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Report No. FAA-SS-72-05

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SST Technology
Follow-On Program — Phase I

TITANIUM ALLOYS 6Al-4V AND 3Al-2.5V HYDRAULIC TUBING

William E. Quist
The Boeing Company
Commercial Airplane Group
P.O. Box 3707
Seattle, Washington 98124

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FINAL REPORT
Task 1

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Prepared for

FEDERAL AVIATION ADMINISTRATION
Supersonic Transport Office
800 Independence Avenue, S.W.
Washington, D.C. 20590

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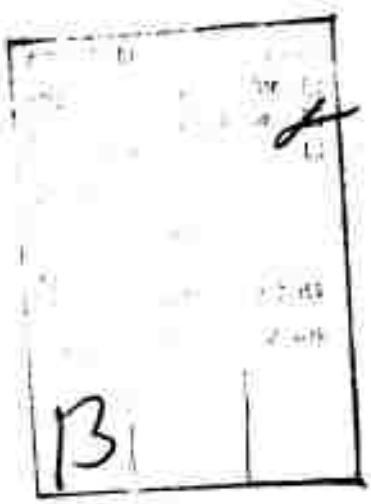

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16. Abstract

This report summarizes investigations on Ti-6Al-4V and Ti-3Al-2.5V hydraulic tubing ~~conducted by The Boeing Materials Technology Staff from 1968 to the termination of the SST program in March, 1971~~. All aspects of tubing technology relative to the development of sound procurement specifications and the subsequent use of the material for aircraft hydraulic systems were considered. Principal efforts were centered on (1) relating various metallurgical characteristics to the fatigue behavior of the tube, (2) the effects of joints, (3) formability, and (4) various surface finishes and treatments. In 1969 tubing alloy Ti-3Al-2.5V was selected for use on the SST based on the status of its development in relation to cost and time schedules, although Ti-6Al-4V was considered to show much future potential as a high strength tubing alloy.

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Tubing	Crystallographic texture	
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PREFACE

This is one of a series of final reports on Titanium Materials Technology submitted in fullfillment of Task 1-A of Department of Transportation contract DOT-FA-SS-71-12, dated 30 June 1971. The report was prepared by the Materials Technology organization of The Boeing Company, Commercial Airplane Group, Seattle, Washington.

The author acknowledges the assistance of numerous colleagues who aided in various aspects of this tubing development program. The many titanium tube producing companies with whom The Boeing Co. dealt throughout this program also gave invaluable assistance and contributed greatly to the steady improvement realized in tubing quality.

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CONTENTS

Page

1.0 INTRODUCTION 1

2.0 DESIGN, COST, AND MANUFACTURING CONSIDERATIONS CONTRIBUTING TO ALLOY SELECTION 3

3.0 CHARACTERIZATION TESTING 9
3.1 Quality Control Test Procedures and Techniques 9
3.1.1 Chemical Analysis 9
3.1.2 Mechanical Property Tests 10
3.1.3 Flare Tests 11
3.1.4 Hydrostatic Pressure Resistance Tests 11
3.1.5 Flattening Tests 11
3.1.6 Bending Tests 11
3.1.7 Residual Stress Tests 12
3.1.8 Microstructure Tests 12
3.1.9 Ultrasonic Inspection (Ti-3Al-2.5V) 13
3.2 Quality Control Receiving and Inspection Data 14
3.3 Engineering Evaluation Tests–Ti6Al-4V Annealed Tubing 14
3.3.1 Etching (Following Forming) 14
3.3.2 Stress Relieving 18
3.3.3 Shot Peening 20
3.3.4 Surface Coatings For Prevention of Fretting Fatigue 20
3.3.5 In-Place Fusion Welding 21
3.3.6 Hydraulic Fittings 29
3.3.6.1 Resistoflex Fittings 29
3.3.6.2 Aeroquip Union Fittings 29
3.3.6.3 MIL-FLO Fittings 30
3.3.7 Effects of Forming on Strength 34
3.3.8 Surface Characteristics: Finish and Defects 35
3.3.8.1 Effects of Surface Finish on Ultrasonic Indications 35
3.3.8.2 Effect of Chemical Milling (Etching) on Surface Finish and Defects 41
3.3.8.3 Effects of Defects on Fatigue Life 41
3.3.9 Methods of Chemical Milling 45
3.3.10 Minimum Wall Thickness Requirements 47
3.3.11 Preferred Method of Oxygen and Hydrogen Analysis 47
3.3.12 Formability 48
3.4 Engineering Evaluation Tests–Ti-3Al-2.5V Cold Worked and Stress Relieved Tubing 49
3.4.1 Fatigue Performance (Failure Analysis) 49
3.4.2 Surface Finish and Defects 54
3.4.2.1 Types of Defects 54

CONTENTS (continued)

Page

3.4.2.2 The Effects of Surface Finish on Fatigue Properties 56
3.4.3 Shot Peening 63
3.4.4 Formability 76
3.4.4.1 Minimum and Preferred Bend Radii 76
3.4.4.2 Angular and Radial Springback 76
3.4.4.3 Percent of Stretch 76
3.4.4.4 Ovality 76
3.4.4.5 Wall Thickness Change 79
3.4.5 Crystalographic Texture 79
3.5 Microstructure 79
3.5.1 Widmanstatten (Basketweave) Structure 79
3.5.2 Alpha Case 86

4.0 ANALYSIS OF TEST RESULTS 87
4.1 Surface Condition 87
4.2 Defects 88
4.3 Microstructure 90
4.4 Crystalographic Texture 90

5.0 CONCLUSIONS 93

6.0 RECOMMENDATIONS 95

APPENDIX A 97
Development of Specifications 97
Vendor Qualification 120

REFERENCES 123

FIGURES

No.		Page
1	Techniques Used in SACH's Boring Out Method	13
2	Typical Vendor Quality Control Test Report for Ti-3A1-2.5V Cold Worked and Stress Relieved Tubing	15
3	Boeing Quality Control Test Report Covering the Same Material Reported in Figure 2	16
4	An example of how a Sanding Strike Mark can act as a Fatigue Crack Origin. This tube was sanded (grit not specified) and chemically milled, but not suffieiently to remove all sanding marks	19
5	Butt Weld Joint Configurations	22
6	Butt Weld Bead Configuration	22
7	Butt Weld Configuration for Fitting and Tube	23
8	Weld Bead Configuration for Shear Load Joints	23
9	Weld Bead Configuration for Single Melt through Butt Joints	23
10	Specimen and Joint Configurations for Fatigue Test Specimens	25
11	Specimen and Joint Configuration for Fatigue Test Specimens	28
12	MIL-FLO Fitting and Tube Configuration	32
13	Areas From Which Specimens were Taken From Bent Ti-6A1-4V Tubes	34
14	I.D. Surface Marks and Associated Strip Chart Ultrasonic Indications. (1½ in. x .035 in. tube) Complete Saturation	36
15	Profile of I.D. Surface Marks Shown in Figure 14 Above, Depth From .001 in. to .0025 in.	36
16	Ultrasonic Indications on Strip Chart Made Before Grit Blasting and Pickling of I.D. and O.D. Surfaces (Tube I)	37
17	Same area as in Figure 16 except Recording Produced After Grit Blasting and Pickling of I.D. and O.D. Surface (Tube I)	37
18	Scan Direction from Opposite End of Tube I; Recording Made Before Grit Blasting and Pickling of I.D. and O.D. Surfaces	38
19	Same area as in Figure 18 except Recording Produced After Grit Blasting and Pickling of I.D. and O.D. Surfaces (Tube I)	38
20	Ultrasonic Indication on Strip Chart Made Before Grit Blasting and Pickling of I.D. and O.D. Surfaces (Tube 2)	39
21	Same area as in Figure 20 except Recording Produced After Grit Blasting and Pickling of I.D. and O.D. Surfaces (Tube 2)	39
22	Scan Direction from Opposite End of Tube 2; Recording Made Before Grit Blasting and Pickling of I.D. and O.D. Surfaces	40
23	Same area as in Figure 22 except Recording Produced After Grit Blasting and Pickling of I.D. and O.D. Surfaces (Tube 2)	40
24	I.D. Surface Flaw on Ball-Swaged 1½ in. O.D. x 0.035 in. Wall Tube; The Flaw Consists of a (Wedge-shaped) Ribbon at the Surface with a Crack Beneath It	42
25	Cross-section of Flaw in Figure 24 Before and After Chem-Milling 0.002 in. from the Surface; Depth .0075 in. Before; .004 in. After	42

FIGURES (continued)

No.		Page
26	Same Crack as Shown in Figure 24 Except at Different Location. Chem-Milling 0.002 in. did not Cause Further Growth of Crack. Depth .009 in. Before; .007 in. After	42
27	Another Section of the Crack Shown in Figure 24 Which Shows that an Existing Crack Will Not Grow in Depth During Chem-Milling; Depth .0075 in. Before; .005 in. After	43
28	Severe I.D. Surface Roughness Shown in Plan View at Left and Cross-section at Right, This Condition was Completely Removed by Chem-Milling 0.002 in. of Surface	43
29	Severely Scratched or Scored I.D.; (as shown in Fig. 28) Condition Completely Removed by Chem-Milling 0.002 in. of Surface	43
30	Very Severe I.D. Zig-Zag Pit Marks; View at Left Before Chem-Milling and at Right After Chem-Milling 0.002 in. of Surface	44
31	Longitudinal Cross-Section of Above Tube Shown in Figure 30 Before and After Chem-Milling; the Surface Roughness is Substantially Reduced	44
32	Transverse Cross-Section of the Tube Shown in Figure 30 Before Chem-Milling. The Defects Shown Here are Deep Pits which were Created During Tube Reduction From The Extruded Hollow	44
33	Apparent Stress Corrosion Crack in Ti-6Al-4V Tubing	46
34	Residual Hoop Stress in Tube A (1 in. x .052 in.)	65
35	Residual Hoop Stress in Tube B (¾ in. x .039 in.)	66
36	Residual Hoop Stress in Tube c (5/8 in. x .033 in.)	67
37	Residual Hoop Stress in Tube D (½ in. x .026 in.)	68
38	Residual Hoop Stress in Tube E (3/8 in. x .020 in.)	69
39	Residual Hoop Stress in Tube F (3/8 in. x .020 in.) Unpeened	70
40	Residual Hoop Stress in Tube G-C (¾ in. x .045 in.) As Received from the Vendor.	72
41	Residual Hoop Stress in Tube G-1 (¾ in. x .045 in.) Peened to .005A2	73
42	Residual Hoop Stress in Tube G-2 (¾ in. x .045 in.) Peened to .008A2	74
43	Residual Hoop Stress in Tube G-3 (¾ in. x .045 in.) Peened to .012A2	75
44	Pole Figure Showing Intensity Profiles of Basal Plane Reflections for 1.0 in. x 0.033 in. RMI Tubing. Data for This Tubing Shows the Strongest Radial Orientation in Comparison with Pole Figures for the Other Two Tubing Samples (Figures 45, 46)	80
45	Pole Figure Showing Intensity Profiles of Basal Plane Reflections for 1½ in. x 0.120 in. Zirtech Tubing. The Data Shows the Unit Cell Axes to be Oriented More Strongly in the Radial Direction Than for the ½ in. O.D. Tubing, (Figure 46) with Peak Intensities Occurring Approximately 40° from a True Radial Direction	81
46	Pole Figure Showing Intensity Profiles of Basal Plane Reflections for ½ in. x 0.040 in. Zirtech Tubing. The Data Indicates the Axes of Unit Cells are Distributed Somewhat Randomly Between a Circumferential and a Radial Orientation with a Slight Tendency Toward a Radial Orientation	82

FIGURES (continued)

No.		Page
47	Profile of a Crack with the Origin on the O.D.. The Crack is very Jagged and Tends to Follow Prior Beta Grain Boundaries–Note the Change of Microstructure at Right	83
48	Coarse Widmanstatten Microstructure–Section Taken from the End of the Tube Away from the Brazed Joint	83
49	Profile of Crack in Showing a Coarse Widmanstatten Structure and a Jagged Fracture	84
50	Very Jagged Fractured Surface	85
51	Very Coarse Widmanstatten Microstructure,Especially Towards the O.D. on the Right–Note How Fracture Follows Along Prior Beta Grain Boundaries	85
52	A Pit Type Defect Which Has acted as a Fatigue Crack Origin	89
53	Effect of Processing on Texture and Properties of Titanium Tubing	91

