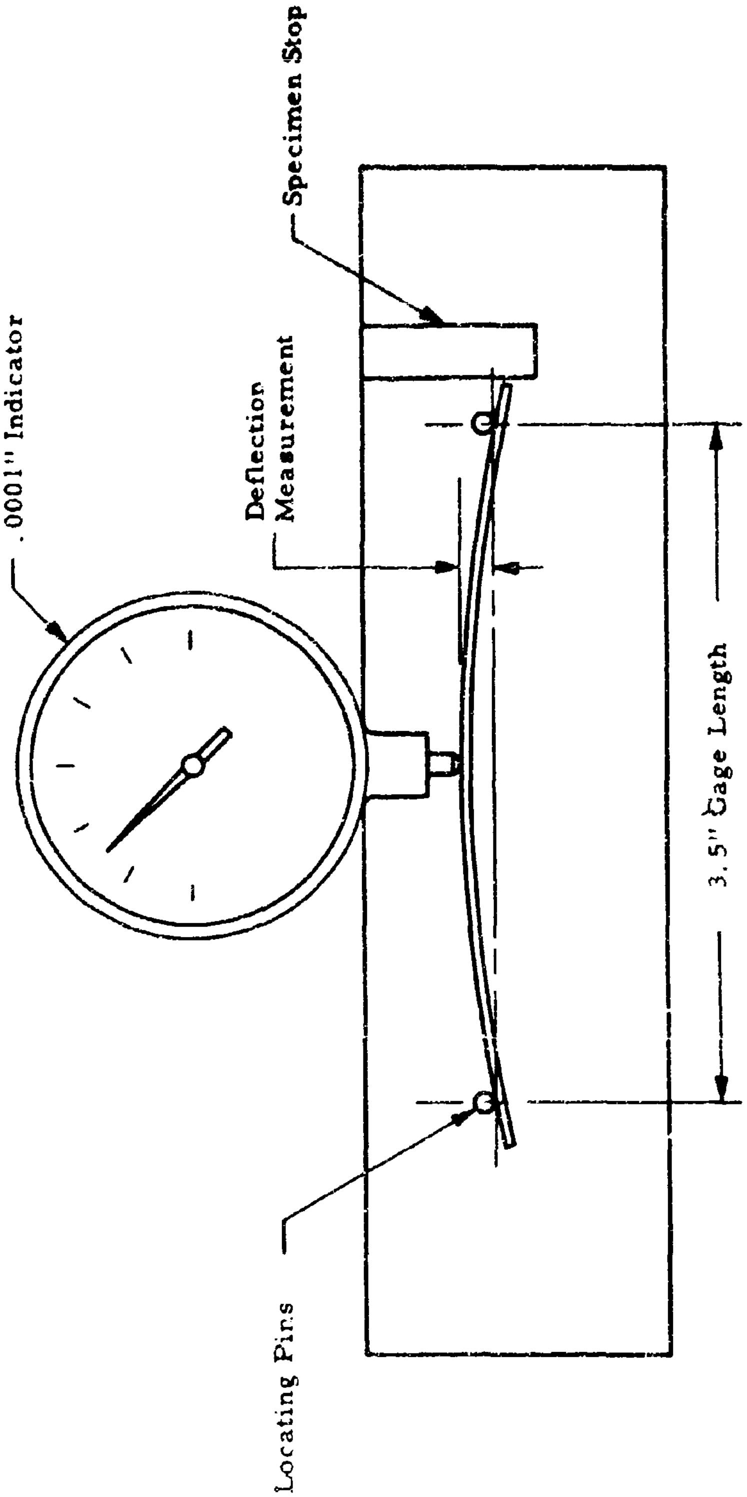
After each etching step, the thickness of the specimen was measured at 10 to 12 different stations to the closest .0001 in. with an indicating micrometer. Localized etching would be accomplished as necessary to achieve uniform layer removal. The thickness of stock removed versus the change in deflection data is then used to calculate the residual stresses at each measured step below the surface of the specimen. The uniaxial stress in the longitudinal direction of the test specimen was calculated using an equation developed by F. Stablein. *

$$S_n = \frac{E}{3\,L^2}\left[(H-h_n)^2\left(\frac{df}{dh}\right)_n - 4\,(H-h_n)\,(f_n) - 2\,(h_n f_o) - 2\int_o^h f\,dh\right]$$

* Stablein, F. - "Spannungsmessungen an einseitig abgeloschten Knuppeln" - Kruppsche Monatshefte, V 12 (1931) pp. 93-98.

Procedures for Measurement of Residual Stress (continued)

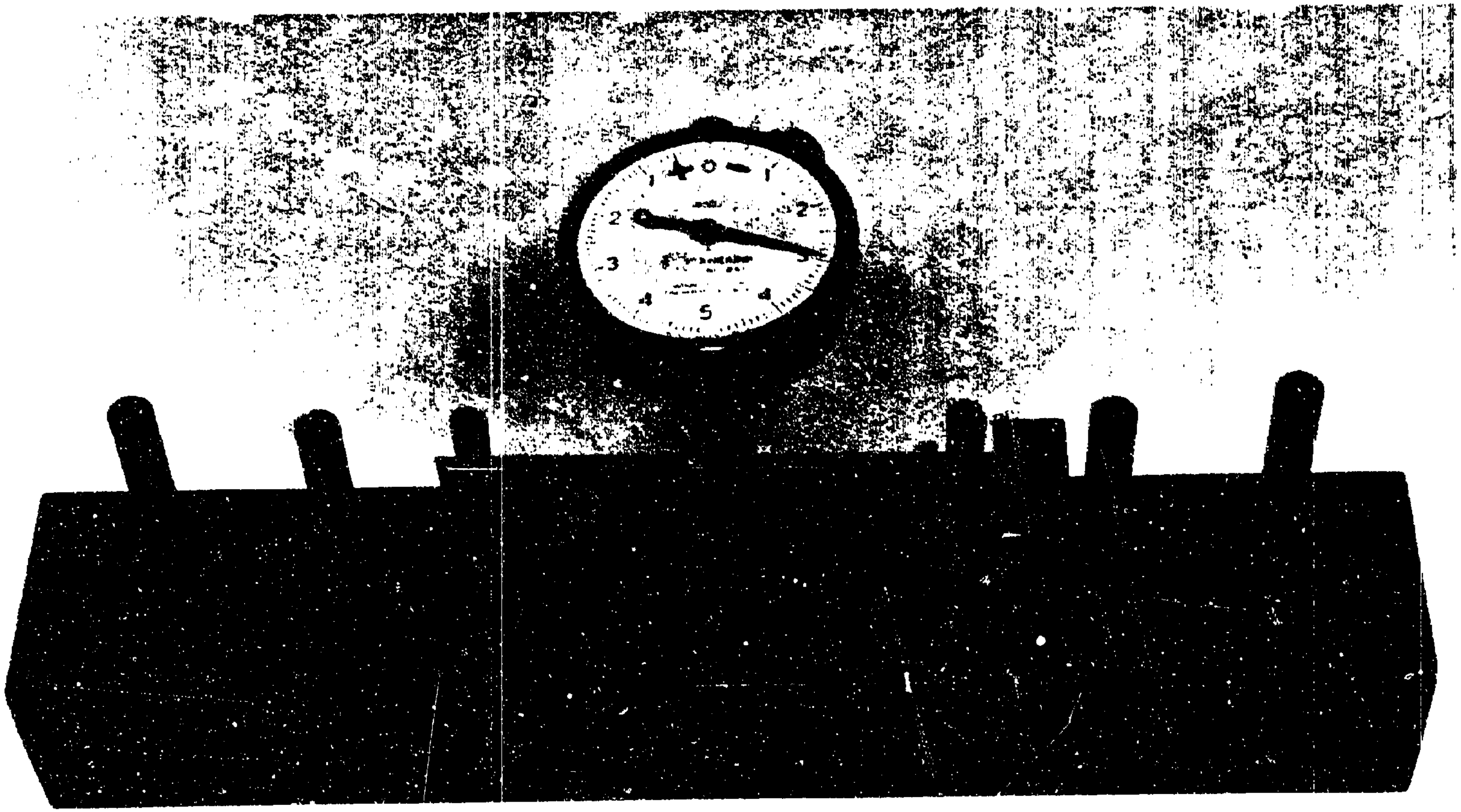
Where:	S_n	=	Residual stress, pounds/square inch
	H	=	Initial thickness of the test specimen, inches
	h	=	Stock removed to any depth, inches
	f	=	Deflection of specimen at any depth, inches
	f_o	=	Initial deflection of the test bar, inches
	L	=	One-half gage length, inches
	E	=	Modulus of elasticity, pounds/square inch
	$\frac{df}{dh}$	=	Slope at any point on deflection versus stock removed curve



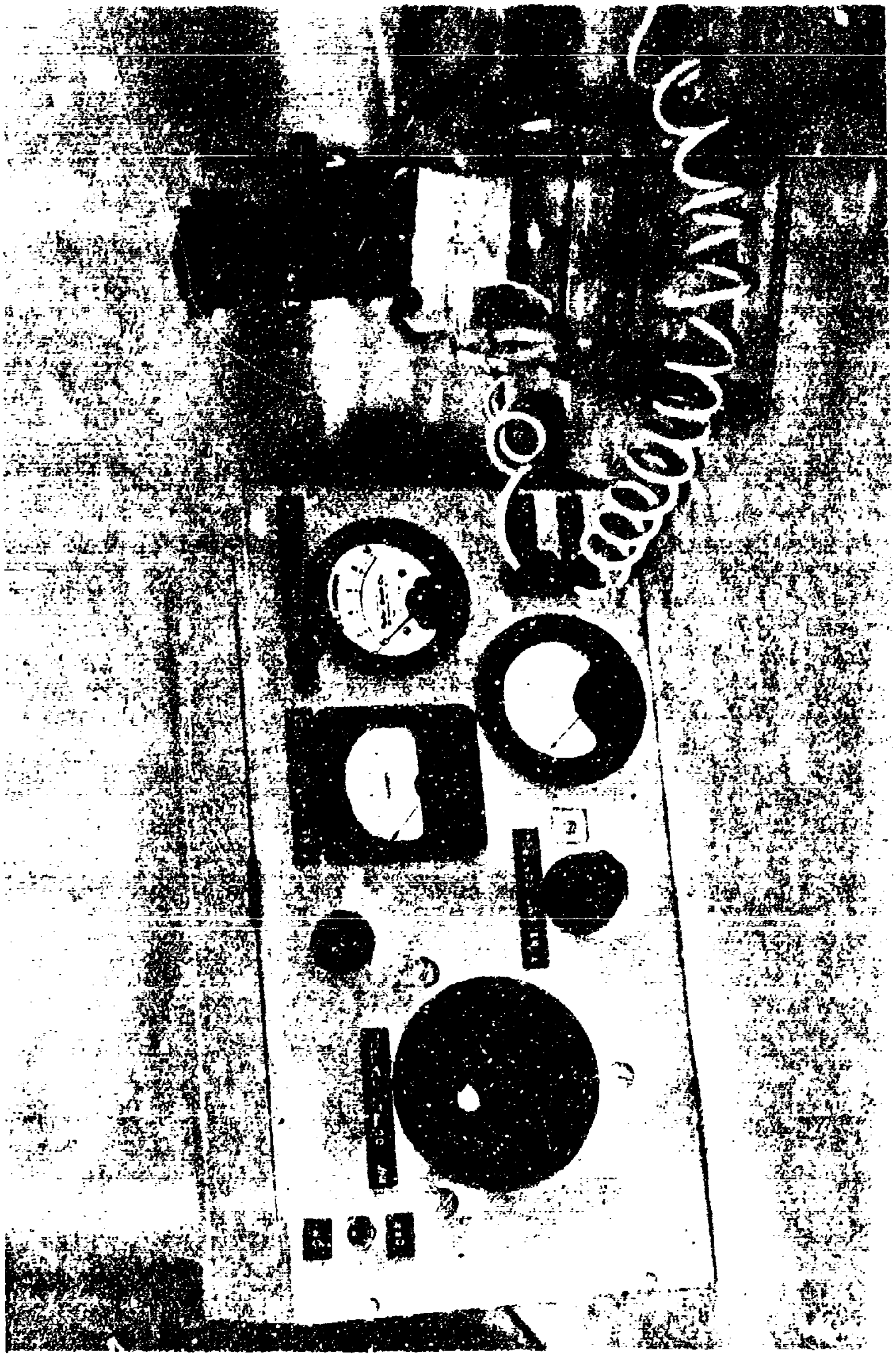
DEFLECTION MEASUREMENT FIXTURE

Figure 189

Figure 190



FIXTURE FOR MEASURING DEFLECTION OF RESIDUAL STRESS TEST SPECIMEN.



ELECTROLYTIC APPARATUS USED FOR DIFFERENTIAL ETCHING OF RESIDUAL STRESS SPECIMENS

Figure 191

APPENDIX II-3

Fatigue Testing Procedures

All fatigue tests summarized in this report were run on cantilever bending specimens at room temperature under fully reversed loading. All tests on titanium were run at Metcut using Sonntag SF-2-U fatigue machines. These units are mechanically excited, constant force machines. Load verification was obtained by standard calibration procedures involving the dynamic readout of instrumented specimens using a light beam oscillograph and cross calibration with specimen deflection measured optically. CHM and initial grinding tests on titanium were run with the type specimen illustrated in Figure 2. Cross-check specimens in gentle grinding plus all of the milling tests on titanium were run with the specimen shown in Figure 3.

All tests on Inconel 718 and 4340 were run by General Electric/Evendale using the type specimen shown in Figure 2. G.E. used a modified Krouse type cantilever bending fatigue machine. The modification consisted of a change in the mechanical coupling to convert this unit from a constant displacement to a constant force machine. In setting up each individual test, the specimen was loaded statically with a load calculated to produce the desired stress in the test section of the specimen. The corresponding static deflection was noted. When the test machine was started dynamically, the dynamic deflection was adjusted so that the half amplitude was equal to the static measurement. Specimen life is monitored with an automatic cycle counter.

In reporting test results, runout stresses are the initially calculated values of the maximum stress in the test section of the specimen. Failure stresses are back calculated and indicate the actual stress at the origin of failure, which may be less than the maximum stress in the specimen.

APPENDIX II-4

Statistical Analysis of Titanium Fatigue Data

A statistically designed experiment was set up for Ti-6Al-4V to evaluate the effect of a wide variety of milling variables on the fatigue strength of the material. Variables examined in this phase of the program included the type of milling, speed, feed, cutting fluid, nominal wearland, and depth of finished cut. An array of 20 combinations of these variables was run, testing ten specimens per set of variables.

After the test data were available, a multiple regression analysis using G.E.'s MULREG computer program was used to develop a mathematical expression for the test data. The purpose of this expression was to define the effects of the variables and the interactions of these variables over the range studied.

The first step in the analysis was to determine the average runout or failure stress. This stress is where 50 percent of the specimens run out past 10^7 cycles or fail before 10^7 cycles. A modified staircase analysis was used to make these determinations. The modification was made to allow analysis of both failure and runout data. Analysis of both types is more efficient and eliminates a possible bias introduced by the selection of runouts or failures for analysis. If runouts are chosen for analysis, the average stress is lower than when failures are considered.

The analysis technique consists of obtaining two failure percentages at each level of stress. The first percentage is directly computed from the failures, while the second percentage is 100 minus the runout percentage. Formulas 1 and 2 are used for calculating the failure percentage and runout percentage, respectively.

$$(1) \quad \%\ \text{Failure} = \frac{Nf}{Nf + Nr + 1} \times 100$$

$$(2) \quad \%\ \text{Runout} = \frac{Nr}{Nf + Nr + 1} \times 100$$

where: Nf = number of failures at given stress or lower

Nr = number of runouts at given stress or higher

Statistical Analysis of Titanium Fatigue Data (continued)

The average failure percentage is then plotted on normal probability paper versus the stress level. The aberage runout/failure stress and the average minus standard deviation is read from the chart. An example calculation is shown for milling condition #1 below and in Figure 192.

Stress (ksi)	No. of Failures	No. of Runouts	(Nf) Cum. Failure	(Nr) Cum. Runout	% Failure	% Runout	% 1-Runout	Avg. %
78.7	1		6		85.6	0	100.0	92.8
75.2	1		5		83.4	0	100.0	91.7
70.6	1		4		80.0	0	100.0	90.0
67.5	1	2	3	2	50.0	33.3	66.7	58.3
65.0		2	2	4	37.6	50.0	50.0	43.8
64.0	1		2	4	28.6	37.2	42.8	35.7
62.5		1	1	5	14.3	71.5	28.5	21.4
61.5	1		1	5	14.3	71.5	28.5	21.4
Total	6	5						

From the probability plot (Figure 192), the average stress for runout is 65.5 ksi. The average minus 1 standard deviation is then 61.5. One standard deviation is the difference, or 4 ksi.

Table XVIII shows the values determined for each of the combinations of milling parameters. The average value of the standard deviation is 3.1. This is approximately 5 percent of the average stress, a typical value of standard deviation. The average runout stress was next listed with the combination of milling conditions as shown in Table XIX.

These average strengths and a normalized set of experimental milling conditions were next run in multiple regression. The first variable checked was the type of milling. The average fatigue strength of the end milled material was found to be 70.94, while the average of the peripheral milled material is 55.44. The difference of 15.5 ksi when checked by the t-test is highly significant. Subsequent evaluations were therefore run separately on the peripheral and end milling.

The end milled results varied considerably less than the peripheral milled results. Results on end milling varied from 63.2 to 79.3 ksi, while the peripheral milled results went from 35.4 to 72.5 ksi. It was not surprising,

Statistical Analysis of Titanium Fatigue Data (continued)

therefore, that little significance could be found from the variables in end milling. Only the wearland was significant. The average effect of changing wearland from .003 in. to .020 in. is to move the fatigue strength from 67.9 ksi to 73.9 ksi. Figure 193 shows a plot of the data points.

In peripheral milling, wearland again effected the biggest change in fatigue strength. Increasing wearland decreased the strength instead of increasing the strength as it did on end milling. Figure 194 shows this wearland effect. The plots in Figure 194 also illustrate the effects of the other variables. Note that two lines had to be plotted -- one for each level of wearland. Next to wearland, the cutting fluid was most significant. Figure 195 plots four lines versus speed and feed -- one for each combination of wearland and cutting fluid. The only variable which did not affect the fatigue strength in peripheral milling was found to be depth of the finish cuts. When all of the variables, except depth of finish cut, were considered, the prediction equation yielded very accurate predictions of fatigue strength. Figure 196 shows predicted and actual values for the regression equation. Equation 3 is the regression equation.

$$\text{(3)} \quad F.S. = 82.32 - 6.7055S - 4.81F + .56\,C.F. - 4.09W$$

Where: F.S. = Completely reversed bending fatigue strength at room temperature

S = Speed; 1 = 100 rpm, 1.5 = 150 rpm

F = Feed; 1 = .004 in., 2 = .008 in.

C.F. = Cutting Fluid; 0 = none, 1 = Hocut

W = Wearland; 1 = .003 in., 6 = .018 in.

(The numbers represent the normalized variables. By using numbers like 1 and 1.5 to represent 100 and 150 rpm, the possibility of round-off error is eliminated.)

Substituting the values of these variables into this multiple regression equation gives the following individual effects for changing from the conditions of level 1 to level 2.

Statistical Analysis of Titanium Fatigue Data (continued)

Variable	Level 1	Level 2	Fatigue Strength
Wearland	.003 in.	.018 in.	-20.4 ksi
Cutting Fluid	None	Hocut	+8.56 ksi
Feed	.004 in.	.008 in.	-4.81 ksi
Speed	100 rpm	150 rpm	-4.35 ksi