TABLES

No.		Page
1	Cost Comparisons for Five Candidate Hydraulic Tubing Materials	3
2	Weight Comparisons for Five Candidate Hydraulic Tubing Materials	4
3	Mechanical and Physical Property Data for Five Candidate Hydraulic Tubing Materials	5
4	Advantages, Disadvantages and Potential Problems for Five Candidate Hydraulic Tubing Materials	6
5	Chemical Composition of Titanium Alloys Ti-6A1-4V and Ti-3A1-2.5V	9
6	Minimum Tensite Properties of Titanium Alloys Ti-6A1-4V and Ti-3A1-2.5V	10
7	Maximum Permissible Size of Defects in Ti-3A1-2.5V Annealed Tubing	14
8	Mechanical Properties and Chemical Composition Data for Ti-6A1-4V Annealed and Ti-3A1-2.5V Cold Worked and Stress Relieved Tubing Procured for the SST Program	17
9	Comparison of the Fatigue Behavior of Tubes Treated with a Nonstructural Adhesive to Prevent Fretting with Untreated Tubes	21
10	The Fatigue Behavior of GTA Fusion Welded Ti-6A1-4V Tube Specimens	29
11	The Fatigue Behavior of Ti-6A1-4V Tubing Fitted with MIL-FLO Hydraulic Fittings and Sleeves	31
12	The Effects of Forming on the Strength of Ti-6A1-4V Annealed Tubing	34
13	The Fatigue Behavior of Formed Ti-6A1-4V Tubing. Some Tubes Contained Surface Defects	41
14	Fabrication Data for Ti-6A1-4V Hydraulic Tubing	48
15	Hardness and Percent Thinning of Ti-6A1-4V Tubes at the Apex of a 120° Bend (min. bend radii)	49
16	Summary of Fatigue Failures in Ti-3A1-2.5V CWSR Hydraulic Tubing	50
17	Summary of Ti-3A1-2.5V CWSR Hydraulic Tubing Fatigue Failures	51
18	Chemical Analysis of Tubes	53
19	Summary of Fatigue Test Failures in Ti-3A1-2.5V CWSR Hydraulic Tubing	54
20	Chemical Analysis of Ti-3Al-2.5V Tubes	54
21	Summary of Ti-3A1-2.5V CWSR Hydraulic Tubing Fatigue Failures	55
22	Fatigue Test Results for Ti-3A1-2.5V CWSR Hydraulic Tubing	57
23	Summary of Fracture Analysis of Ti-3A1-2.5V CWSR Hydraulic Tubing	59
24	Chemical Analysis of Ti-3Al-2.5V CWSR Hydraulic Tubing Test Specimens	63
25	Shot Peen Intensity Ranges Specified for Ti-3A1-2.5V Hydraulic Tubing	64
26	Residual Hoop Stress, Ti-3A1-2.5V CWSR Hydraulic Tubing-Sach's Boring Out Method	64
27	Residual Hoop Stress, Ti-3A1-2.5V CWSR Hydraulic Tubing-Tube Cutting Method	71
28	Formability of Ti-3A1-2.5V CWSR Tubing	77
A1	Primary Original issues and revisions of Ti-6A1-4V and Ti-3A1-2.5V Boeing Materials Specifications	97

1.0 INTRODUCTION

The supersonic transport development program conducted by the Boeing Company and the Department of Transportation over the past decade covered a great many disciplines including hydraulic tubing systems. In considering an optimum hydraulic tubing system items such as weight, development costs, unit costs, fatigue behavior, and prior usage and experience were weighed. The initial selection for tubing material was Ti-6Al-4V in the annealed condition. Development of this system was pursued until the fall of 1969 at which time the emphasis was changed to the alloy Ti-3Al-2.5V in the cold worked and stress relieved condition, (CWSR).

The purpose of this report is to document and summarize the work performed by the Structures Technology–Materials Staff, Commercial Airplane Division of The Boeing Company in support of the development of titanium hydraulic tubing. The time period during which the great majority of this work was accomplished was from early 1968 to the cancellation of the SST program in the spring of 1971.

The report will address itself primarily to the work performed with the Ti-6Al-4V and Ti-3Al-2.5V alloys. Other alloys that have undergone some study will be discussed for comparative purposes only. The work reported herein has been conducted from a metallurgical and process viewpoint, and should be considered with this in mind. Various characterization studies, evaluation programs, and failure analyses make up the bulk of this program.

The developmental effort summarized by this report provided a technological basis for a follow-on program currently being conducted by The Boeing Company with Department of Transportation funding.

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2.0 DESIGN, COST AND MANUFACTURING CONSIDERATIONS CONTRIBUTING TO ALLOY SELECTION

The selection of hydraulic tubing material for advanced aircraft involves an analysis of several basic considerations (ref. 1). The most important of these are 1) structural efficiency, 2) availability, 3) cost, and 4) projected service performance.

Based on these considerations Ti-6Al-4V had been selected initially for use on the SST and extensive developmental effort was conducted on this alloy. In 1969, however, it became apparent from difficulties experienced by the tubing suppliers that cost and schedule targets might not be met. The major technical difficulties being encountered centered about the control of detect levels and surface finishes. Steady improvement in the overall quality of Ti-6Al-4V hydraulic tubing was being realized but the pace of development was slower than hoped. Therefore, a reassessment of five candidate tubing materials was initiated to determine if an alternate material choice could be made. The five materials included in the study were: Ti-6Al-4V annealed, Ti-3Al-2.5V cold worked, and stress relieved Ti-3Al-2.5V annealed, AM 350 stainless steel cold reduced and tempered, and 21-6-9 stainless steel cold worked.

The study is summarized in tables 1 through 4 and resulted in the selection of Ti-3Al-2.5V cold worked and stress relieved tube for use on the prototype SST based on several factors.

TABLE 1. –COST COMPARISONS FOR FIVE CANDIDATE HYDRAULIC TUBING MATERIALS FOR THE PROTOTYPE AIRPLANES

Bases	Ti-6Al-4V Annealed	Ti-3Al-2.5V Cold Worked and Stress Relieved	AM 350 CRT	Ti-3Al-2.5V Annealed	21-6-9 Cold Worked
Assuming High Bid Estimates	$1,057,521	$194,060	$97,250	$194,060	$72,025
Assuming Low Bid Estimates (this is believed to be the more realistic estimate)	$ 589,680	$189,045	$94,180	$189,045	$64,721

- Certain costs for commercially pure tubing not included
- Includes tubing for the systems mock-up, spares, and flight test modifications

TABLE 2.–WEIGHT COMPARISONS FOR FIVE CANDIDATE HYDRAULIC TUBING MATERIALS

Material and Condition	F_{tu}(ksi)		Installation Weight-including supports (lbs.)					
	@R.T.	@400°F	Pressure	Return	Supply*	5% Increase for Perm. Joint Sleeve	Total	ΔWt.
Ti-6Al-4V Annealed	130.0	100.5	1580	1056	564	0	3200	(Baseline)
Ti-3Al-2.5V Cold Worked & Stress Relieved	125.0	97.0	1619	1077	564	135	3395	+195
Ti-3Al-2.5V Annealed	90.0	69.5	1887	1179	564	0	3630	+430
AM 350 CRT-900	185.0	165.5	1800	1281	564	155	3800	+600
21-6-9 Cold Worked	142.0	120.5	2157	1367	564	177	4265	+1065
Total Lengths (Ft.)			4406	3882	467	8755		

NOTE: 5% factor applied to the cold worked material only for a permanent joint sleeve.

*Commercially pure titanium used for all supply lines.

The analysis showed that all of the candidate titanium tubing materials were considerably superior to the steel alloys from a structural efficiency viewpoint and were therefore preferred. Ti-6Al-4V annealed was the strongest of the five materials. The strength to weight ratio of Ti-3Al-2.5V CWSR tubing, the second strongest material, is 5.5% lower than for Ti-6Al-4V annealed tubing at 400°F and the difference in tubing and fluid weight shows a 1.9% advantage for the Ti-6Al-4V annealed material.

However, the high cost of Ti-6Al-4V together with its relatively slow development pace, combined to make this alloy less attractive for the SST prototypes than the Ti-3Al-2.5V material. For example, the tubing costs for the two prototype airplanes and the full scale hydraulic system mock-up ("CODE") would be $589,680 for the Ti-6Al-4V material and only $189,045 for Ti-3Al-2.5V CWSR material. The in-house development costs for the prototype design using Ti-3Al-2.5V cold worked, Ti-3Al-2.5V annealed, or AM 350 cold reduced and tempered steel were estimated to be essentially the same.

TABLE 3.–MECHANICAL AND PHYSICAL PROPERTY DATA FOR FIVE CANDIDATE HYDRAULIC TUBING MATERIALS

Tube Material	Condition	F_{tu}(ksi)			Density (lb./in.^{3})	Strength to Weight Ratio $\frac{F_{tu} \text{ @ Max. Temp.}}{\text{Density}}$	Elongation In 2 Inches, Minimum (%)
		R.T.*	400°F*	450°F			
Ti-6Al-4V Seamless	Annealed	130.0	100.5	104.0** 97.0*	0.160	606,000** @ 450°F 634,000 * @ 400°F	10
Ti-3Al-2.5V Seamless	Cold Worked & Stress Relieved	125.0	97.0	–	0.162	599,000	10
AM 350 Seam Welded	Cold Reduced & Tempered (CRT)	185.0	165.5	–	0.282	588,000	18 to 25
Ti-3Al-2.5V Seamless	Annealed	90.0	69.5	–	0.162	429,000	15
21-6-9	Cold Worked	142.0	120.5	–	0.286	421,000	20

*New Allowable obtained from Structural Allowables per CS SA2-5522 – SST 742 (Ref. 4).

**Allowables used for tube sizing in Fiscal Year 1969.

The choice between the annealed and cold worked condition of Ti-3Al-2.5V was based in part upon the permanent joining methods to be used on the prototype airplanes. The attractive step-joint butt weld method causes localized annealing in the tube which negates some of the advantage of cold working and lends some impetus toward the selection of annealed tubing. The cold worked tubing is much stronger, however, and results in an overall lighter system weight.

A further factor leading to the selection of Ti-3Al-2.5V tubing for prototype use was that the experience gained with this material would help toward solving many of the design and manufacturing problems related to the use of the Ti-6Al-4V alloy which is still considered to show most promise for the production airplanes.

Use of Ti-3Al-2.5V CWSR tubing required that testing be performed in SST tube sizes and wall gages under SST operating pressures and environmental conditions. Test work that had been completed by Boeing to date showed excellent results for new airplane applications. Lockheed initially selected this material for C-5A applications, and Grumman for the F-14 airplane.

TABLE 4. –ADVANTAGES' DISADVANTAGES AND POTENTIAL PROBLEMS FOR FIVE CANDIDATE HYDRAULIC TUBING MATERIALS

Tubing Type	Advantages	Disadvantages	Potential Problems
Ti-3Al-2.5V Cold Worked & Stress Relieved (Seamless)	• High strength to weight ratio (2nd highest) • Medium cost • Sources Developed – Reactive Metals, Whittaker, Wolverine, Zirtech • Tested by Lockheed (C-5) and Grumman (F-14) Lockheed has tested sizes through -20. Qualified for use with swaged flareless sleeves. A small quantity has been installed on some C-5 aircraft. Grumman has tested sizes through -20 with Aeroquip brazed and Weatherhead welded joints. • Good quality tubing should be available. • Flexibility – low stress per unit deflection. • Tested by Boeing C.A.G. Research Group. (Tubing was procured, inspected and tested on a simulated 727 spoiler test rig.)	• Weld reinforcement may be required to compensate for loss in properties in the heat affected zone. • Fretting with sleeve type designs expected.	• Weld development required. • Swaging problem may be encountered with the heavier wall thicknesses.
AM 350 CRT (Seam Welded)	• High strength to weight ratio (3rd highest). • Good quality is available – low risk • Medium cost.	• Weld reinforcement may be required to compensate for loss in properties in the heat affected zone. • Thin gauges are more susceptible to thinning and amplification of defects.	• Development required for forming • Weld development required.

TABLE 4. –ADVANTAGES, DISADVANTAGES AND POTENTIAL PROBLEMS FOR FIVE CANDIDATE HYDRAULIC TUBING MATERIALS (continued)

Tubing Type	Advantages	Disadvantages	Potential Problems
AM 350 (cont)	• Boeing experience (X-20). • Used on Concorde, however tubing is annealed. • Used on L1011.		• Possible stress corrosion problem (protective finishing would be required for the SST environment). • Swaging problems may be encountered with the heavy wall thicknesses.
Ti-3Al-2.5V Annealed	• Medium cost. • Little development required for the prototype. • Flexibility – low stress per unit deflection.	• Low strength to weight ratio. • Larger wall thicknesses would present welding problems (1¼" O.D. & above). • Fretting problems with sleeve type designs expected.	• Weld development may be required for maximum wall thicknesses & O.D.
21-6-9 Cold Worked (Seam Welded)	• Lowest cost. • Good quality is available. • Boeing experience (747). • Brazed joints are being qualified by Douglas for the DC 10. • Sources developed. • Welded joints are being qualified by Lockheed for the L1011.	• Low strength to weight ratio.	• Weld development required for maximum wall thickness & O.D. • Swaging problems may be encountered with the heavy wall gages.
Ti-6Al-4V Annealed (Seamless)	• Highest strenth to weight ratio. • Basic welding program is complete (additional flexure testing required).	• High cost. • Not in production.	• Availability of good quality tubing. Manufacturing procedures require more development, but Boeing tests show progress being made. The most comprehensive tests conducted

TABLE 4. –ADVANTAGES, DISADVANTAGES AND POTENTIAL PROBLEMS FOR FIVE CANDIDATE HYDRAULIC TUBING MATERIALS (continued)

Tubing Type	Advantages	Disadvantages	Potential Problems
Ti-6Al-4V (cont)	• Tubing presently on hand for testing. • Flexibility – low stress per unit deflection.		on this material are: a) flexure tests on 120° bent tube specimens. b) pressure impulse tests (conducted on the same specimens).

AM 350 (CRT) was not seriously considered for the SST prototype airplanes because it was predicted that development costs would roughly equal that required for Ti-3Al-2.5V and because it would be unsatisfactory from a weight standpoint for the production airplanes. Tubing cost for two prototype airplanes and the "CODE" would be approximately $94,180.

The 747 airplane tubing material, 21-6-9 cold worked, has a relatively low strength to weight ratio and would result in severe weight penalties compared to the titanium alloys.

3.0 CHARACTERIZATION TESTING

Ti-6Al-4V annealed and Ti-3Al-2.5V cold worked and stress relieved tubing was characterized with respect to a large number of mechanical, forming, chemical and metallurgical parameters. Many of these tests were performed by tubing suppliers and the Boeing Company's Quality Control Departments to insure conformance to applicable tubing specifications. The Boeing Company engineering departments also conducted a great variety of specialized tests, with the purpose of improving processing techniques as well as material, manufacturing, and in-flight performance.

3.1 QUALITY CONTROL TEST PROCEDURES AND TECHNIQUES

A large variety of tests were performed on each shipment of titanium tubing received by Boeing and its subcontractors in order to isolate and examine all pertinent parameters. The various tests are described in this section together with the standard procedures used.

3.1.1 Chemical Analysis

The chemical composition of Ti-6Al-4V and Ti-3Al-2.5V alloys was required to conform to the limits shown in table 5 (refs. 2, 3).