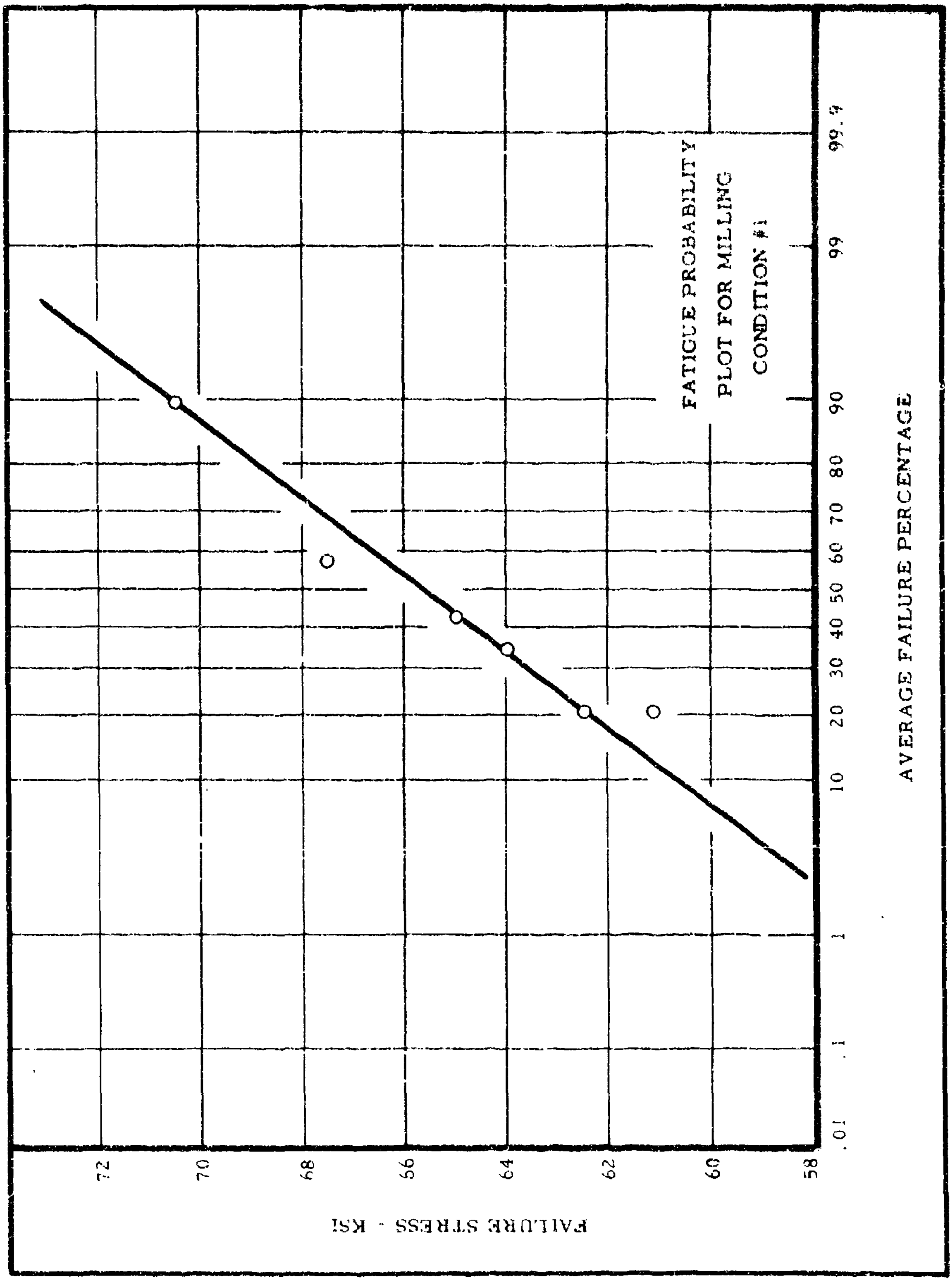

FATIGUE PROBABILITY
PLOT FOR MILLING
CONDITION #1
AVERAGE FAILURE PERCENTAGE
.01
.1
1
10
20
30
40
50
60
70
80
90
99
99.9
FAILURE STRESS - KSI
72
70
68
56
64
62
60
58

Figure 192

References for 4. Recommendations: Guidelines for Material Removal and Post Processing

1. Kahles, John F.; Bellows, Guy; Field, Michael, 1969. Surface Integrity Guidelines for Machining. Paper No. MR69-730. Dearborn, Michigan: American Society of Tool and Manufacturing Engineers.

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4. Field, Michael; Mehl, Clarence L.; Kahles, John F., August 1968. 1968 Supplement to Machining Data for Numerical Control. AFMDC 68-2. Cincinnati, Ohio: Air Force Machinability Data Center.

5. Zlatin, Norman; Field, Michael; Gould, John V., July 1963. Final Report on Machining of Refractory Materials. ASD-TDR-63-581. Cincinnati, Ohio: Metcut Research Associates Inc.

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8. Zlatin, Norman et al, May 1969. Machinability Parameters on New and Selective Aerospace Materials. AFML-TR-69-144. Cincinnati, Ohio: Metcut Research Associates Inc.

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2b. GROUP

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SURFACE INTEGRITY OF MACHINED STRUCTURAL COMPONENTS

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11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

Air Force Materials Laboratory
Research and Technology Division
Wright-Patterson AFB, Ohio 45433

13. ABSTRACT

A program has been run to evaluate the effects of different metal removal methods and variations of these methods on surface integrity. Three alloys were studied: beta rolled Ti-6Al-4V; AISI 4340, quenched and tempered, 50 R_c; and Inconel 718, solution treated and aged.

Various grinding procedures caused the titanium alloy to exhibit a fatigue strength range of 13 to 62 ksi. The fatigue strength of 4340 due to grinding variables ranged from 62 to 102 ksi, while Inconel 718 showed a range of 24 to 60 ksi. Abusive grinding conditions always resulted in fatigue strengths at the minimum of these ranges.

Milling variables exhibited a fatigue strength range of 32 to 72 ksi in the beta rolled titanium alloy. EDM and ECM on Inconel 718 yielded 22 and 39 ksi, respectively, compared to 60 ksi for gentle grinding.

Guidelines for processing aerospace hardware considering surface integrity requirements are presented in the report.

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Unclassified

Security Classification

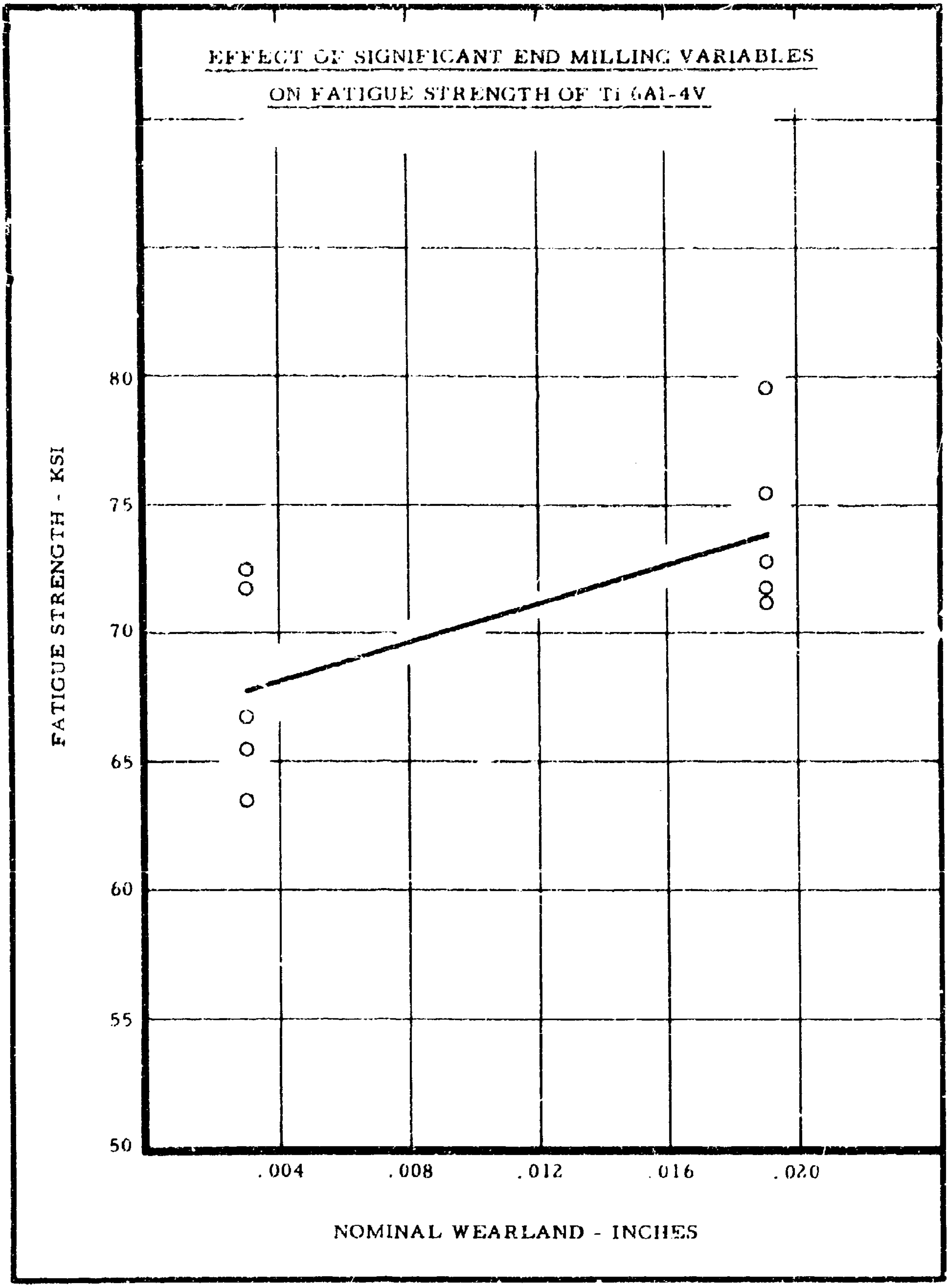
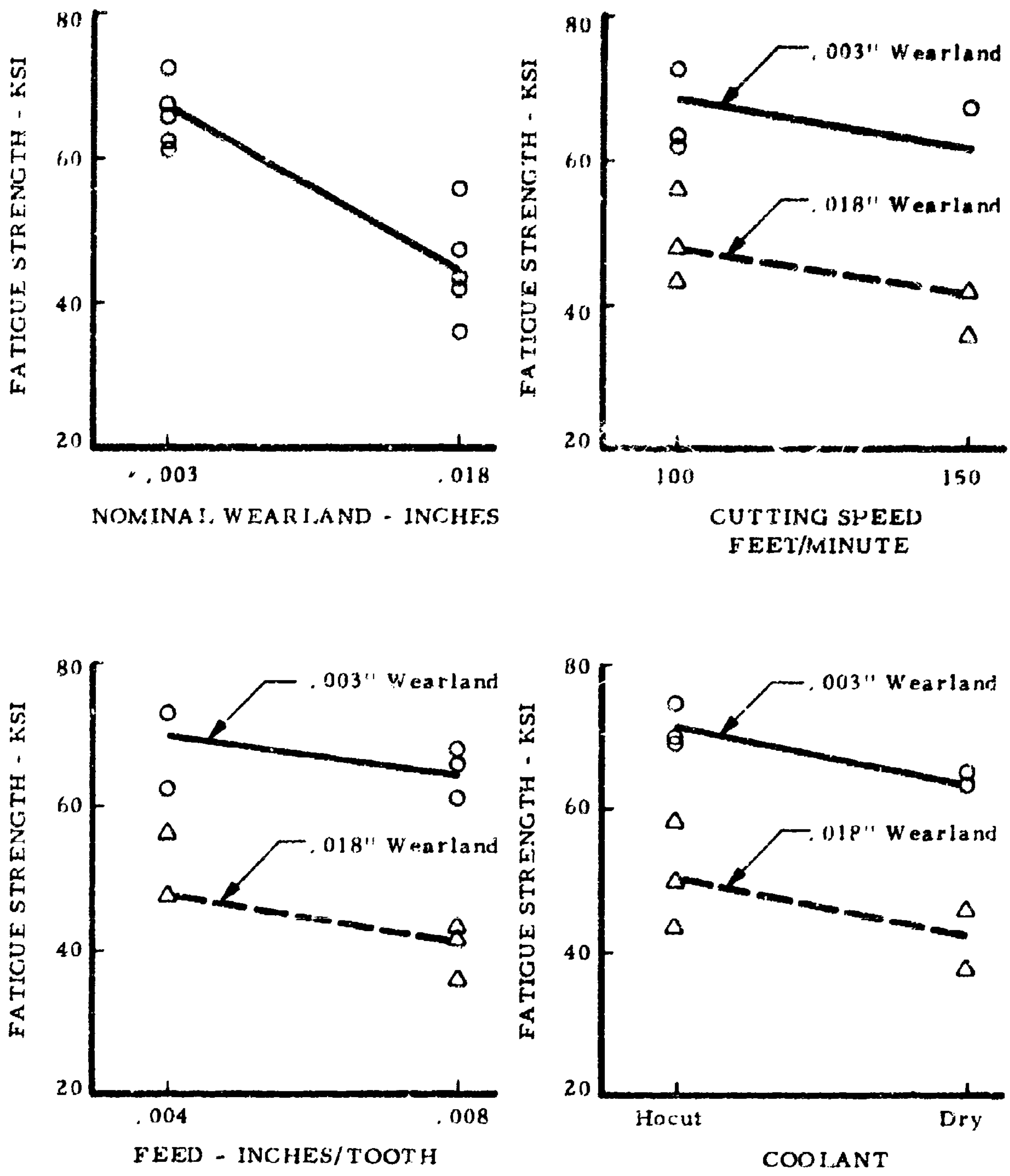
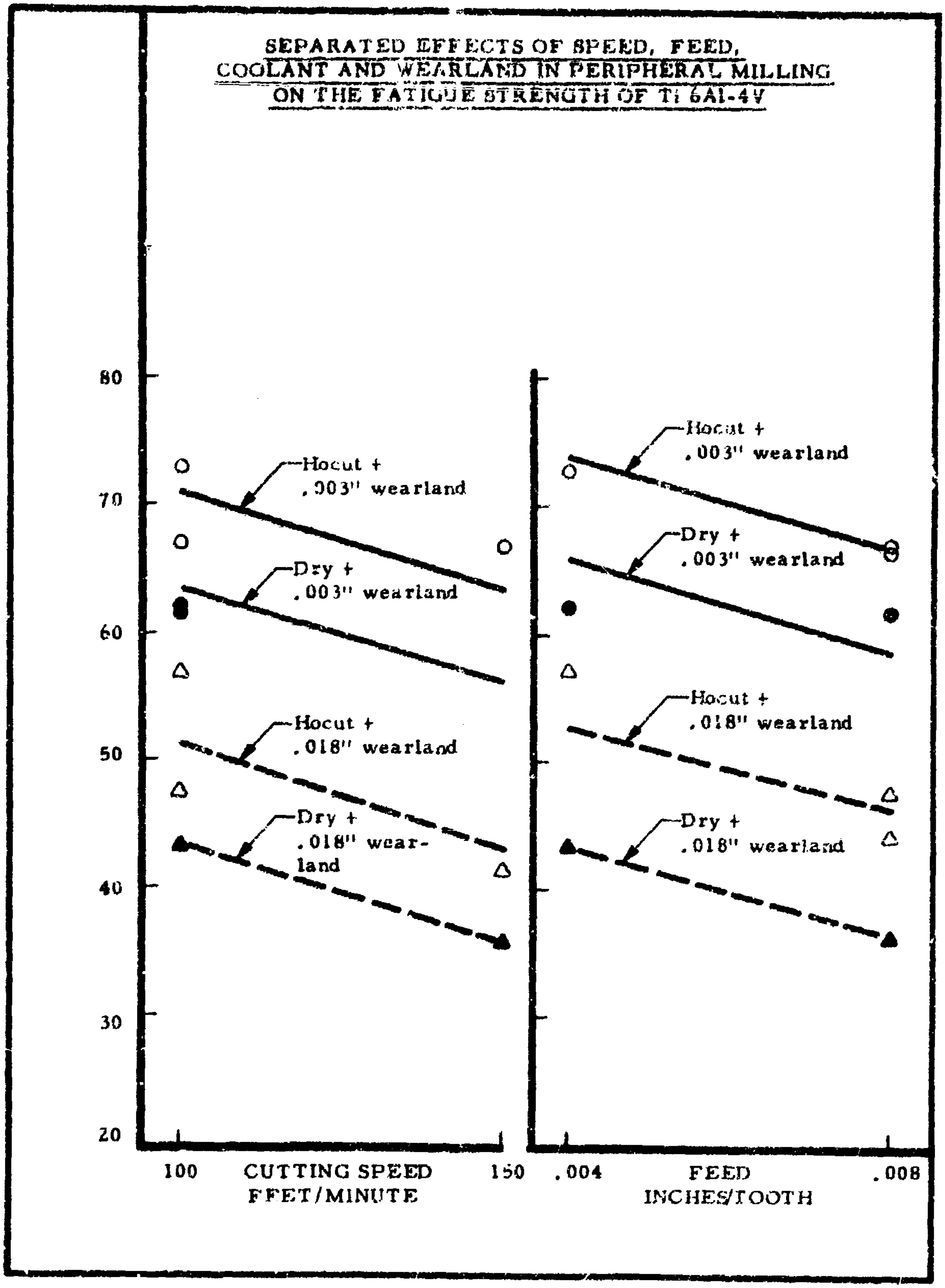

EFFECT OF SIGNIFICANT END MILLING VARIABLES
ON FATIGUE STRENGTH OF Ti 6Al-4V
FATIGUE STRENGTH - KSI
80
75
70
65
60
55
50
.004
.008
.012
.016
.020
NOMINAL WEARLAND - INCHES

Figure 193



EFFECT OF SIGNIFICANT PERIPHERAL MILLING VARIABLES ON FATIGUE STRENGTH OF Ti 6Al-4V

Figure 194



SEPARATED EFFECTS OF SPEED, FEED, COOLANT AND WEARLAND IN PERIPHERAL MILLING ON THE FATIGUE STRENGTH OF Ti 6Al-4V
80
70
60
50
40
30
20
Hocut + .003" wearland
Dry + .003" wearland
Hocut + .018" wearland
Dry + .018" wear-land
Hocut + .003" wearland
Dry + .003" wearland
Hocut + .018" wearland
Dry + .018" wearland
100
CUTTING SPEED FEET/MINUTE
150
.004
FEED INCHES/TOOTH
.008

Figure 195

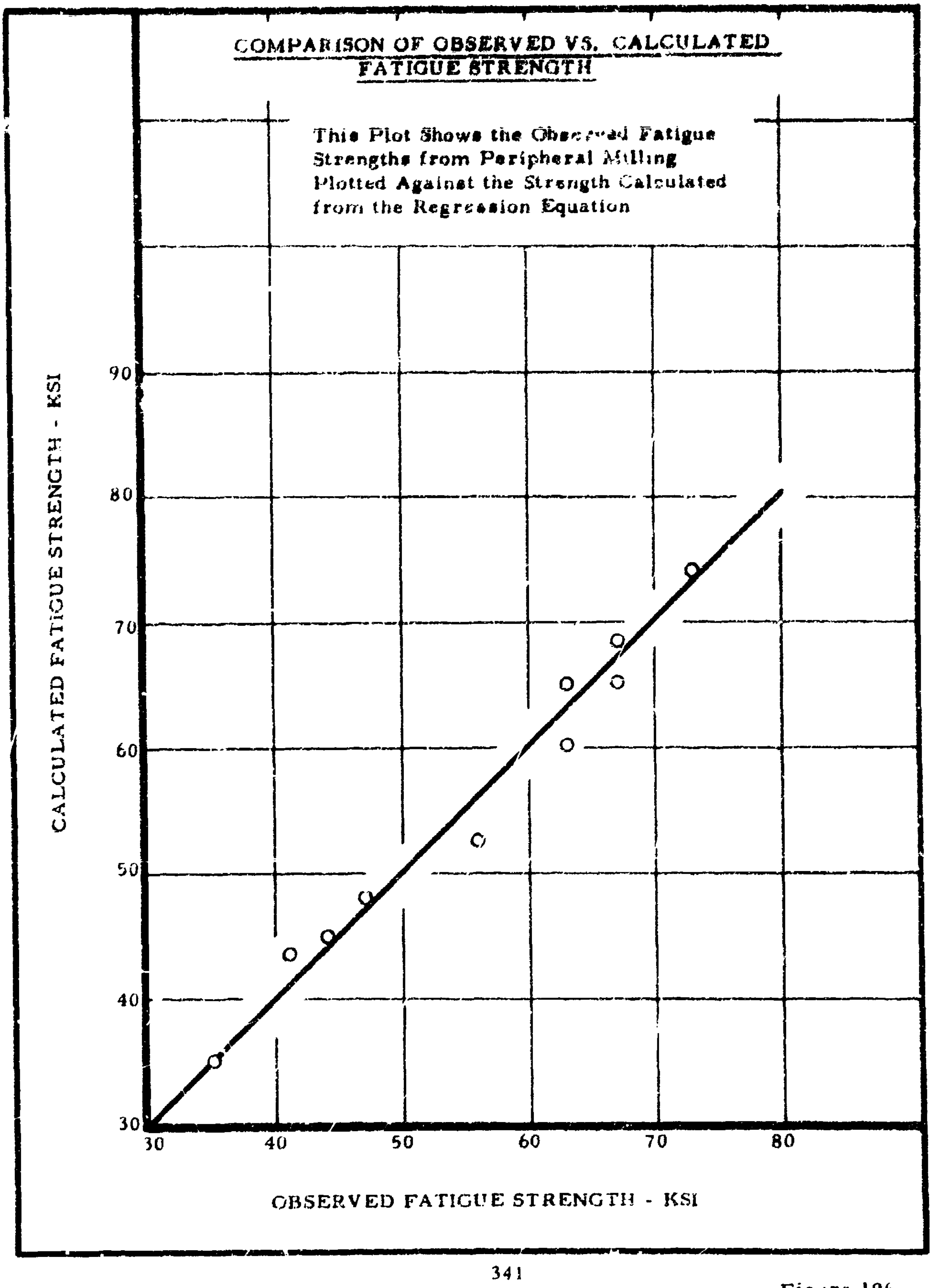

COMPARISON OF OBSERVED VS. CALCULATED FATIGUE STRENGTH
This Plot Shows the Observed Fatigue Strengths from Peripheral Milling Plotted Against the Strength Calculated from the Regression Equation
CALCULATED FATIGUE STRENGTH - KSI
90
80
70
60
50
40
30
30
40
50
60
70
80
OBSERVED FATIGUE STRENGTH - KSI