Each heat was analyzed for conformance to this requirement. The tubing supplier was allowed to use raw material certification except for oxygen, hydrogen, and nitrogen analysis which were determined after final processing of the tubing.

TABLE 5.–CHEMICAL COMPOSITIONS OF TITANIUM ALLOYS Ti-6Al-4V AND Ti-3Al-2.5V

Element	Ti-6Al-4V (Wt. %)	Ti-3Al-2.5V (Wt. %)
Aluminum	5.5 - 6.75	2.5 - 3.5
Vanadium	3.4 - 4.5	2.0 - 3.0
Iron	0.25 (Max.)	0.30 (Max.)
Carbon	0.08 (Max.)	0.05 (Max.)
Hydrogen	0.0125 (Max.)	0.015 (Max.)
Oxygen	0.1300 (Max.)	0.12 (Max.)
Nitrogen	0.03 (Max.)	0.02 (Max.)
Other Elements, Total	0.40 (Max.)*	0.40 (Max.)*
Titanium	Remainder	Remainder

*Any individual element shall not exceed 0.10%.

Chemical composition for all elements except hydrogen was determined using ASTM E-120. Analysis for hydrogen was performed using the hot extraction method described in ASTM E-146. Limits for check analysis were according to AMS 2249 (ref. 3). Any other analyses having equivalent or better accuracy and precision than the above methods were allowed provided they were approved by The Boeing Company, Quality Control Department. Analysis for oxygen content was performed by a technique having an accuracy of 50 ppm.

For Boeing check analysis, the oxygen content of tubing was determined using the neutron activation technique (ref. 4). Studies reported in reference 5 showed that this technique was more reliable than the vacuum fusion method. Hydrogen analysis was made using the hot extraction technique with 0.3 gram minimum analytical samples. Boeing findings (ref. 6) show that the hot extraction technique gives a higher degree of confidence in results than does the vacuum fusion method.

3.1.2 Mechanical Property Tests

The room temperature tensile properties of tubing were determined on one specimen per 1000 feet of tubing in each lot with a minimum of three specimens per lot. Testing was required to be on the full cross-section of the tubing. Properties were to be in accordance with table 6 (refs. 2, 3).

TABLE 6.–MINIMUM TENSILE PROPERTIES OF TITANIUM ALLOYS Ti-6Al-4V AND Ti-3Al-2.5V

Material	Ultimate Tensile Strength (ksi)	Yield Strength at 0.2% Offset (ksi)	Elongation In 2 Inches (%)
Ti-6Al-4V (Ann)	134*	126*	10*
Ti-3Al-2.5V (Ann)	90	74	15
Ti-3Al-2.5V (CWSR)	125	105	10

*Latter revisions of XBMS 7-178 give these properties as 130, 120 and 10 respectively.

Specimens were tested in accordance with ASTM E-8 or Federal Test Method 151. The strain rate was .003 - .007 inch/inch/minute through 0.2% offset plastic strain, and .075 - .125 inch/inch/minute to failure. A lot is defined as tubing of the same diameter and wall thickness made from one heat of material processed in a similar manner and stress relieved together. When a dispute occured between the purchaser and supplier over a yield strength value, a referee test was performed on a machine having a strain rate pacer, using a strain rate of .005 inch/inch/minute through the yield strength.

3.1.3 Flare Tests

Flare tests were performed per ASTM B-338 (ref. 2, 3). Ti-3Al-2.5V CWSR tubing was required to be capable of being flared to a minimum of 1.2 times the original diameter without cracking or tearing of the material. For Ti-6Al-4V a 15% expansion was required. sion was required.

3.1.4 Hydrostatic Pressure Resistance Tests

Specimens for hydrostatic pressure testing were 10-12 inches long and were hydrostatic pressure tested to a pressure determined by the formula:

$$P = f_{ty} \frac{D^2 - d^2}{D^2 + d^2}$$

In which

P = hydrostatic test pressure (p.s.i.)

d = maximum permissible inside diameter (D less twice the minimum permissible wall thickness, in inches)

D = maximum permissible outside diameter (Nominal O.D. plus diametrical tolerance, in inches)

f_{ty} = minimum yield strength per table 6.

Specimens were subjected to two (2) pressure applications with the calculated pressure being maintained for at least two (2) minutes during each cycle.

The tubing was required to show no evidence of cracking or tearing when examined at 5X magnification (refs. 2, 3).

3.1.5 Flattening Tests (Ti-3Al-2.5V CWSR)

Flattening tests were performed on specimens with a length equal to twice their diameter (ref. 3). They were flattened at room temperature between parallel plates until the distance between the plates did not exceed fourteen (14) times the nominal thickness. One specimen was tested for each ten (10) tubes in a lot. The tested tubing was required to show no evidence of cracking or tearing when examined at a magnification of 5X.

3.1.6 Bending Tests (Ti-3Al-2.5V)

Bend specimens were bent through 180° at room temperature about a suitable bending block. The tube centerline was required to be 2 radii from the outside diameter of the tube for Ti-3Al-2.5V annealed (ref. 7) tubing and 3 for Ti-3Al-4V CW SR tubing (ref. 3).
An appropriate mandrel or tube filler was provided to restrict flattening to a value that did not exceed 5% of the nominal outside diameter.

The tubing was required to show no evidence of cracking, open sanding striations or tearing when examined at 5X magnification.

3.1.7 Residual Stress Tests

Two types of residual stress determinations have been performed on titanium tubing. The first is to determine the overall circumferential stress and the second was to determine the stress pattern through the thickness of the tube.

Ti-3Al-2.5V CWSR tubing procured by the Boeing Company was not allowed to have more than 15 ksi residual hoop stress (ref. 3). Specimens for circumferential stress determinations were at least 3 times the tube diameter in length (ref. 8). The specimen diameter was measured before (D_o) and after (D_1) making a longitudinal saw cut normal to the measured diameter; the cut being made by a sharp hack saw blade. The residual stress was determined using the following formula:

$$S_r = \frac{E}{1-\mu^2}\, t\left(\frac{1}{D_o} - \frac{1}{D_1}\right)$$

Where:

$E = 14.1 \times 10^6$ psi

$\mu = 0.31$

t = wall thickness

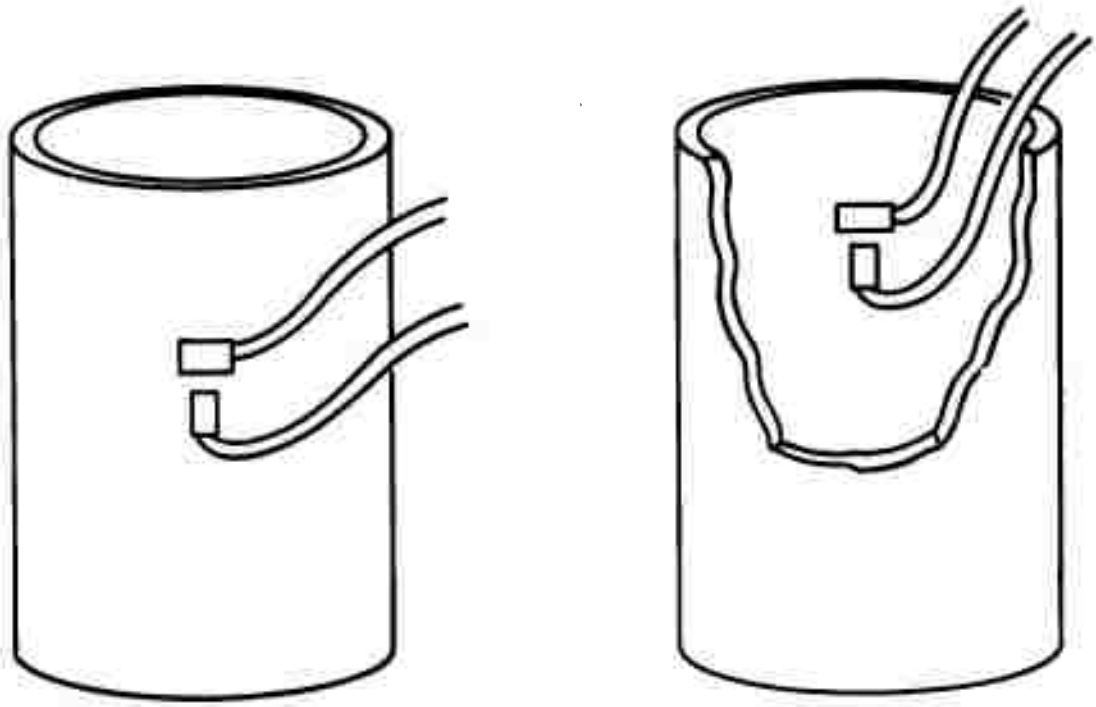
D_o = O.D. before splitting

D_1 = O.D. after splitting

Through-the-thickness stress determinations were conducted using the Sach's boring out method (ref. 9), which allowed residual stress profiles to be generated across the tube wall thickness. Two different techniques were utilized as shown in figure 1. Technique A involved strain gauging on the outside surface of the tube and metal removal from the inside surface. Technique B is the reverse of A. Technique A produces a residual stress curve that is more accurate from the inside diameter to about mid-tube. Technique B is more accurate from the outside diameter to about mid-tube.

3.1.8 Microstructure Tests

Microstructural examination of titanium tubing was performed on full cross sections at magnification from 50X (ref. 2) to 500-750X (ref. 3). The metallurgical condition required for tubes was a fine grained equiaxed microstructure. No evidence of a Widmanstatten structure was allowed in the most recent Boeing specifications. The outside and inside surfaces of the tubing were to be free from alpha-case. Specimens were usually etched in an aqueous solution containing 1 volume percent hydrofluoric acid.



A
Strain gage on outside surface. Etched from the inside surface.

B
Strain gage on inside surface. Etched from the outside surface.

FIGURE 1.–TECHNIQUES USED IN SACH'S BORING OUT METHOD

3.1.9 Ultrasonic Inspection (Ti-3Al-2.5V)

Finished tubing was 100% ultrasonic inspected for inside and outside defects per the requirements of BAC 5439-2 (refs. 3, 7). Inspection was performed with the tube run in one direction and then run in the opposite direction if only two transducers are used: one run each for longitudinal and transverse defects. If four transducers were used and the transducers were positioned from opposite directions the tubes were run in only one direction.

For Ti-3Al-2.5V CWSR tube, defect limits were standard notches Class A-2 per BAC 5439-2 for wall thicknesses less than 0.046 inch and Class B-3 for wall thicknesses 0.046 inch and greater.

For Ti-3Al-2.5V Ann. tube standard notches were in conformance with the defect limits shown in table 7 for the applicable wall thickness. Length of the standard notch was 0.060 inch for wall thicknesses less than 0.046 inch and 0.125 inch for wall thicknesses 0.046 or greater.

TABLE 7.--MAXIMUM PERMISSIBLE SIZE OF DEFECTS IN Ti-3Al-2.5V ANNEALED TUBING

Nominal Wall Thickness (Inches)	Maximum Depth of Defects (Inches)
up to 0.060	0.002
0.061 to 0.080	0.003
0.081 to 0.100	0.004
0.101 to 0.120	0.005
0.121 and over	0.006

3.2 QUALITY CONTROL RECEIVING AND INSPECTION DATA

Tubing procured from various suppliers was required by appropriate specification to be accompanied by a test report giving the results of chemical, mechanical, dimensional and NDT tests. See Appendix A. An example of such a test report is shown in figure 2.

Boeing quality control also performs certain tests on incoming material to assure that the vendor data is accurate in all respects. The extent of in-house testing depends on the degree of confidence that the Boeing Quality Control department has acquired for the item being procured. Thus, sampling and testing plans will vary on a specific item from time to time. An example of a Boeing Quality Control data sheet, covering the same material reported in figure 2 is shown in figure 3.

The Quality Control test reports from all Ti-6Al-4V and Ti-3Al-2.5V hydraulic tubing material procured by Boeing during the SST program are retained in the company files. Thus an accounting of any piece of identifiable tubing can be easily made and its certified properties determined.

Data that has been accumulated by the Quality Control department has been analyzed with respect to mechanical properties and chemical composition. The average values obtained for these items together with standard deviations and high and low values are tabulated in table 8.

3.3 ENGINEERING EVALUATION TESTS – Ti-6Al-4V ANNEALED TUBING

In addition to the Quality Control characterization tests described in section 3.1, many different types of engineering evaluation tests were performed during the titanium tubing program. A large portion of these were concerned with the influence of some parameter on fatigue life. A review of the various property interactions investigated for the alloy Ti-6Al-4V (annealed) is as follows.

3.3.1 Etching (Following Forming)

Two tubes with 120° bends were used to determine the effect of O.D. surface roughness on flexure fatigue life (ref. 10). One tube was tested in the "as-formed" condition while the

WROUGHT PRODUCT CERTIFICATION

ZIRCONIUM TECHNOLOGY CORPORATION
P.O. BOX [illegible] ALBANY, OREGON 97321

CUSTOMER The Boeing Co. W 180
CUSTOMER ORDER Y-885875-4212 W
CUSTOMER SPECIFICATION BMS 7-203A; Class B
ZIRTECH ORDER 70157 MATERIAL T1 3Al-2.5V
ZIRTECH LOT NO. 075-T4-032-157
CONDITION Stress relief annealed, 400-600 polished and cher
WEIGHT 43.5 PIECES 4 (46.55 Ft.) mille
SIZE AND FORM 1 1/2" O.D. x 0.120" W x R/L Tube
INGOT NUMBER BC-90
INGOT HARDNESS (BHN) Avg. RANGE (BHN)

ALLOY ANALYSIS (%)

Sn			
Fe			
Cr			
Ni			
Sum			
Al		3.03	
V		2.55	

IMPURITY ANALYSIS (PPM)

Al			
B			
C		200	
Ca			
Cd			
Cl			
Co			
Cu			
Cr			
Fe		2000	
* H	16	14	
Hf			
Mg			
Mn			
Mo			
* N	88	89	
Na			
Ni			
* O	00	1140	
Pb			
Si			
Sn			
Ti			
U			
U-235			
V			
W			

* D[illegible] ates that analysis was performed on the fi[illegible] product. All other results were obtained [illegible] or [illegible] alyzing samples taken from the ingot.