Figure 196

TABLE XVIII

PROBABILITY PLOT SUMMARY

Group No.	Avg. ($\bar{X}$)	σ	$\bar{X} - \sigma$
	Stress for Runout - Ksi		
#1	65.5	4.0	61.5
#2	71.5	2.7	68.8
#3	72.7	2.3	70.4
#4	72.3	1.9	70.4
#5	66.8	3.6	63.2
#6	71.0	4.7	66.3
#7	71.8	2.9	68.9
#8	75.3	2.1	73.2
#9	63.2	2.0	61.2
#10	56.4	2.8	53.6
#11	62.2	3.8	53.4
#12	44.0	3.9	40.1
#13	67.0	4.6	62.4
#14	62.4	3.0	59.4
#15	47.0	5.0	42.0
#16	35.4	0.6	34.8
#17	66.4	3.4	63.0
#18	41.1	3.1	38.0
X1	79.3	3.8	75.5
X2	72.5	2.2	70.3

TABLE XIX

MILLING CONDITIONS USED FOR MAKING TEST CUTS ON Ti-6Al-4V SPECIMENS AND RESULTS

Cond. No.	Type* Cut	Cutting Speed (ft./min.)	Feed (in./tooth)	Cutting Fluid	Tool Wearland (in.)	Depth of Finish Cut (in.)	Fatigue Strength (ksi)
1	End	100	.004	Hocut	.003 max.	.030	65.5
2	End	100	.004	Dry	.018-.020	.005	71.5
3	End	100	.004	Hocut	.018-.020	.005	72.7
4	End	100	.008	Dry	.003 max.	.030	72.3
5	End	100	.008	Hocut	.003 max.	.005	66.8
6	End	100	.008	Dry	.018-.020	.030	71.0
7	End	150	.008	Dry	.003 max.	.005	71.8
8	End	150	.008	Hocut	.018-.020	.030	75.3
9	End	150	.008	Dry	.018-.020	.005	63.2
10	Peripheral	100	.004	Hocut	.018-.020	.030	56.4
11	Peripheral	100	.004	Dry	.003 max.	.005	62.2
12	Peripheral	100	.004	Dry	.018-.020	.030	44.0
13	Peripheral	100	.003	Hocut	.003 max.	.005	67.0
14	Peripheral	100	.008	Dry	.003 max.	.030	62.4
15	Peripheral	100	.008	Hocut	.018-.020	.005	47.0
16	Peripheral	150	.008	Dry	.018-.020	.030	35.4
17	Peripheral	150	.008	Hocut	.003 max.	.005	66.4
18	Peripheral	150	.008	Hocut	.018-.020	.030	41.1
X1	End	100	.004	Hocut	.018-.020	.030	79.3
X2	Peripheral	100	.004	Hocut	.003 max.	.030	72.5

Radial Rake: (all conditions) 0°

Axial Rake: End Milling, +5°
Peripheral Milling, +15°

* Milling Technique:

End Milling - End Cutting: Mill on center
End Milling - Peripheral Cutting: Climb mill

APPENDIX II-5

Procedure for Stress Corrosion Evaluation

Ti-6Al-4V

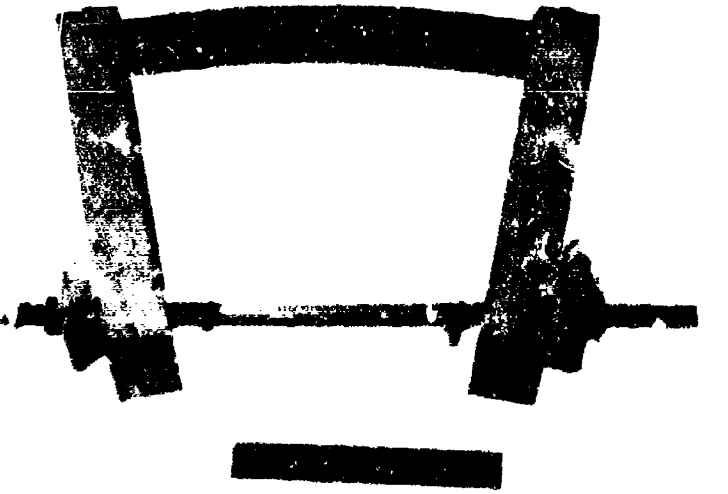
Specimens per Figure 4 were cleaned with acetone, rinsed with alcohol, washed in a water-detergent solution, rinsed in water and then in alcohol. Following this, the titanium specimens were immersed in a saturated sodium chloride solution and then dried with forced warm air. This process was repeated usually two or three times until a visible coating of salt adhered to the gage section of the specimen.

Salt coated specimens were then exposed in stress rupture frames at 800°F/40 ksi for a period of 100 hours. This particular set of test conditions had previously been developed in titanium evaluation work at General Electric/Evendale as being suitable for evaluating the stress corrosion sensitivity of Ti-6Al-4V. In this test, susceptibility to stress corrosion is judged by loss of tensile ductility (elongation) exhibited by room temperature testing after salt exposure. Tensile tests on coupons without having been exposed to salt and also those which had the stress salt exposure were run in conventional hydraulic tensile testing equipment.

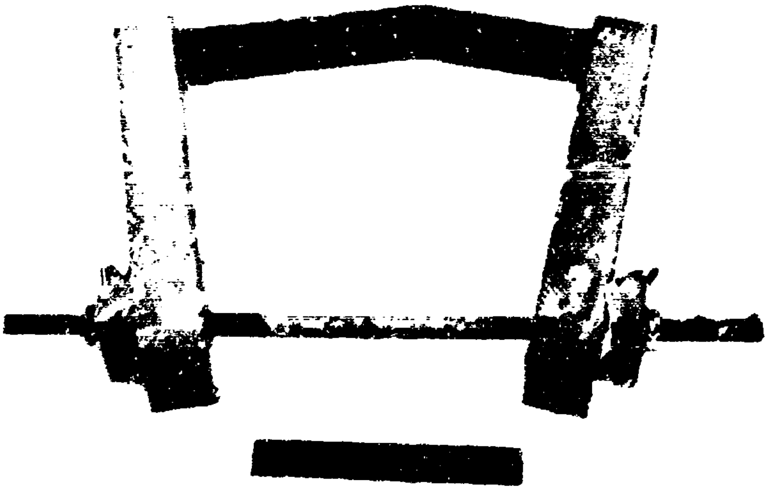
AISI 4340

Specimens per Figure 5 were clamped into fixtures which prestrained them in bending as shown in Figure 197. Specimens were stressed to 165 ksi which was approximately 75% of the yield strength of the material. They were exposed until failure or an elapsed time of 1000 hours, whichever occurred first. The exposure environment consisted of 3.5% sodium chloride solution at room temperature meeting the purity and pH requirements of Method 811 of Federal Test Method Standard 151. Alternate immersion between the salt solution and air was accomplished on a continuous exposure cycle of 10 minutes immersion in the solution and 50 minutes out of the solution. Samples were examined approximately once each day and failure times noted. A photograph of a typical failed specimen is also included in Figure 197.

All stress corrosion testing on 4340 was accomplished at Boeing/Seattle.



BEFORE FAILURE



AFTER FAILURE

PHOTOGRAPHS OF 4340 TEST SPECIMENS MOUNTED
IN STRESS CORROSION FIXTURING

APPENDIX II-6

Fractographic Procedures

Fractographic analysis consisted of first examining the fractured surface by electron microscopy at high magnifications in order to determine the precise location of the failure nucleus. Once this had been pinpointed, samples were sectioned and mounted for optical metallographic examination to determine the microstructural condition at the origin of the failure.

Investigations using the electron microscope were carried out by General Electric/Evendale using the following steps.

1. Determine the approximate location of the origin with a stereo microscope at 60X magnification.

2. Clean the fracture surface with acetate tape by repeated stripping (three to six times).

3. Replicate the surface with 10 mil nitrocellulose tape softened in amyl acetate; let dry for four hours, then peel from the surface.

4. Vapor deposit in vacuum a 400A film of germanium on the plastic replica at an angle of 25 to 45 degrees to the horizontal.

5. Vapor deposit in vacuum a 800A carbon film on top of the germanium shadowed plastic replica.

6. Trim the composite replica, place on a small copper screen.

7. Dissolve the plastic from the carbon replica in 1-1/2 hours using three baths of amyl acetate.

8. Examine the carbon replica in a Philips Model 100B electron microscope at 6000X.

A crack propagating through the material under cyclic application of stress progresses by advancing a small increment with each cycle of stress. This incremental crack growth results in striations that correlate with the number of cycles and the direction of crack progression. Since a fatigue crack usually grows from its origin leaving striations that resemble the

Fractographic Procedures (continued)

wave pattern generated by a splash of a stone in calm water. It is possible to study and map these striations and locate the failure origin. The failure origin itself is usually free of striations, although it may contain a microstructural discontinuity such as an inclusion which would contribute to the origin of failure.

Once fractrographic maps of various specimens were studied and probable fatigue origins pinpointed, these samples were then sectioned metallographically by Metcut using the standard techniques outlined in Appendix II-1. A summary of the findings on sections examined, both with respect to fatigue nucleus location and microstructure condition at that location, are included in Section 6.4.5.

References for 4. Recommendations: Guidelines for Material Removal and Post Processing

1. Kahles, John F.; Bellows, Guy; Field, Michael, 1969. Surface Integrity Guidelines for Machining. Paper No. MR69-730. Dearborn, Michigan: American Society of Tool and Manufacturing Engineers.

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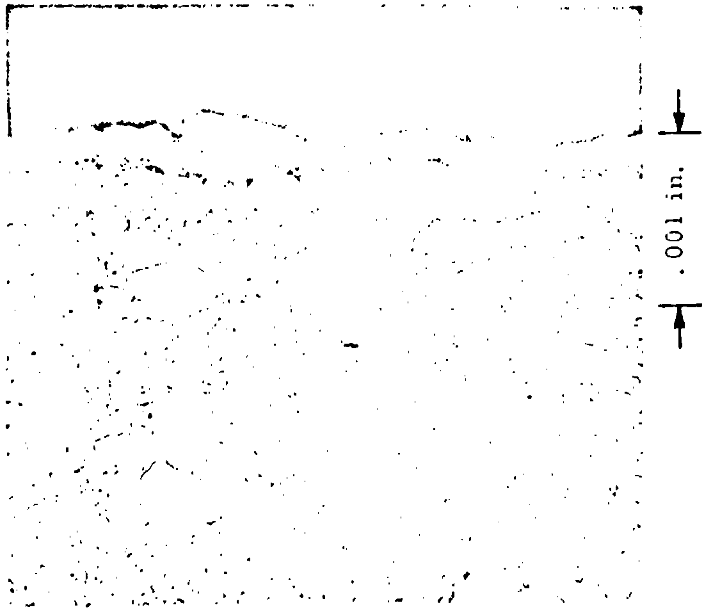
14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Surface integrity						
Surface damage						
Surface alterations						
Machining						
Grinding						
Nonconventional machining						
ECM						
EDM						
Fatigue						
Residual Stress						
CHM						
ELP						
Ti-6Al-4V						
4340 - 50 R_c						
Inconel 718						

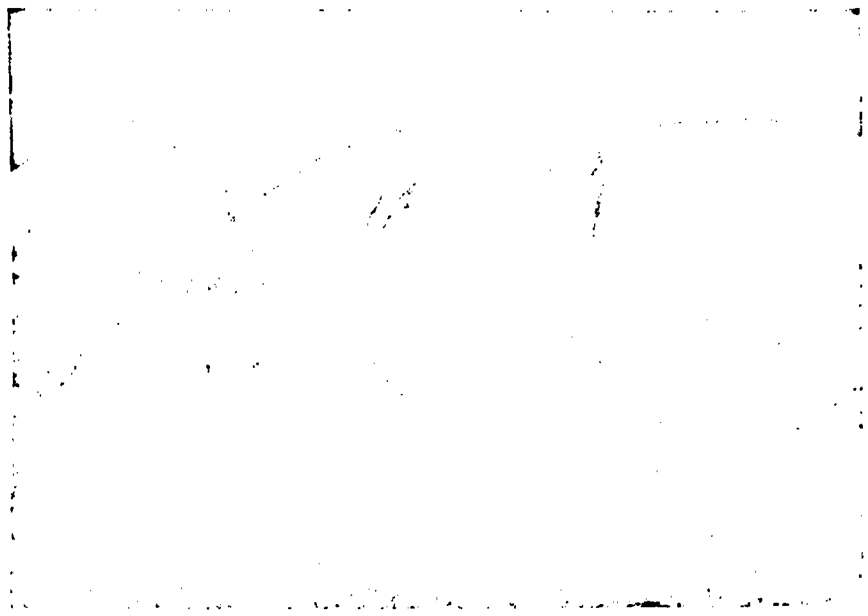
SUPPLEMENTARY

INFORMATION

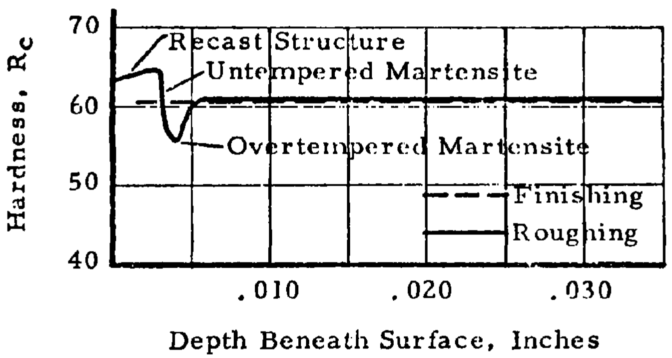
AD-870146



(a) **Finishing Conditions** - A thin discontinuous recast layer .0001-.0002" deep was produced on the surface.
1000X

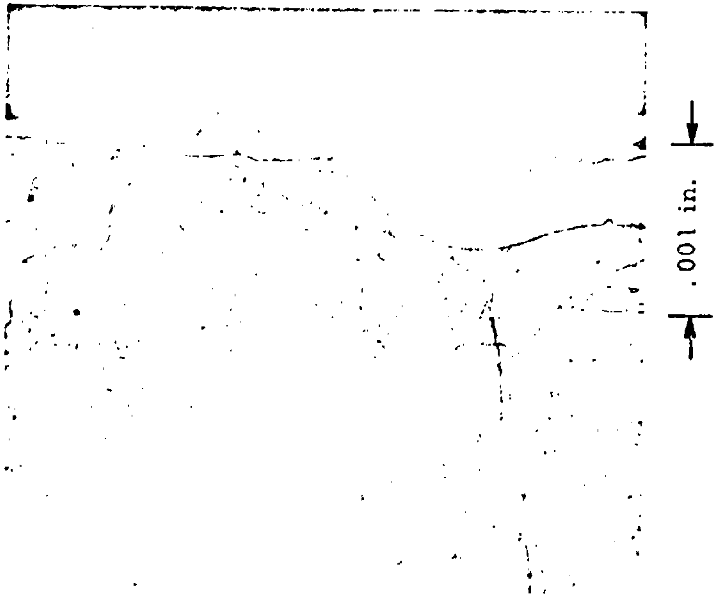


(b) Roughing Conditions - A band of cracked recast metal and underlying layers of untempered and overtempered martensite were formed. The total heat affected depth was approximately .005".
1000X

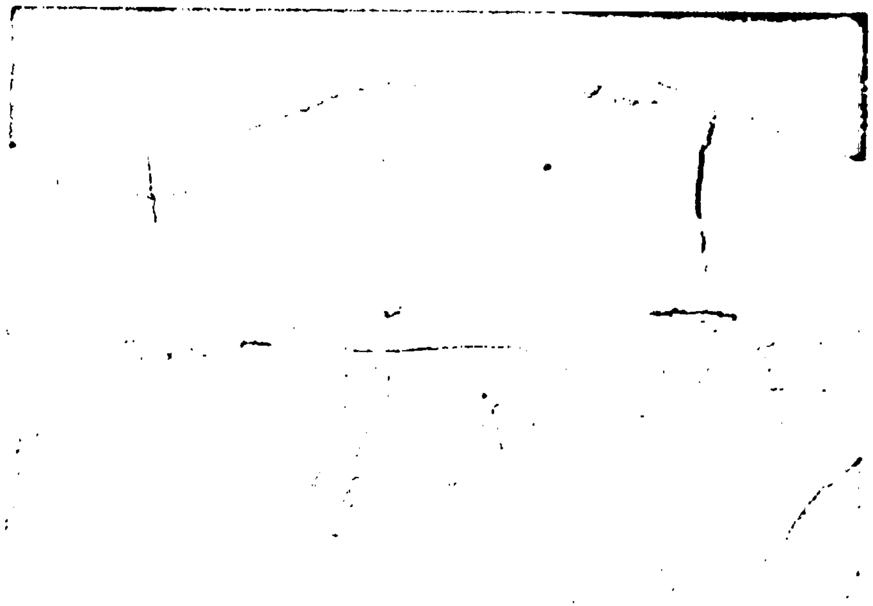


SURFACE CHARACTERISTICS OF
TYPE D2 TOOL STEEL (Quenched and Tempered, 61 R_c)
PRODUCED BY EDM

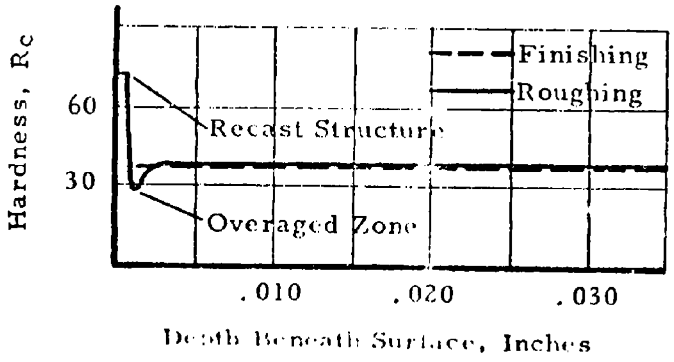
Figure 98



(a) Finishing Conditions - A spotty recast layer with deposits up to .0002" thick may be seen, but without evidence of other structural changes. 1000X

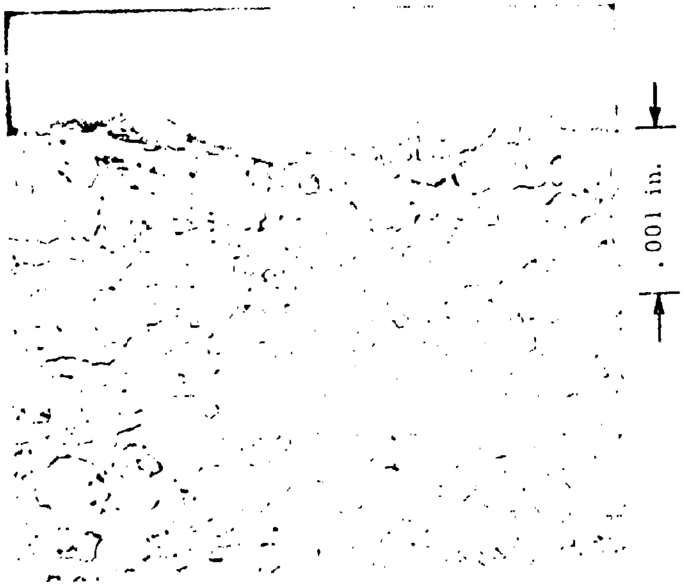


(b) Roughing Conditions - A continuous recast layer up to .002" deep and extensively cracked was deposited on the surface. A softened or overaged zone was noted beneath the surface for a total affected depth of .003". 1000X



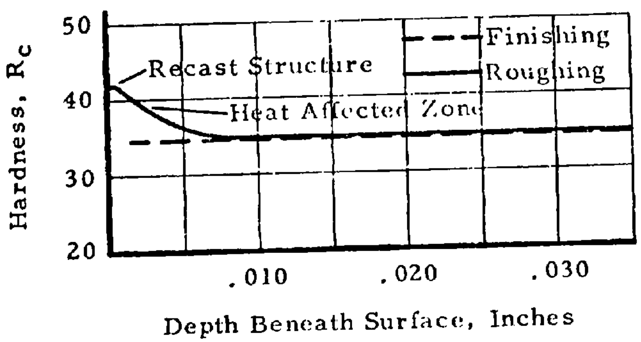
SURFACE CHARACTERISTICS OF
CAST 17-4PH STAINLESS STEEL (Aged, 37 R_c)
PRODUCED BY EDM