TESTING AND INSPECTION DATA

GRAIN SIZE: LONGITUDINAL- TRANVERSE-
HYDRIDE ORIENTATION, F_N: GRID-
PRODUCT HARDNESS, R_B

TENSILE TEST

ROOM TEMPERATURE ULT. PSI	YIELD PSI	ELONG %	ELEVATED TEMP. °F ULT. PSI	YIELD PSI	ELONG %
127,500	106,300	18.0			
129,100	111,300	14.5			
127,700	106,000	18.0			

CORROSION: STEAM ☐ WATER ☐ TIME, DAYS:
TEMP. °F PRESSURE, PSI:
APPEARANCE ACCEPT ☐
WEIGHT GAIN, mg/dm²

BURST TEST: BURST PRESSURE, PSI CIRC. ELONG. %

FLARE TEST ACCEPT ☒ BEND TEST ACCEPT ☒
HYDROSTATIC PRESSURE TEST ACCEPT ☒
FLATTENING TEST ACCEPT ☐ MICROSTRUCTURE ACCEPT ☐
ALPHA CASE NEGATIVE ☒

ULTRASONIC FLAW INSPECTION, 100 %
LONGITUDINAL ACCEPT ☒ TRANSVERSE ACCEPT ☒
ULTRASONIC WALL INSPECTION, 100 % ACCEPT ☒
SURFACE FINISH: I.D. ACCEPT ☒ O.D. ACCEPT ☒
OUTSIDE DIAMETER ACCEPT ☒ INSIDE DIAMETER ACCEPT ☐
OVALITY ACCEPT ☒ STRAIGHTNESS ACCEPT ☒
END CONFIGURATION;
SQUARENESS ACCEPT ☐ CHAMFER ACCEPT ☐

This is [illegible] certify that the product manufactured to the above order and covered by this report has been tested and inspected in accordance with the purchase order and specification(s) referenced above and has been found to meet the specified requirements.

SIGNATURE Ivan Barsov
QUALITY CONTROL MANAGER
DATE 10-15-70
20002

FIGURE 2.—TYPICAL VENDOR QUALITY CONTROL TEST REPORT FOR Ti-3Al-2.5V COLD WORKED AND STRESS RELIEVED TUBING

THE BOEING COMPANY. LABORATORY REPORT NO. 616157

Purpose _____ Model SST Date OCT 28, 1970

To: ART THOMPSON Org'n. 9-6111 Part No. T/N 20,002

Subject: _____

Source ZIRTECH. ~~Reinsp. Req.~~ LOT 075-74-032-157

Purchase Order Y-885-875 R.R. 2 Date Rec'd. 10-19-0 Quan. 46 Acc. 0 Rej. 46

Material 1.50 OD x .120 W 3AL-2.5V CLASS B Ti TUBE Spec. BMS 7-203A

[X] Chem. Lab. _____ [ ] Sonic _____ [X] Met. Lab. _____ [X] Mechanical _____

[ ] X-Ray _____ [ ] Mag/Penetrant _____ [ ] _____

Reference: C.C. to:

REJ TAG NO. FILE

CHEMISTRY:

AL	2.95%	Fe	0.13%	H2	36 PPM (.0036%)	N2	< 200 PPM
V	2.18%	C	.01%	O	810 PPM (.081%)	Ti	BAL.

MECHANICAL:

Ftu (KSI)	Fty (KSI)	% ELONG.
125.9	101.9	13

FLARE, FLATTEN AND BEND TEST:

MAT'L MEETS SPECIFICATION REQUIREMENTS

METALLURGICAL: SEE LAB REPORT AND PHOTOMICROGRAPHS ATTACHED.

TIME 6.3 HRS

Prepared by Dave Macdonald Approved by _____ Org'n. 2-4748

U3 4161 7000

20002

FIGURE 3.—BOEING QUALITY CONTROL REPORT COVERING THE SAME MATERIAL REPORTED IN FIGURE 2

TABLE 8.—MECHANICAL PROPERTIES AND CHEMICAL COMPOSITION DATA FOR Ti-6Al-4V ANNEALED AND Ti-3Al-2.5V COLD WORKED AND STRESS RELIEVED TUBING PRODURED FOR THE SST PROGRAM

Parameters	Ti-6Al-4V Procured Per XBMS 7-178 (142 Data Points)				Ti-3Al-2.5V Procured Per BMS 203A (Class B) and XBMS 7-234 (258 Data Points)			
	Mean	Maximum	Minimum	Standard Deviation	Mean	Maximum	Minimum	Standard Deviation
Properties								
UTS, ksi	143.9	157.2	131.5	12.3	130.0	151.7	115.8	~ 10.5
TYS, ksi	129.2	144.7	108.0	6.6	111.3	136.3	92.0	~ 10.0
Elongation, %	17	27.0	7.5	4.5	15.1	24.0	10.0	~ 3.9
Composition (Wt. %)								
Oxygen	0.117	0.204	0.040	0.030	0.096	0.162	0.06	0.011
Nitrogen	0.024	0.073	0.006	0.018	0.024	0.086	0.005	0.021
Hydrogen	0.0041	0.0115	0.0008	0.0022	0.0029	0.0079	0.0006	0.0019
Carbon	0.031	0.090	0.005	0.015	0.022	0.050	0.008	0.011
Aluminum	6.2	6.7	5.6	0.2	3.1	3.5	2.5	0.2
Vanadium	4.1	4.4	3.7	0.2	2.5	2.7	2.0	0.1
Iron	0.13	0.18	0.08	0.03	0.18	0.26	0.10	0.04

other had been etched ~ 0.002" from the outside surface after forming to improve surface smoothness, then tested. Both tubes were Ti-6Al-4V ELI (MA)1 x .057 x 30 inches in length and were formed with a standard tube bending machine using a close-tolerance four-ball bronze mandrel and wiper die. The tubes were pressurized to 3000 psig with XBMS 3-10 hydraulic fluid during fatigue testing and failure was sensed by a drop in pressure which automatically stopped the test.

The formed tube specimens were fatigue tested in rotary flexural bending at a maximum axial bending stress of 21,000 psi and an internal pressure of 3000 psig. These tests were performed at an accelerated rate of 108,000 cycles per hour. The fatigue life of each tube specimen was as follows:

Unetched	61,100 cycles
Etched	– 335,000 cycles

The fatigue life goal was 10×10^6 cycles so that failure of both tubes was considered premature although a five-fold improvement was attained by etching the O.D. surface after forming.

The mode of failure in both tubes was fatigue, but crack initiation in each case was different; the crack on the unetched tube started at the O.D. on the inside of the bend, while the crack on the etched tube started at the I.D. The microcracks or "strike marks" at the O.D. surface around the bend served as nuclei for fatigue crack initiation on the unetched tube. These cracks initiated in the transverse direction, then rotated and propagated in the longitudinal direction. In the etched tube the tool marks at the I.D., such as scoring, were dominant, resulting in failure from the I.D. instead of the O.D. However, in neither case were the surface defects of critical size to produce early failure by themselves except in the bend area where the applied stresses also were high.

Based on the results of these two tests, etching of at least 0.002 inch from the outside surface after forming can be highly beneficial to the fatigue life of formed tubes. The significant improvement attained is attributed to removal of short microcracks or "strike-marks" produced by belt-sanding. See figure 4.

3.3.2 Stress Relieving

Two Ti-6Al-4V tubes with 120° bends were tested in rotary flexural fatigue after stress relieving at 1250°F in argon followed by chemical milling 0.002 inches of material from the O.D. (ref. 11). The removal of 0.002 inch minimum from the O.D. was necessary to eliminate the microcracks produced along belt-sanding striations during bending. The tube specimens were 1½ x 0.086 x 30 inches long annealed Ti-6Al-4V ELI. Stress relieving was performed after bending to determine the effect of this process on fatigue life compared with two similarly tested tubes which had been chemically milled only. Tubes for both programs were from the same lot of material and were produced to the requirements of XBMS 7-178.

FIGURE 4.–AN EXAMPLE OF HOW A SANDING STRIKE-MARK CAN ACT AS A FATIGUE CRACK ORIGIN. THIS TUBE WAS SANDED (GRIT NOT SPECIFIED) AND CHEMICALLY MILLED, BUT NOT SUFFICIENTLY TO REMOVE ALL SANDING MARKS.

The sequence of process operations used in preparation of the stress relieved tubing was as follows:

- R.T. bending with a precision three-ball mandrel and wiper die.
- Light pickle in HF-HNO_3 solution.
- Stress relieved at 1250°F for 30 minutes in an argon atmosphere.
- Chemically milled (etched) 0.002-inch from the O.D. surface.
- Fluorescent penetrant inspected with ZL-2A.
- Cut to length with an abrasive cutoff wheel.

The cycles to failure of the stress relieved tubes were found to be very short compared to tubes that had been chem-milled only. The results were as follows:

Not Stress Relieved	– Unetched	–	650,000 cycles
	Etched	–	6,800,000 cycles
Stress Relieved	– Etched	–	162,000 cycles
	Etched	–	86,400 cycles

Fractographic analysis show that the stress relieved tubed failed in fatigue with the cracks originating on the I.D. near the neutral axis. The crack on one of the tubes started near the start of the bend while the other started at the apex of the bend. Both failures occurred at the neutral axis as would be expected as this is the point of highest circumferential stress.

No oxygen contamination was found either on the microsections or by chemical analysis. All tubes had a fine-grain equiaxed alpha microstructure with no evidence of an alpha case. (Chemical miling 0.002 inch from the surface would be expected to remove any surface contamination present.)

The cause of early failure of both stress relieved tubes could not be attributed to distinct and identifiable defects such as pits, scratches or cracks. The large spread in fatigue life between the stress relieved tubes and those not stress relieved is considered to have been caused by the elimination of beneficial residual stresses.

3.3.3 Shot Peening

A 1½ x .110 inch Ti-6Al-4V tube was bent 120 to a 6-inch radius (R/D = 4) (ref. 12). After bending, the part was shot peened on the O.D. by Pangborn at South Gate, California. Shot peening parameters were not given.

The part was proof pressure tested to 8300 psi then successfully pressure impulse tested for 20,000 cycles at 70°F, -50°F, and 200°F. The tubing failed at 400°F after 21,000 cycles due to a leak through a small crack. Inspection of the fracture showed that the point of origin was a lap defect on the I.D. The obvious conclusion to be drawn from this study is that peening on the outside diameter will not prevent failure from originating at a defect on the inside diameter.

3.3.4 Surface Coatings for Prevention of Fretting Fatigue

During the first phases of flexure fatigue testing of welded tube joints, efforts were plagued by early failures induced by fretting at the collet chucks gripping the tube ends. In order to test the effectiveness of a nonstructural adhesive in preventing fretting fatigue, two butt-welded tube specimens, made from 1½ x 0.085 x 20.75 inch long Ti-6Al-4V ELI tubing, were fatigue tested in single-plane reverse bending (ref. 13). These specimens contained a thin layer of BMS 5-29 nonstructural adhesive between the tube and collet at the fixed end. The purpose of adding an adhesive layer was to avoid fretting between the faying surfaces of the tubes and collets. The results of the tests are shown in table 9.

TABLE 9. –COMPARISON OF THE FATIGUE BEHAVIOR OF TUBES TREATED WITH A NONSTRUCTURAL ADHESIVE, (BMS 5-29) TO PREVENT FRETTING WITH UNTREATED TUBES

No Adhesive	R1A4D-1F –	1,205,000 cycles –	fretting fatigue
	R1A4D-2F –	468,000 cycles –	fretting fatigue
	R1A4D-3F –	445,000 cycles –	fretting fatigue
	R1A4D-4F –	526,000 cycles –	fretting fatigue
	R1A4D-5F –	562,000 cycles –	fretting fatigue
Adhesive	R1A4D-6F –	6,180,000 cycles –	fretting fatigue
	R1A4D-7F –	14,850,000 cycles –	no failure

These tests indicate a tremendous improvement in fatigue life was attained by adding a thin layer of BMS 5-29 at faying surfaces.

Fatigue failure of Tube 6F, containing this layer of adhesive, was induced by fretting in exactly the same manner as the no-adhesive tests. The fretting did not occur, however, until the thin layer of adhesive was squeezed out and metal-to-metal contact was established during cyclic loading of the test part. As in the previous tests, a fatigue crack then developed in this highly stressed area. By comparison, the fatigue life of this specimen was increased by five-fold over the highest in the previous five tests.

Testing of Tube 7F was discontinued after 14,850,000 cycles with no failure either at the faying surface or the weld. None of the welds on the previous tests failed. Based on strain gage readings the maximum bending stress at the welds was about 24,000 psi, demonstrating that butt-welds are satisfactory under these test conditions.

On the basis of these findings it was concluded that fretting-induced fatigue of Ti-6Al-4V tubing could be prevented if a soft, nonfretting material such as teflon (fabroid), adhesive film, anodic hard coating, or solid film lubricant is placed between all surfaces subject to any localized movement or rubbing.

3.3.5 In-Place Fusion Welding

An engineering developmental program was carried out on the development of joint configurations for in-place and bench type fusion welding of titanium alloy tubing (ref. 14). Mechanized orbital gas tungsten arc welding of joints was employed in two near-extreme sizes of Ti-6Al-4V tubing. The following general conclusions can be made with a high degree of confidence, based upon the program results.

1. Butt joints are the most satisfactory type, based upon flexure testing, ease of welding, and visual and radiographic inspectability. These joints may be produced using any of the detail tube end configurations shown in figure 5.

   Each of the configurations shown in figure 5 results in a butt fusion welded joint of the type shown in figure 6.

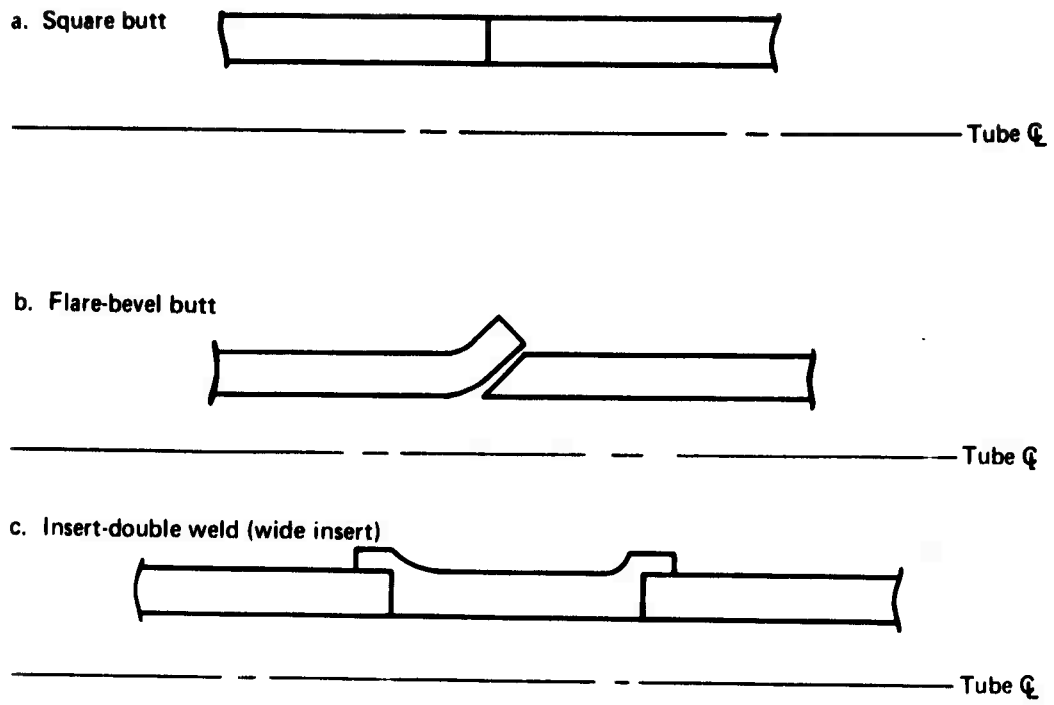


FIGURE 5.—BUTT WELD JOINT CONFIGURATIONS

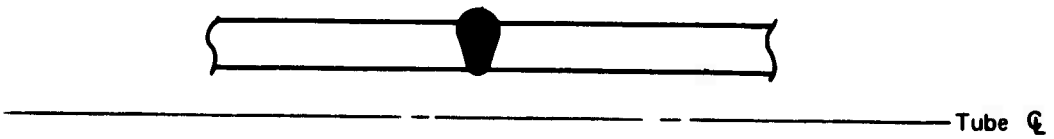


FIGURE 6.—BUTT WELD BEAD CONFIGURATION

The square butt configuration is the simplest form. The flare-bevel butt configuration, where applicable, should permit greater amounts of end fitup tolerance than the square butt, and it provides filler metal addition to the joint. However, the joint is more difficult to accomplish than a properly set up square butt joint. This joint cannot be made in thick gages because of inability to flare the tubing.

The insert double weld configuration likewise should tolerate a greater amount of end fitup variation than the square butt configuration, and it provides controlled filler metal addition. It can be employed for almost any tubing size and can be custom designed to suit specific joint requirements. The insert may be used in tube-to-tube joining, and can also be used for repairing tubing and welded tube joints in many cases. The insert end configuration can also be incorporated into fittings designed for weld attachment to tubing as shown in figure 7.

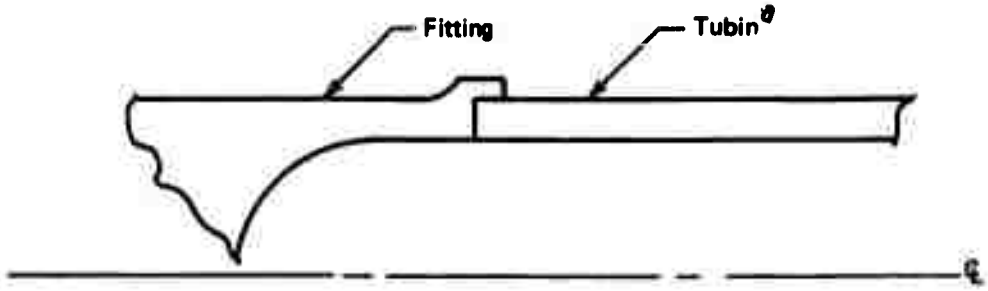


FIGURE 7.–BUTT WELD CONFIGURATION FOR FITTING AND TUBE

2. Shear load transfer sleeve type joints (double weld melt through), figure 8, are undesirable primarily from the standpoint of flexural fatigue and weldability in thick gages. These joints are heavier in all cases than the butt types shown in figure 5. In addition, the lap surfaces are traps for possible contaminants.

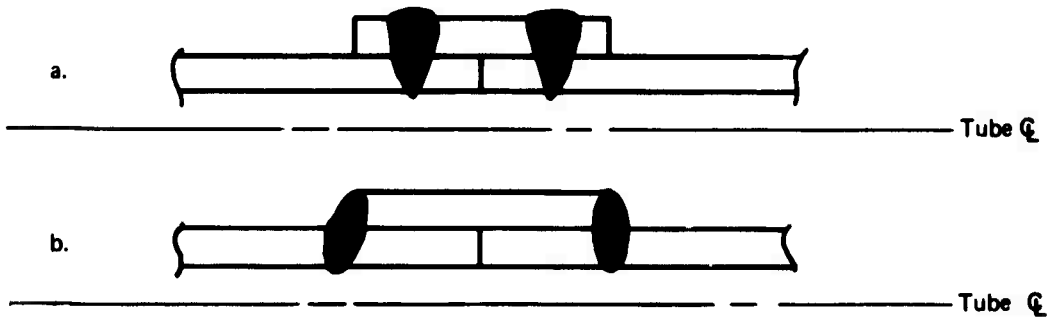


FIGURE 8.–WELD BEAD CONFIGURATION FOR SHEAR LOAD JOINTS

3. Single melt through sleeve but joints, figure 9, are more difficult to produce then the butt joints described in Item 1 because of difficulty in aligning the electrode with the tube ends, as well as increased difficulty in radiographic interpretation of the weld. Preliminary data also indicates that the flexural fatigue life for this type of joint is more erratic than for joints described in Item 1. This joint is also heavier than the joints described in Item 1.

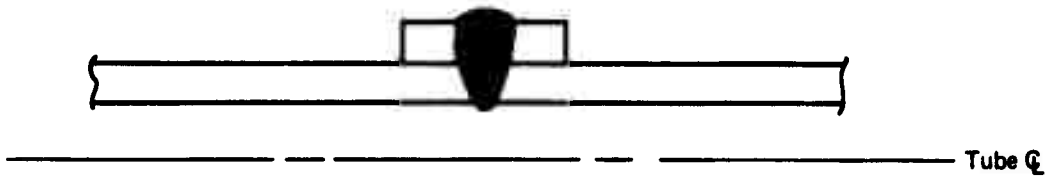


FIGURE 9.–WELD BEAD CONFIGURATION FOR SINGLE MELT THROUGH BUTT JOINTS

Several investigations have been performed to investigate the fatigue behavior of welded tube specimens. Most tests resulted in failures from items other than the weld or the weld heat affected zone and in general indicated that properly welded joints would satisfactorily meet fatigue requirements. Results from three of these investigations are summarized below:

1. Failure Analysis of Butt-Welded ½ x 0.029 inch Ti-6Al-4V Tubes After Fatigue and Pressure Impulse Testing

The purpose of this program was to evaluate butt-welding techniques on ten ½ x 0.029 inch tube specimens that had been produced with varying gap sizes ranging from zero (net) to 0.014 inches. In-place welding was accomplished with a Boeing-modified Astro-Arc welding head using weldtronic controls. Three of the tested tubes were submitted for examination of the failure. The test results for the three specimens are as follows:

Specimen	Gap Size	Cycles to Failure	Location of Failure
SK-072620-5A	Zero (net)	3,390,000	Tube – 1 inch from weld area
SK-072620-1A	0.003 in.	183,500	Tube – 2½ inches from weld area
SK-072620-2	0.006 in.	486,000	Tube – 1 inch from weld area

All of the tubes were found to have failed away from the weld area such that there could not have been any influence of the weld on the cause of failure.

Of the remaining seven specimens, one failed during single-plane flexure bending after 9×10^6 cycles. Three others survived 10×10^6 cycles of flexure bending but failed subsequently during pressure impulse testing. Three specimens did not fail after both the 200,000 pressure impulses at 2250 psi peak pressures and the 10×10^6 flexure bending cycles.

Based on the test data and failure modes, it is concluded that in-place butt-welded Ti-6Al-4V tubing can survive the designated test requirements provided the tube and welds are of good quality.

2. Failure Analysis of GTA Welded Joints on Twentysix 1½ x 0.110 in. Ti-6Al-4V Tube Specimens Tested in Fatigue

This report covers the results of testing twenty-six GTA fusion welded tube specimens in both pressure impulse and rotary flexure fatigue (ref. 16). All tubing consisted of mill annealed 1½ x 0.110 in. Ti-6Al-4V ELI produced to XBMS 7-178. Each specimen was fabricated by welding a 12-inch tube section to the tubular section of a machined adapter designed to concentrate the bending load at the weld. The adapter was machined from Ti-6Al-4V bar stock. GTA fusion welding was accomplished using a "double uphill" technique.

Two weld joint configurations were evaluated: a square-butt weld (16 specimens) and an overlap butt weld (10 specimens). Of the first group, three specimens were welded in the vertical position and 13 in the horizontal position. Of the second group, five were tested in the "as-welded" condition and the other five after having been stress relieved at 1300°F for 10 minutes in argon.

A sketch of the test specimen and joint configuration is shown in figure 10.

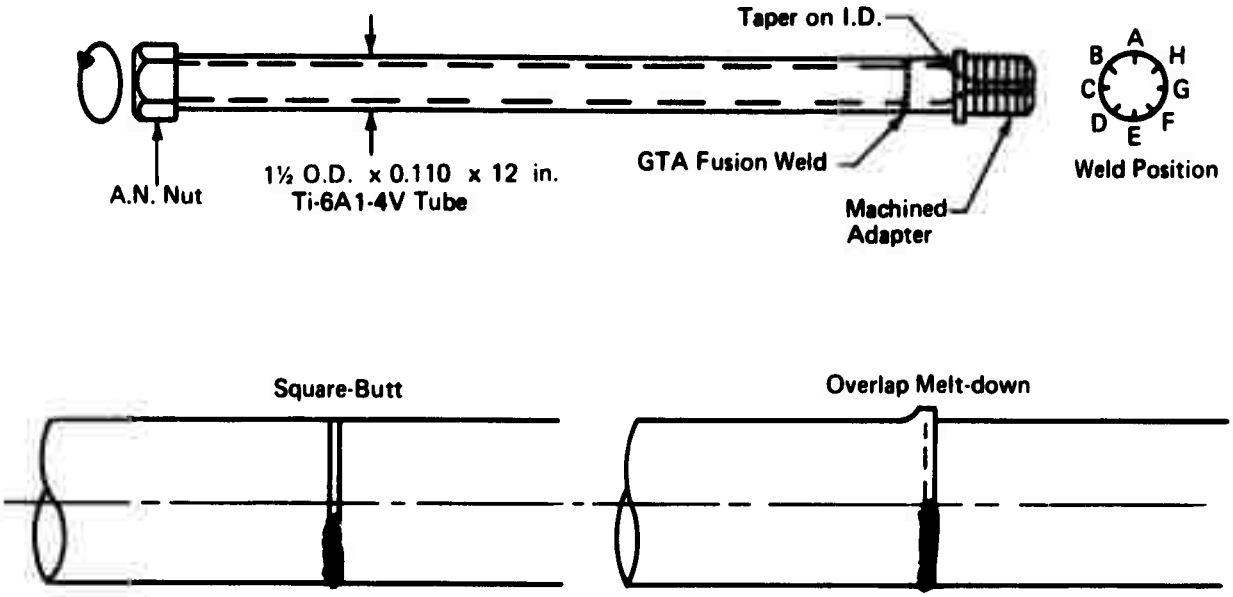


FIGURE 10.– SPECIMEN AND JOINT CONFIGURATIONS FOR FATIGUE TEST SPECIMENS

All of the specimens were tested first in pressure impulse for 100,000 cycles to a peak pressure of 6000 psi for 20,000 cycles each at RT, -50°, +200°, and +425°F. All specimens that survived were subsequently tested in rotary flexure to failure or 10^7 cycles whichever came first, while maintaining an internal pressure of 4000 psi. These later tests were performed at 108,000 cycles per hour at a designate double-amplitude deflection, usually ~0.29 inch.

Welding in both cases was accomplished using a Sciaky GTA power supply-programmer and a Boeing-modified Astro-Arc welding head. A recently developed "double uphill" welding sequence was programmed into the machine as an approach for making more consistent weld bead contour with a minimum of underfill and greater weld penetration. Arc-current pulsing was employed except when changing direction and during tailout for better control of weld puddle. The high current pulses were in the range of 65-105 amperes dc and the low current pulses at 16-26 amperes dc. A mixture of 90 percent helium-10 percent argon gases were utilized as protective atmosphere. Later, all of the welds were x-ray radiographic inspected per BAC 5915-2 using the double-wall technique. The overlap melt-down butt welds were also x-ray inspected by the single-wall technique in order to assure thorough inspection. This consisted of eight shots in two directions for a total of 16 shots per specimen. In neither case were any weld defects found by single-wall or double-wall techniques which could have been considered of rejectable size per D6A10682-2.