Figure 99



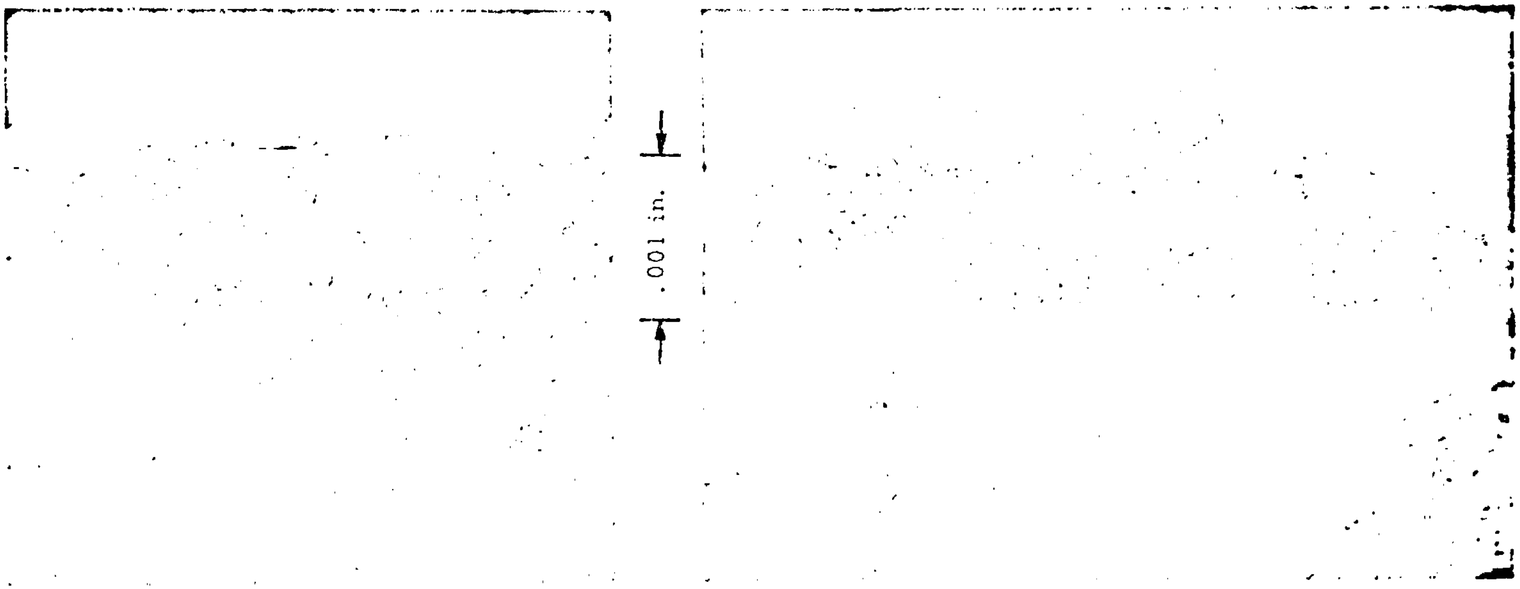
(a) **Finishing Conditions** - A very thin discontinuous recast layer was produced on the surface. Microhardness changes were not detected. 1000X

(b) Roughing Conditions - A discontinuous recast layer averaging .001" deep was formed on the surface. A light etching heat affected zone was also produced. Visually this surface was approximately .001" deep although microhardness data indicated a total affected depth averaging .008". 1000X



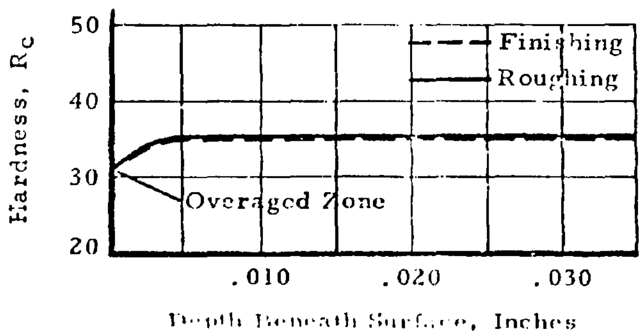
SURFACE CHARACTERISTICS OF TITANIUM 6Al-4V (Annealed, 35 R_c) PRODUCED BY EDM

Figure 100

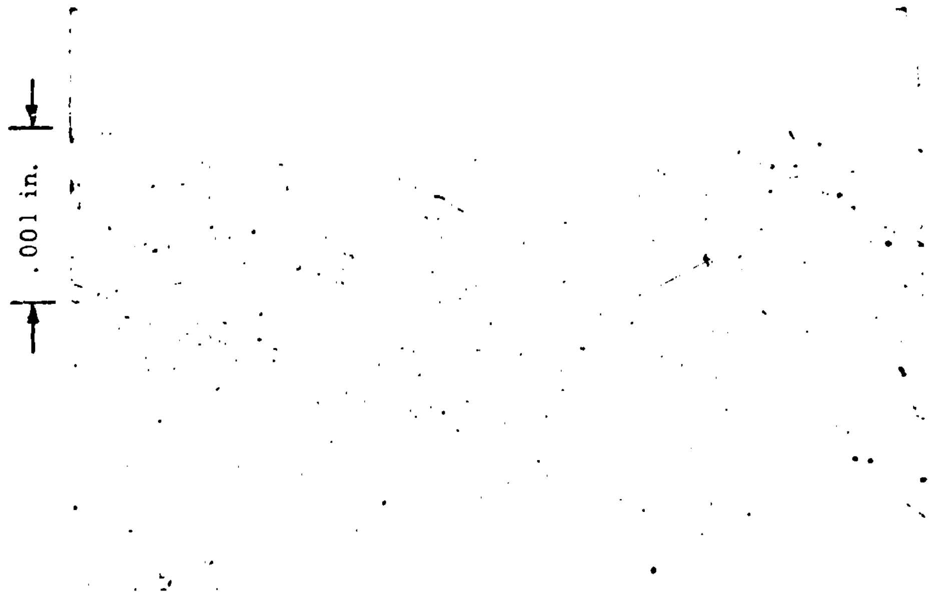


(a) Finishing Conditions - A thin discontinuous recast layer was produced. A softening attributed to overaging was also detected. 1000X

(b) Roughing Conditions - An irregular layer of recast metal up to .003" deep was produced. This recast structure, contrary to most, exhibited a hardness lower than the basic metal. A softened, presumably overaged, layer was detected on the surface beneath the recast zone. 1000X

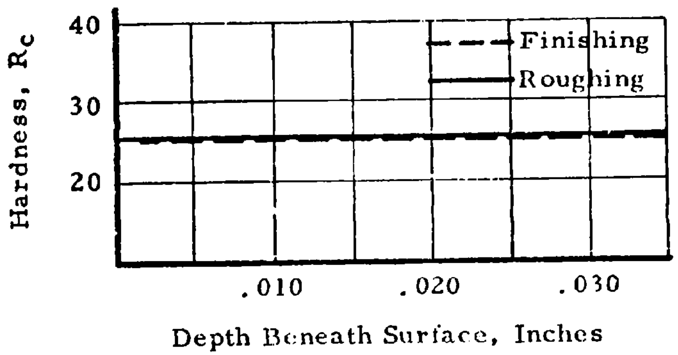


SURFACE CHARACTERISTICS OF TITANIUM 6AL-4V (Aged, 35 R_c) PRODUCED BY EDM



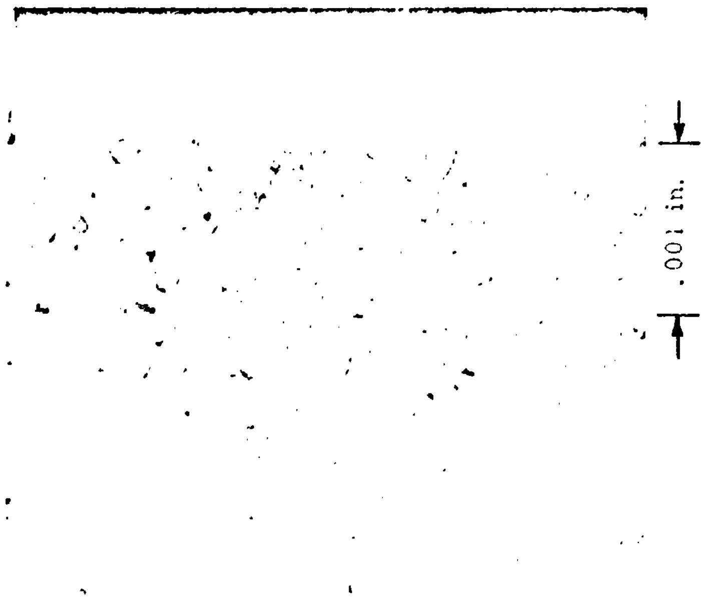
(a) Finishing Conditions - No visible microhardness or structural changes were detected. 1000X

(b) Roughing Conditions - No visible microhardness or structural changes were detected although a somewhat rougher surface was produced. 1000X



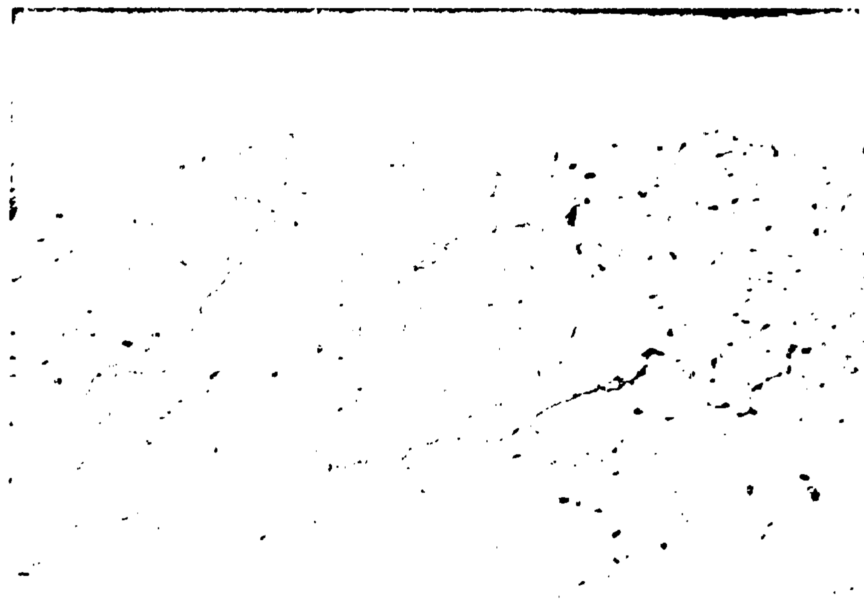
SURFACE CHARACTERISTICS OF MOLYBDENUM ALLOY TZM (Forged and Stress Relieved, 26 R_c) PRODUCED BY EDM

Figure 102



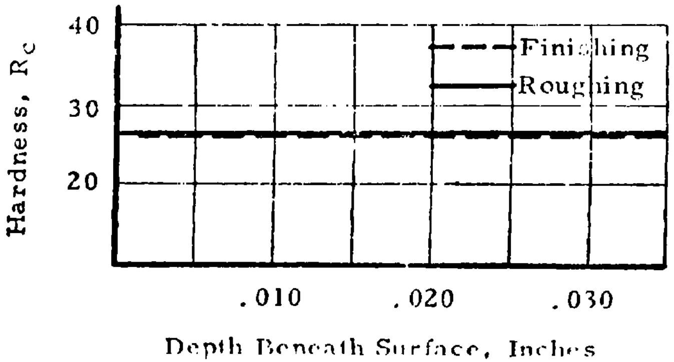
(a) Finishing Conditions - No microhardness or structural effects are noted. The fine cracks are thought to be grain boundaries intersecting the surface.