To check residual stresses, a split-ring technique using Crampton's formula was used for analysis. In no case were the circumferential residual stresses over 3000 psi.

The oxygen and nitrogen content was checked in the weld area for possible contamination. There was no evidence to show that contamination due to improper shielding was responsible for any of the failures.

All of the square-butt welded specimens failed prematurely while the overlap butt welded specimens survived 100,000 cycles of pressure impulse and 10^7 cycles of rotary flexure without a single failure. Six square butt-welded specimens welded in the horizontal position exhibited a failure at the geometric top of the specimen in the weld region.

A typical crack started at the thinned section of the weld on the ID. Thinning ranged up to about 17 percent of the tube wall thickness. Maximum thinning always occurred at the toe of the weld with approximately the same amount on both sides of the fusion zone on specimens welded in the horizontal position. Thinning was caused by a lack of metal at the fusion zone and was aggravated by underfill and underbead due to differences in width.

Several specimens displayed vertical sagging of the weld bead due to gravity which produced a thinned condition at the upper edge of the weld. Failures originated at these thinned sections with the crack propagating in the longitudinal direction rather than transverse.

A typical transverse weld failure occurred where thinning at the toe of this weld was from 10 to 17 percent. Of the 13 specimens that failed in this manner, no defects were found on the respective fracture faces at or near the origin.

Several failures occurred during pressure impulse testing and were caused by an existing ID tube defect. On these specimens, the ID defects consisted of a few isolated short laps ranging in length from ¼ inch to 0.1 inch and up to 0.003 inch in depth. On three specimens where these lap defects were noted, stress corrosion (branch cracking) was found beyond the tip of the crack. Thus, failure is attributable both to an existing defect and a stress corroded condition. The cause of the stress corrosion is not yet known but has been found only on those tubes pressure impulse tested at elevated temperatures of 425°F.

There is some belief that weld failures can also be dependent on the size of the included angle at the toe of the weld. The smaller the included angle the greater the propensity to early weld failure when loaded in bending, due to a notch effect.

Microhardness tests were made across various welds to determine differences in hardness of the base metal, Heat Affected Zone (HAZ), and weld. There was almost no difference, as averages ranged from R_C 30.3 for the lowest to R_C 34.8 for the highest hardnesses.

Based on the foregoing, Ti-6Al-4V ELI tubing can be successfully welded by GTA fusion welding techniques to produce highly reliable permanent joints. Welding must incorporate a method for maintaining wall thickness at the joints approximately equal to that of the tubes being joined in order to prevent a drastic reduction in fatigue life associated with thinning. In addition, tubing must not contain defects which may be aggravated by stress corrosion cracking and/or serve as origins for fatigue cracks.

In summary the following factors are of paramount importance:

- Avoid welding conditions which produce excessive thinning of the fusion weld zone. For making permanent joints on tubing, use the overlap-butt weld or a similar arrangement which guarantees retention of a wall thickness at the fusion zone approximately equal to the base metal and greater than that obtained by a simple square-butt weld.

- Minimize underfill of the weld by utilizing a well-programmed weld sequence and arc current pulsing.

- Employ only the highest quality tubing possible.

3. Failure Analysis of Five Welded 1½ x 0.086 in. Ti-6Al-4V Tube Specimens with A Wide-Insert Forming the Weld Joint

Five welded specimens, consisting of a Ti-6Al-4V tube and a machined adapter both welded to a wide insert, were fatigue tested for the purpose of evaluating the two weld joints (ref. 17). Of these five specimens, only one failed in test.

In making these specimens, a 10-5/8 in. long tube was welded to a machined tubular wide-insert containing a small lip for melt-down on each side. Opposite the tubing was welded the machined adapter which contained a slight taper on the I.D. designed to concentrate the bending load on the weld joints. A sketch of the test specimen and joint design is shown in figure 11.

GTA fusion welding of the tubular joints at two locations on each specimen was accomplished by a single-pass technique with about 60° circumferential overlap from the starting point. A Boeing-modified Astro-Arc tube welding head, connected to a Sciaky GTA power supply-programmer, was utilized in conjunction with arc-current pulsing. The high pulses ranged from 30 to 70 amperes DC and the low pulses from 7 to 17 amperes DC. To preclude weld contamination, the OD and ID were continuously flushed with a mixture of 80% helium and 20% argon inert gas atmosphere. Electrode travel speed, adjusted to produce consistent weld penetration, was approximately one inch per minute. After welding, all joints were x-ray radiographic inspected by the double wall technique. All welds were found to be of acceptable quality.

The overlapping lips on each side of the wide insert were melted down during the weld cycle providing additional filler metal to the weld joint. With this approach, thinning around the joint was kept to a minimum; a desirable condition for improving fatigue life. Development of a thicker joint is particularly important when tested in bending such as rotary flexure.

Testing was performed in the hydraulics laboratory in accordance with the following schedule:

- Proof pressure at ambient temperature to a pressure of 6000 psi.

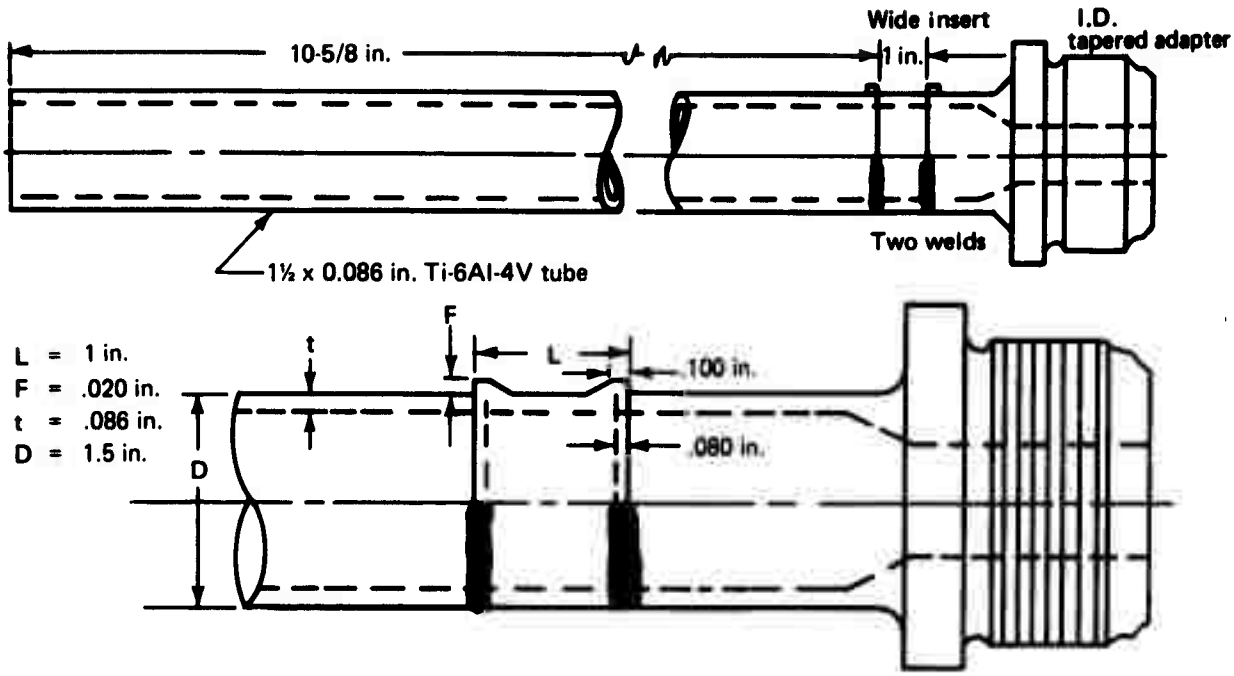


FIGURE 11.– SPECIMEN AND JOINT CONFIGURATION FOR FATIGUE TEST SPECIMENS

- Pressure impulse to a peak pressure of 4500 psi at a pressure rise of 200 to 244 ksi/sec at the four temperatures shown.

Ambient	–	20,000 cycles
-50°F	–	20,000 cycles
+200°F	–	20,000 cycles
+425°F	–	40,000 cycles

- Proof pressure at ambient temperature to a pressure of 6000 psi.

- Rotary flexure tests at 1750 rpm, a radial deflection of ± 0.101 and internal pressure of 3000 psi (bending stress of about 21,000 psi).

WSX 7597 hydraulic fluid was used for pressurization during all testing listed above. These rotary flexure tests were performed at ambient temperature. The results of the tests are shown in table 10.

Analysis of the one failed specimen (B1D3-1) indicated that the fatigue crack originated at the O.D. along the toe of the weld on the wide-insert side towards the adapter. The crack propagated approximately ¼ in. before testing was stopped as a result of pressure drop caused by leakage. No evidence of a pre-existing tube defect or prior weld crack was detected. The microstructure was normal of a welded zone in Ti-6Al-4V.

TABLE 10.–THE FATIGUE BEHAVIOR OF GTA FUSION WELDED Ti-6Al-4V TUBE SPECIMENS

Specimen	Cycles In Pressure Impulse	Cycles In Rotary Flexure	Type of Failure
B1D3-1	100,000	336,000	Circ. crack on weld
B1D3-2	100,000	9.95×10^6	No failure
B1D3-3	100,000	1.007×10^7	No failure
*B1D3-4	100,000	1.005×10^7	No failure
B1D3-5	100,000	1.006×10^7	No failure

*The high temperature impulse tests (40,000 cycles) on this specimen were conducted at 400°F with a pressure peak of 6200 psi, a working pressure of 4150 psi, and a pressure rise of 320 ksi/sec.

3.3.6 Hydraulic Fittings

Several different types of hydraulic fittings have been used with Ti-6Al-4V tubing to determine the most satisfactory of those that are available. The following information, with respect to the fatigue behavior of tubes fitted with various fittings has been acquired.

3.3.6.1 Resistoflex Fittings

A sample of 1½ x 0.35 in. Ti-6Al-4V tubing with Resistoflex dittings was fatigue tested at ±21,000 psi in flexure with an internal pressure of 1500 psi (ref. 18). After approximately 792,000 cycles the tube failed in the change of section adjoining the fitting. Examination of the failed tube showed that the fatigue nucleus was on the internal surface at the change in section. There were no defects associated with the failure. The position of failure was influenced by a residual stress which resulted from the application of the fitting. The tube wall thickness was reduced 20% during swaging.

3.3.6.2 Aeroquip Union Fittings

Three Aeroquip union fittings were induction brazed by the Aeroquip Corporation, Jackson, Michigan, with an in-place brazing head using 48Ti-48Zr-4Be braze alloy. These brazed specimens were subsequently fatigue tested by Boeing in single-plane reverse bending (ref. 19). The tubing used was Ti-6Al-4V annealed and was ½ x 0.029 x 17 inches long.

For testing, the brazed union fittings were set adjacent to the fixed end on the test fixture; on the opposite end was applied the cyclic bending load. While being tested the assembly was pressurized to 3000 psi with MIL-S-5606 hydraulic fluid.

Test results were as follows:

Specimen 1 – 75,600 cycles
Specimen 2 – 2,400,000 cycles
Specimen 3 – 10,000,000 cycles – no failure

The fatigue-life goal for these specimens was 10×10^6 cycles.

Specimen 1 failed when a leak developed through a pin-hole on one edge of the union fitting. It is likely that a series of voids eventually joined during testing to form a continuous tunnel through the brazement. This pin-hole was located at the widest gap in the joint where numerous voids were found. They were probably caused by outgassing of the acrylic binder in the braze alloy. In general, the overall condition of the brazed joint in this union fitting was considered very poor.

Specimen 2 failed when fatigue crack formed in the tube at a distance of 1.5 inches from the brazed union fitting. This crack was not associated with the brazing operation.

Based on the foregoing tests the following recommendations are set forth to assure better brazing of Ti-6Al-4V hydraulic tubing by Aeroquip's in-place methods:

- Reappraise 48Ti-48Zr-4Be braze alloy for outgassing, flowability, and erosion.
- Use better techniques and controls for the X-ray examination of brazed joints.

3.3.6.3 MIL-FLO Fittings

Several investigations have been performed to evaluate the performance of MIL-FLO fittings in fatigue. Three of these are as follows:

1. Failure Analysis of Eight MIL-FLO Hydraulic Fittings and Sleeves on ½ inch Ti-6Al-4V Tubing

Eight tube test assemblies, containing a MIL-FLO adapter, nut and sleeve, were fatigue tested as a rotating beam by MIL-FLO, Inc., Dayton, Ohio (ref. 20). After testing, the failed specimens were submitted to Boeing for failure analysis. Five of these tube assemblies contained a Type 420 stainless steel sleeve (annealed) and the other three contained a 6061-T6 aluminum alloy sleeve. The nuts and adapters used in the tests were made from 17-4PH stainless steel.

Fatigue testing was performed at a vertical bending stress of about 26,000 psi and a horizontal bending stress of about 25,000 psi on all the test specimens. They were rotated at a speed of 1780 rpm and a test torque of 60 ft.-lbs. while maintaining an internal pressure of 1000 psi. All tests were conducted with an offset at 5-in. from the outer end of the sleeve of the tube. The offset was measured in the horizontal and vertical planes with a dial indicator by rotating the tube by hand.

The dimensions of the Ti-6Al-4V tubes used as test specimens were ½ x 0.028 x 5 inches long. Test results are shown in table 11.

Four of the tubes failed in fatigue, there was no failure in specimen 4, and the remaining three developed slow leaks by wearing at the ends of the flare beneath the sleeve.

None of the tube failures were in any way related to the sleeve materials investigated as part of these eight tests. The major factor which caused early failure was excessive wear at the edge of the tube due to fretting beneath the sleeve.

TABLE 11.– THE FATIGUE BEHAVIOR OF Ti-6A1-4V TUBING FITTED WITH MIL-FLO HYDRAULIC FITTINGS AND SLEEVES

Test Specimen	Sleeve Material	Cycles to Failure	Bending Stress, * psi	Type of Failure
1	420 SS	60,520	27,086 26,214	Fatigue; 0.1-in from end
2	420 SS	939,840	25,996 24,465	Fatigue; center or midpoint
3	420 SS	840,160	25,996 24,465	Fatigue; beneath sleeve
4	6061-T6	14,601,340	25,793 24,685	No failure – Tube used again in 5
5**	420 SS	1,290,500	24,903 23,593	Fatigue; center or minpoint
6	420 SS	13,973,000	26,650 25,340	Wear at edge; very slow leak
7	6061-T6	4,207,920	26,214 25,122	Wear at edge; very slow leak
8	6061-T6	9,311,180	26,214 25,122	Wear at edge; very slow leak

*The first valve is the vertical bending stress, the second, the horizontal bending stress

**Tube in specimen 4 was used again in specimen 5 with sleeve on opposite end.

Specimen 1 was subjected to a slightly higher bending stress than any of the other test specimens which may account for the shorter fatigue life.

2. Metallurgical Examination of MIL-FLO Test Specimens with ½ x 0.029 in. Titanium 6Al-4V Seamless Tubing

Metallurgical examination of two fatigue tested Ti-6Al-4V seamless tubing specimens fitted with MIL-FLO fittings, 8MFT/6 and 8MFT/10, showed that both specimens failed from the outside diameter (ref. 21). The 8MFT/6 tube failure initiated on the O.D. at the section which was reduced when the fitting was installed. There was, in addition, a circumferential line of fretting adjacent to the failure. The microstructure was normal with no evidence of surface contamination.

Examination of the fracture surface of 8MFT/10 showed that the initial fatigue failure origin was on the outside diameter of the tube at a fretted area. This structure was normal with no surface contamination.

Surface finish determinations gave the following values:

	8MFT/6	8MFT/10
Inside Diameter	75 RHR	75 RHR
Outside Diameter	70 RHR	65 RHR

Knoop microhardness determinations were made and gave converted Rc values of 30.6 for both tubes.

It is concluded that 8MFT/6 failed as a result of the reduction in diameter caused by the application of the fitting.

Specimen 8MFT/10 failed on the outside diameter of the tube at a fretting mark that was associated with the fitting.

3. Failure Analysis of Three MIL-FLO Fittings on Ti-6Al-4V Tubing Evaluated for the SST Hydraulic Systems

Three Ti-6Al-4V tube specimens, fitted with 17-4 PH MIL-FLO sleeves, were evaluated for use as reconnectable fittings on the SST hydraulic systems (ref. 22). The tubing material consisted of 1½ x 0.110 in. Ti-6Al-4V ELI annealed produced to XBMS 7-178. Specimens were proof pressure tested at 9300 psi, followed by five repeated pressure impulse tests and finally (for two specimens) rotary flexure fatigue tested.

Installation of the MIL-FLO sleeve was accomplished with two special tools, which sized the tube to the sleeve and flared the end of the tube. See figure 12.

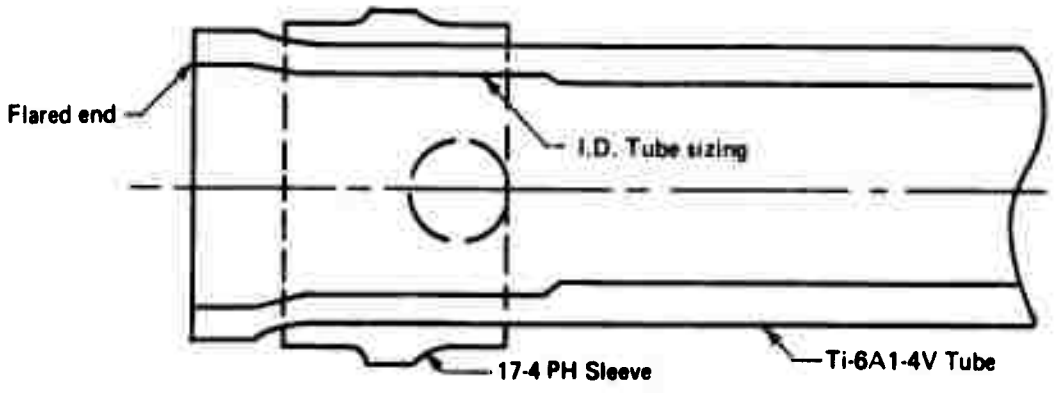


FIGURE 12.–MIL-FLO FITTING AND TUBE CONFIGURATIONS

Pressure impulse testing of the specimens was accomplished according to the following schedule using different test temperatures and peak pressures as indicated.

Temperature	No. of Cycles	Peak Pressure	Rate of Rise ksi/sec
Ambient	20,000	6300	400
-50°F	20,000	6250	400
+200°F	20,000	6150	390
+400°F	40,000	6100	340

WSX 7597 hydraulic fluid was used for pressurization during all the tests. Rotary flexure testing was accomplished at 105,000 cycles per hour with a radial deflection of 0.178 inch double amplitude. Pressurization during rotary flexure was at about 4150 psi. Test results were as follows:

Specimen No.	Cycles Press. Impulse	Cycles Rotary Flexure	Cause of Failure
24110M-1	100,000	1,530,000	Loosened sleeve resulted in leakage
24110M-2	100,000	326,000	Fretting fatigue beneath the sleeve
24110M-3	40,000	–	Existing I.D. lap defect near the sleeve

Specimen -1 became loosened during rotary flexure testing resulting in leakage. Since no protective material was used between the sleeve and tubing, severe fretting occurred in Specimen -1 became loosened during rotary flexure testing, resulting in leakage. Since condition led to fatigue cracking and failure of the specimen. Specimen -3 failed prematurely during pressure impulse due to an existing I.D. tube defect. This type of failure has been common on other test specimens due primarily to inadequate ultrasonic inspection of the tubing.

Based on this investigation the following conclusions may be made:

- Fretting-induced fatigue cracking of the Ti-6Al-4V tubing was caused by the relative movement of the MIL-FLO sleeve in the connection. Fretting of the Ti-6Al-4V tubing could be reduced by coating the I.D. surface of the MIL-FLO sleeve with a copper plate or solid film lubricant and/or by incorporating serrations on the I.D. of the sleeves similar to those used on Resistoflex fittings.

- Existing I.D. tube defects may cause early failure of tubes even at the relatively low stress conditions of the pressure impulse testing.

3.3.7 Effects of Forming on Strength

Test specimens for this investigation were 1 x 0.057 x 30 in. long Ti-6Al-4V ELI (MA) tubes and were formed with a standard tube bending machine using a close-tolerance four-ball bronze mandrel and wiper die (ref. 10).

Subsize tensile specimens, with 0.50-inch gage length and 0.125-inch width, were taken from the bend and straight areas of the specimen after fatigue testing. Figure 13 shows the areas from which specimens were taken.

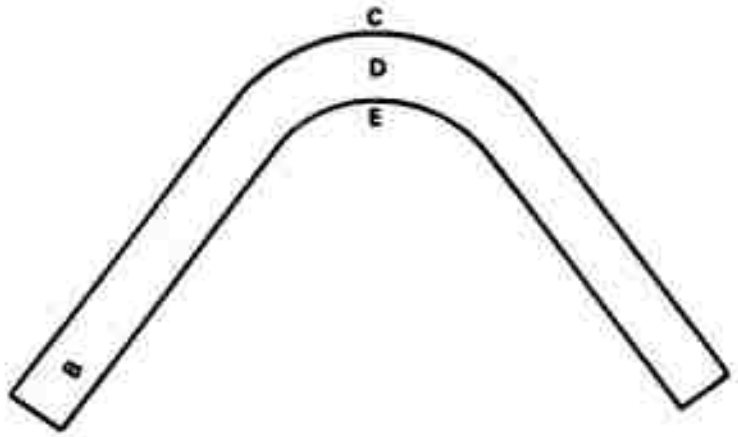


FIGURE 13.–AREAS FROM WHICH SPECIMENS WERE TAKEN FROM BENT Ti-6Al-4V TUBES

The tensile test results for these specimens are shown in table 12.

TABLE 12.–THE EFFECTS OF FORMING ON THE STRENGTH OF Ti-6Al-4V ANNEALED TUBING

Specimen	Ultimate Strength	Yield Strength	% Elongation
B	142,900	128,600	12
C	167,200	125,000	6
D	144,300	108,600	12
E	141,000	80,800	14

The data indicates that a substantial amount of strengthening occurs on the tension side of the bend, particularly in the ultimate strength value. Likewise a substantial drop in strength is noted in the compression area of the tube. This reduction in properties is primarily reflected in the yield strength value and is probably due to the Bauschinger effect.

3.3.8 Surface Characteristics: Finish and Defects

Many investigations have been carried out to characterize the effects of surface finish and defects on various properties and processes. These investigations are summerised as follows:

3.3.8.1 Effects of Surface Finish on Ultrasonic Indications

Two lots of 1½ x 0.035 in. Ti-6Al-4V ELI tubing (200 feet) were ultrasonic inspected and found to be over 90 percent defective (ref. 23). Subsequent studies by metallographic methods and with a right-angle boroscope showed that only 16 percent of the tubing was actually defective in accordance with the requirements of XBMS 7-178. It was determined that the ultrasonic transducers were unable to distinguish between numerous small I.D., discontinuities and larger defects, resulting in an almost continuous pattern of rejectable indications on the strip chart recordings. Since these small I.D. discontinuities are in themselves undesireable, as well as negate the detecting potential of ultrasonic techniques for large cracks, a more stringent control of I.D. surface finish is obviously required.

Representative pieces of tubing showing different types of "gross ultrasonic defects" were cross-sectioned for examination under a microscope. In most cases, these indications were less than .002 inch in depth and within acceptable limits of XBMS 7-178.

Types of surface discontinuities found on the I.D. surface were as follows:

- Drawn-in and smeared chips
- Winding ridges and valleys (Gopher mounds)
- Herringbone zig-zag patterns of small pit marks
- Scattered islands of tiny pits
- Surface scratches and die marks

Ultrasonic inspection tests were conducted on pieces of 1½ x 0.035 x 50 inch long Ti-6Al-4V seamless tubing before and after grit blasting the I.D. to determine the effect of surface finish on ultrasonic response during inspection of the tubes for surface defects such as cracks, seams and laps. (ref. 24) The tubes tested contained a series of zigzagging rows of pitting marks 0.001 to 0.0025 inches in depth (Figures 14 and 15) throughout the I.D.

Sections of the strip chart recordings, made during ultrasonic inspection of the two tubes under study are presented in figures 16 through 23. Corresponding sections, before and after grit blasting, are matched in figures 16 and 17, 18 and 19, 20 and 21, and 22 and 23 respectively.

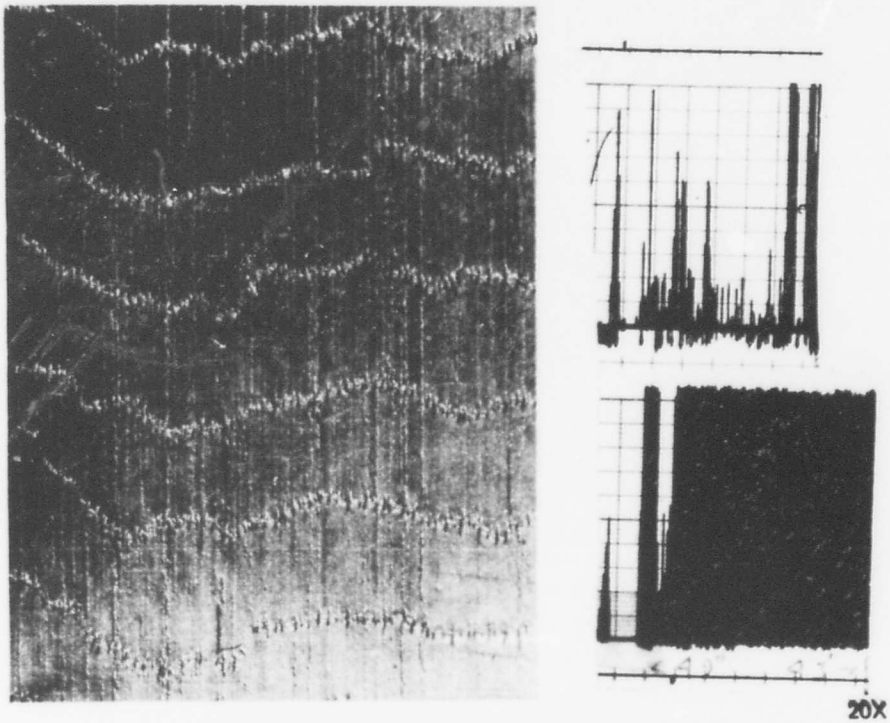


FIGURE 14.—I.D. SURFACE MARKS AND ASSOCIATED STRIP CHART ULTRASONIC INDICATIONS (1½ IN. X .035 IN. TUBE) COMPLETE SATURATION

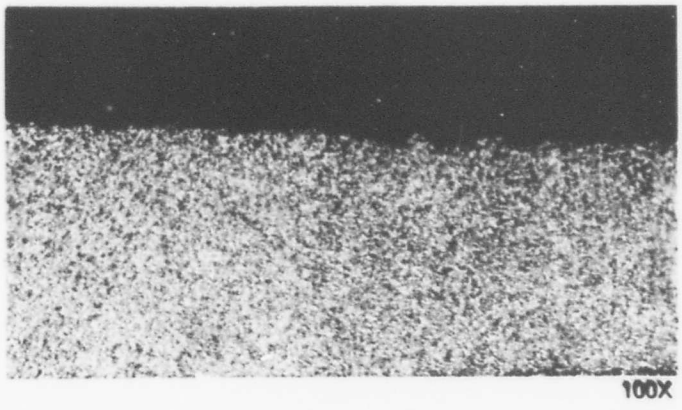


FIGURE 15.—PROFILE OF I.D. SURFACE MARKS SHOWN IN FIGURE 14 ABOVE, DEPTH FROM .001 IN. TO .0025 IN.