1000X



(b) Roughing Conditions - Surface erosion and grain boundary attack as noted above were typical although no recasting or continuous surface layer effects were noted.

1000X

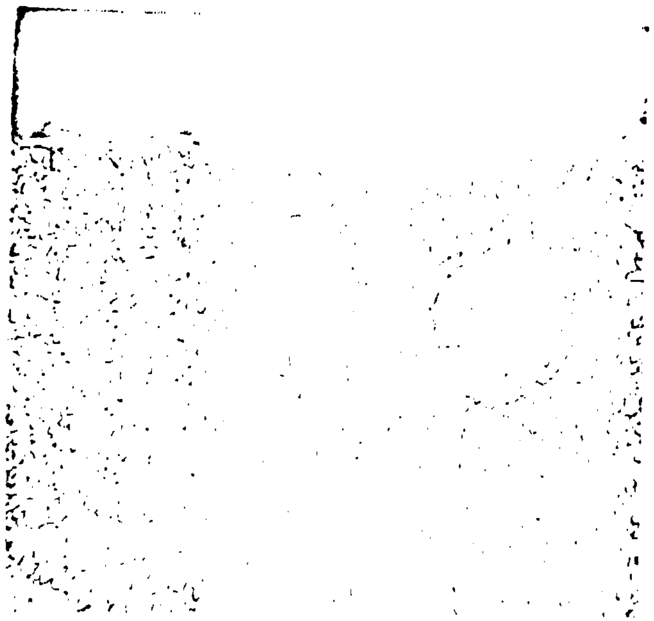


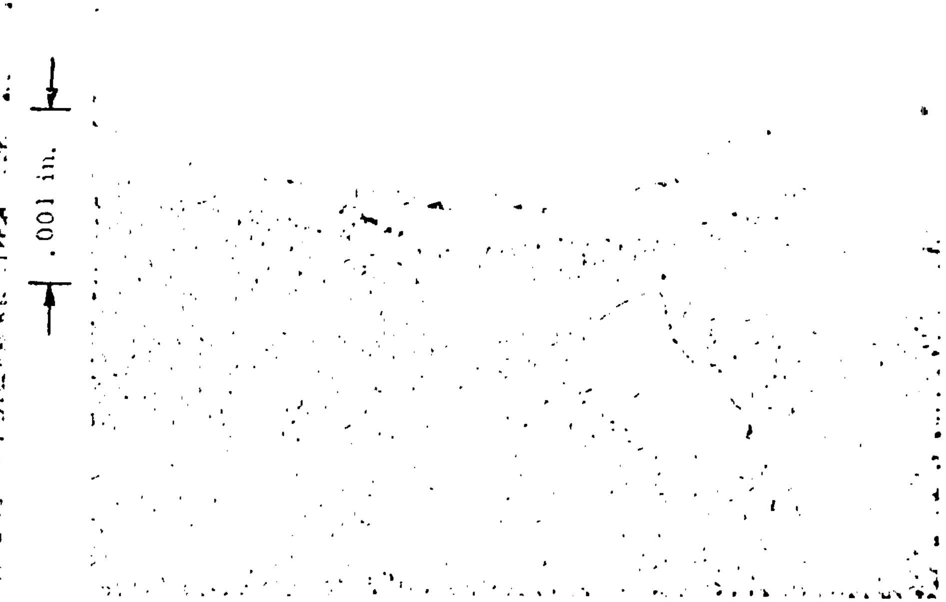
SURFACE CHARACTERISTICS OF UNALLOYED TUNGSTEN (Pressed and Sintered, 93% Density, 27 R_c) PRODUCED BY EDM

Figure 105

.010 .020 .030
Depth Beneath Surface, Inches

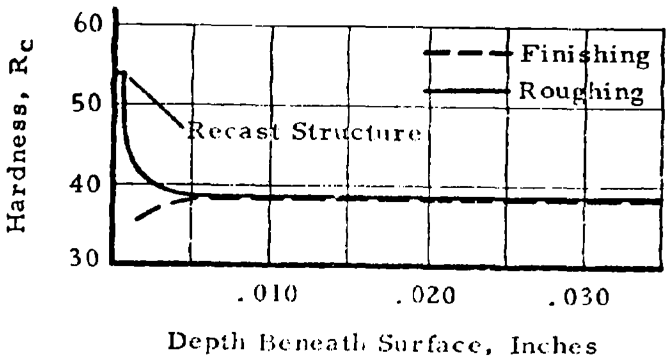
93% Density, 37 R) ...





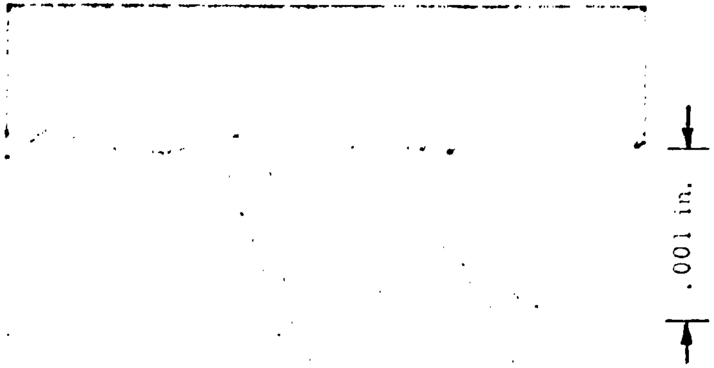
(a) Finishing Conditions - A thin recast layer less than .0001" was formed on the surface. Note also slight sub-surface softening. 1000X

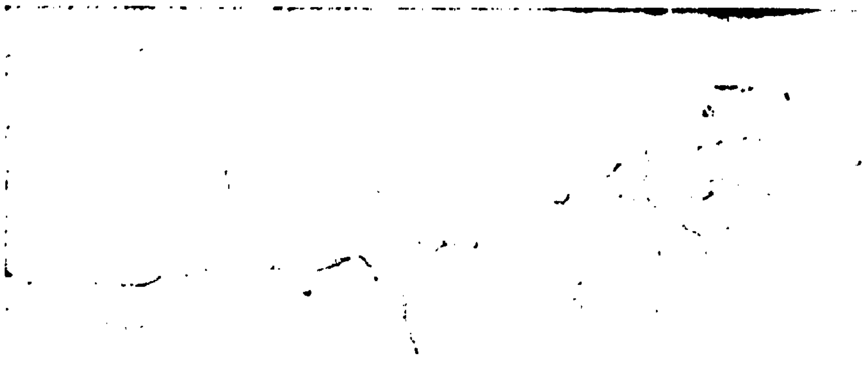
(b) Roughing Conditions - A thin recast layer averaging .0003" deep was formed on the surface. The surface finish was somewhat roughened. The total heat affected zone was approximately .005". 1000X



SURFACE CHARACTERISTICS OF
CAST IN 100 (As Cast, 37 R_c) PRODUCED BY EDM

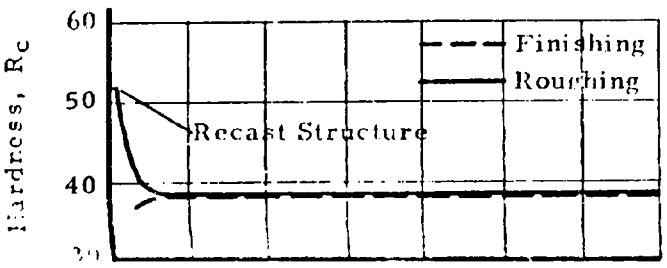
Figure 104





(a) Finishing Conditions - A continuous recast layer .0002" deep was formed on the surface. Microhardness data indicates slight softening immediately beneath this layer.

1000X



(b) Roughing Conditions - A thin recast layer plus extensive surface deposits of spattered metal were found on the surface. The total heat affected zone was approximately .003".

1000X

SURFACE CHARACTERISTICS OF
CAST IN 100 (Aged, 38 R_c) PRODUCED BY EDM

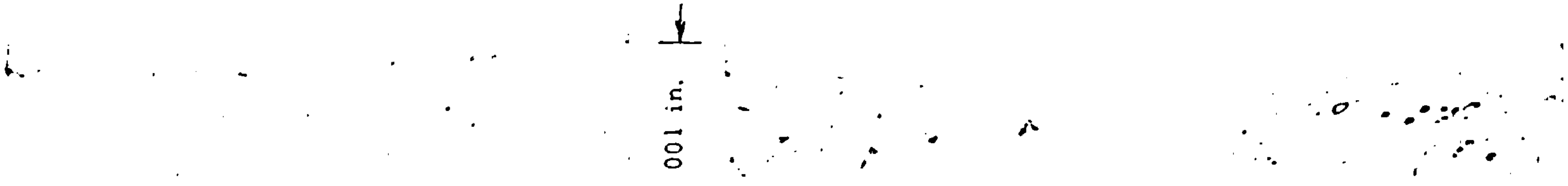
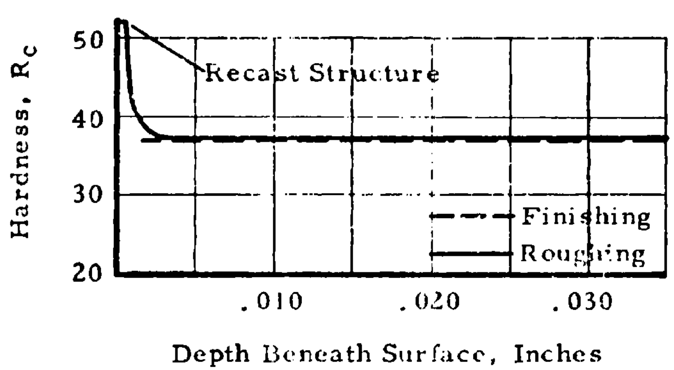


Figure 105

(a) Finishing Conditions - A very thin recast layer less than .0001" was produced on the surface. 1000X

(b) Roughing Conditions - A continuous recast layer averaging .0003" was produced on the surface. A thin heat affected zone as judged by microhardness change was observed beneath this recast layer. 1000X



SURFACE CHARACTERISTICS OF RENE' 41 (Solution Treated, 37 R_c) PRODUCED BY EDM