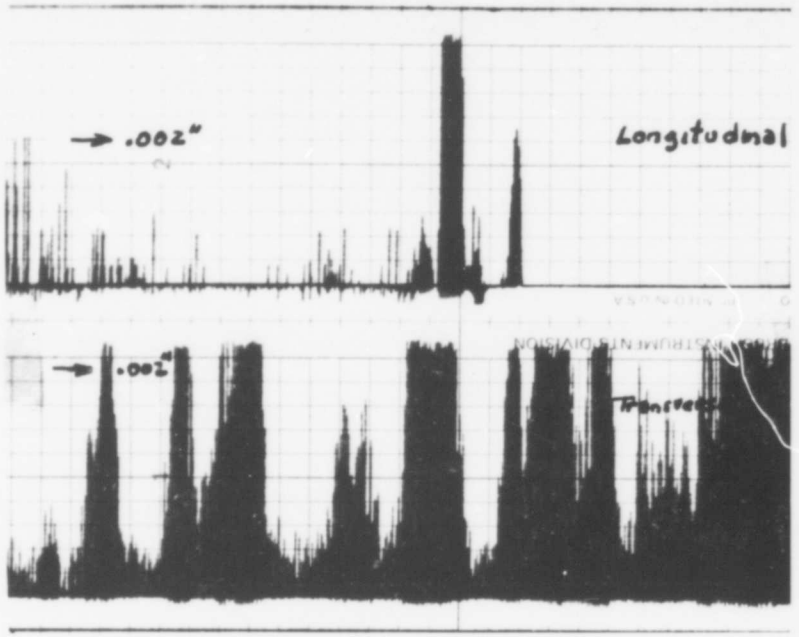


FIGURE 16. –ULTRASONIC INDICATIONS ON STRIP CHART MADE BEFORE GRIT BLASTING AND PICKLING OF I.D. AND O.D. SURFACES (TUBE 1)

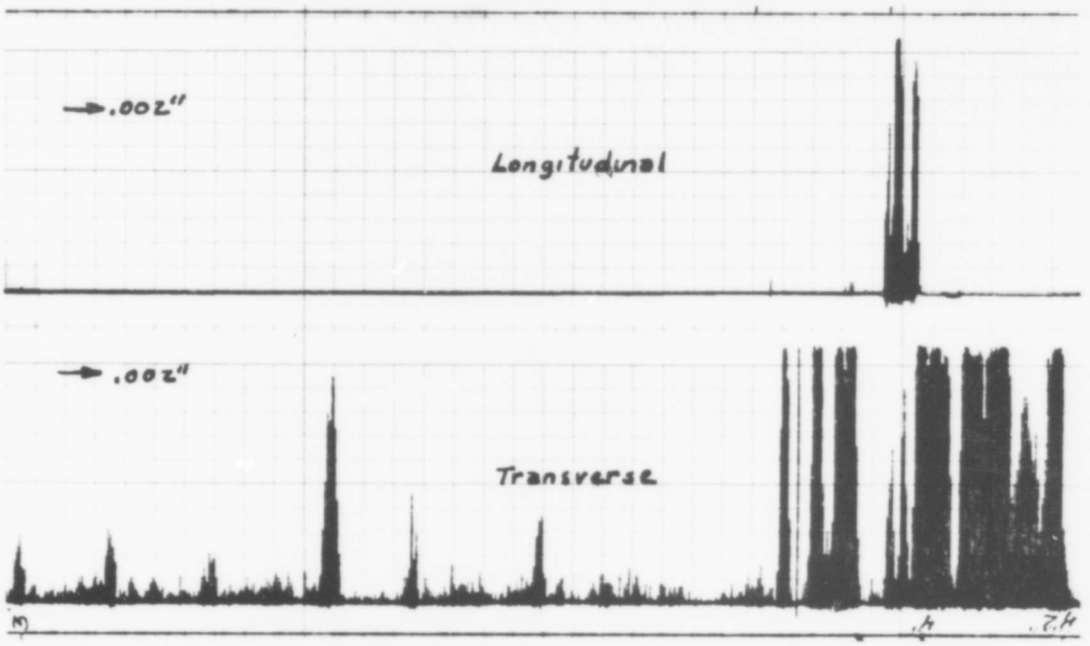


FIGURE 17.–SAME AREA AS IN FIGURE 16 EXCEPT RECORDING PRODUCED AFTER GRIT BLASTING AND PICKLINF OF I.D. AND O.D. SURFACES (TUBE 1)

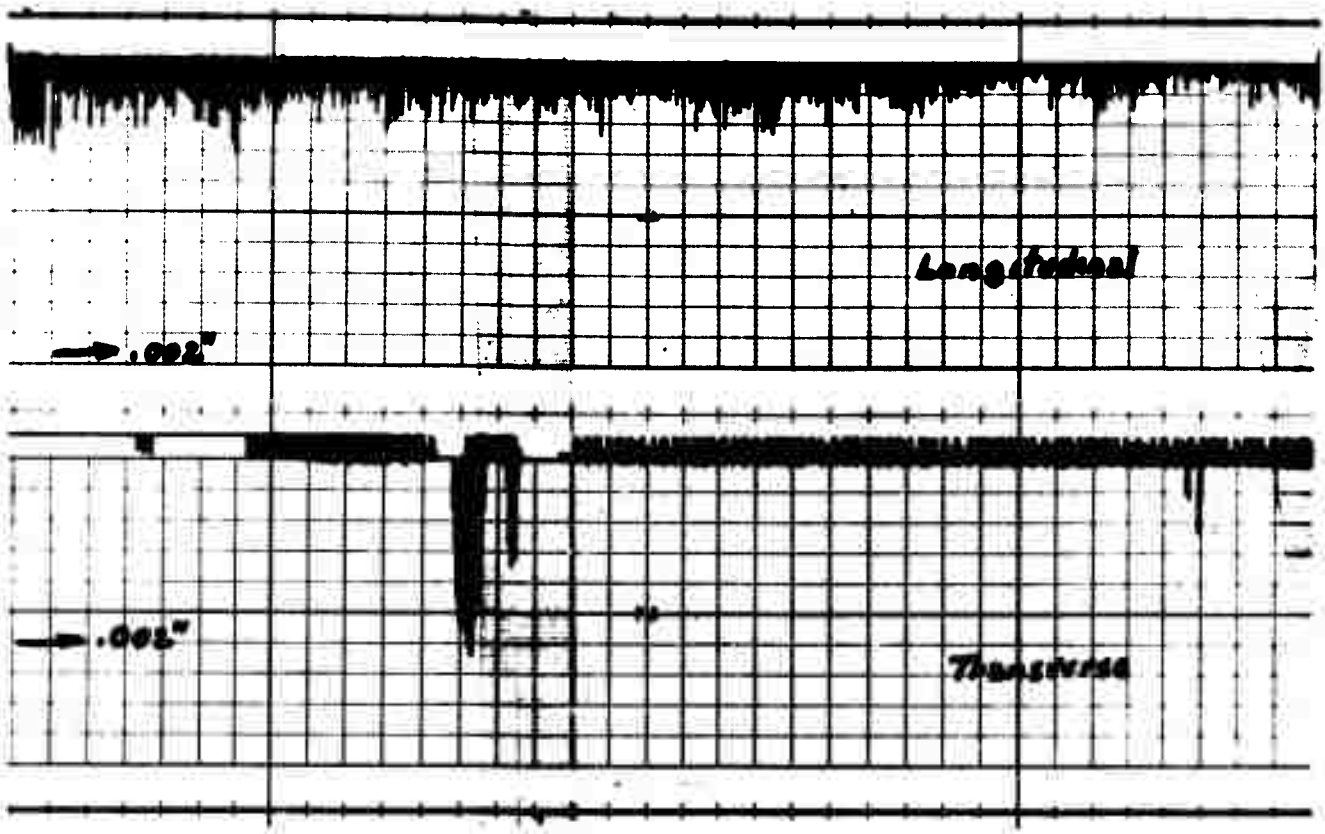


FIGURE 18. –SCAN DIRECTION FROM OPPOSITE END OF TUBE I; RECORDING MADE BEFORE GRIT BLASTING AND PICKLING OF I.D. AND O.D. SURFACES

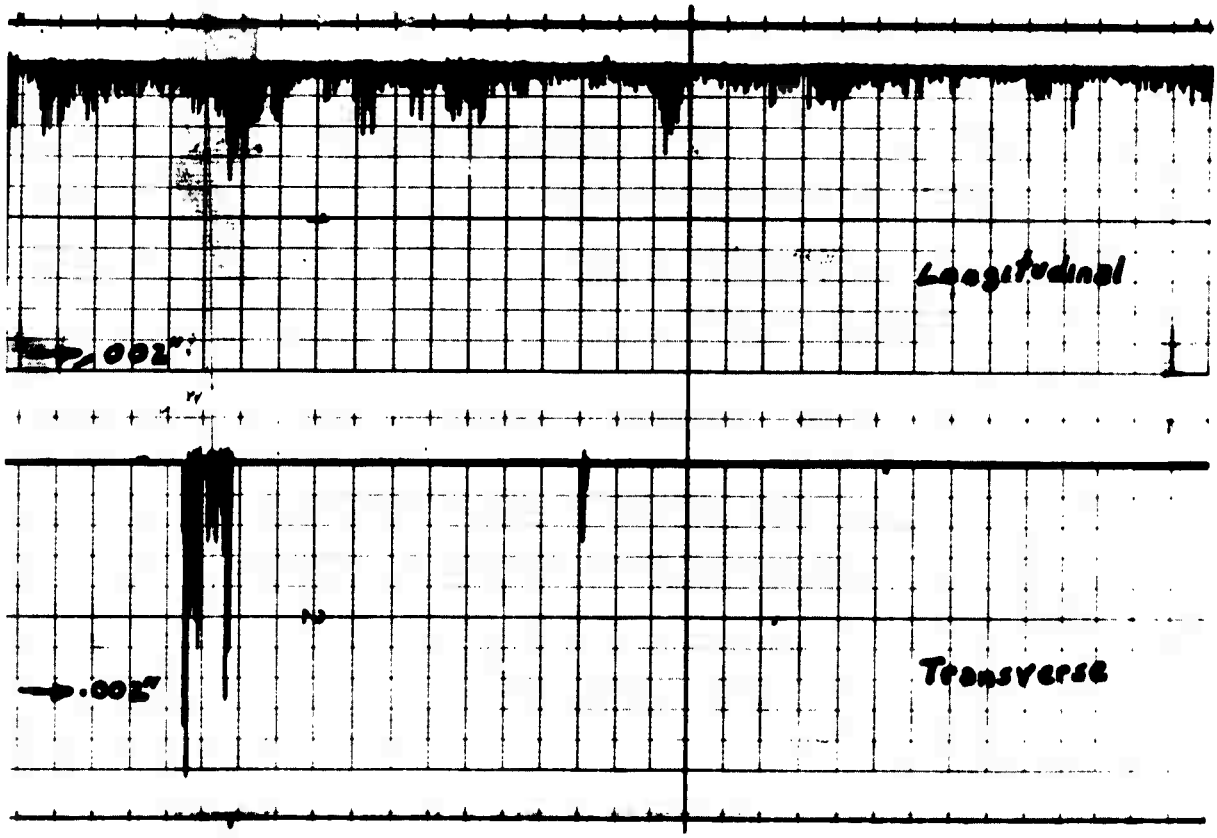


FIGURE 19.–SAME AREA AS IN FIGURE 18 EXCEPT RECORDING PRODUCED AFTER GRIT BLASTING AND PICKLING OF I.D. AND O.D. SURFACES (TUBE 1)

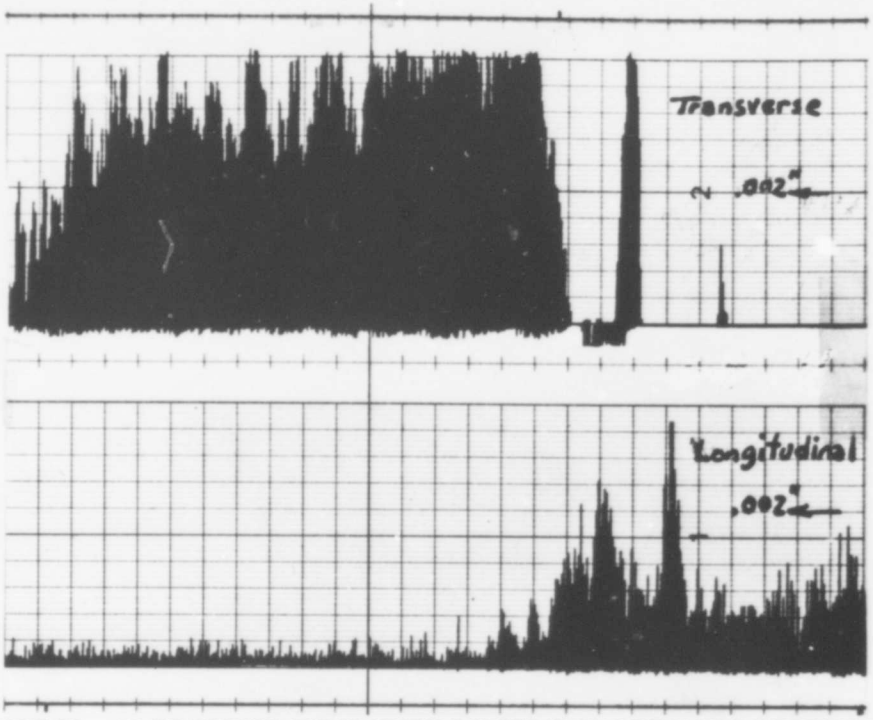


FIGURE 20. –ULTRASONIC INDICATION ON STRIP CHART MADE BEFORE GRIT BLASTING AND PICKLING OF I.D. AND O.D. SURFACES (TUBE 2)

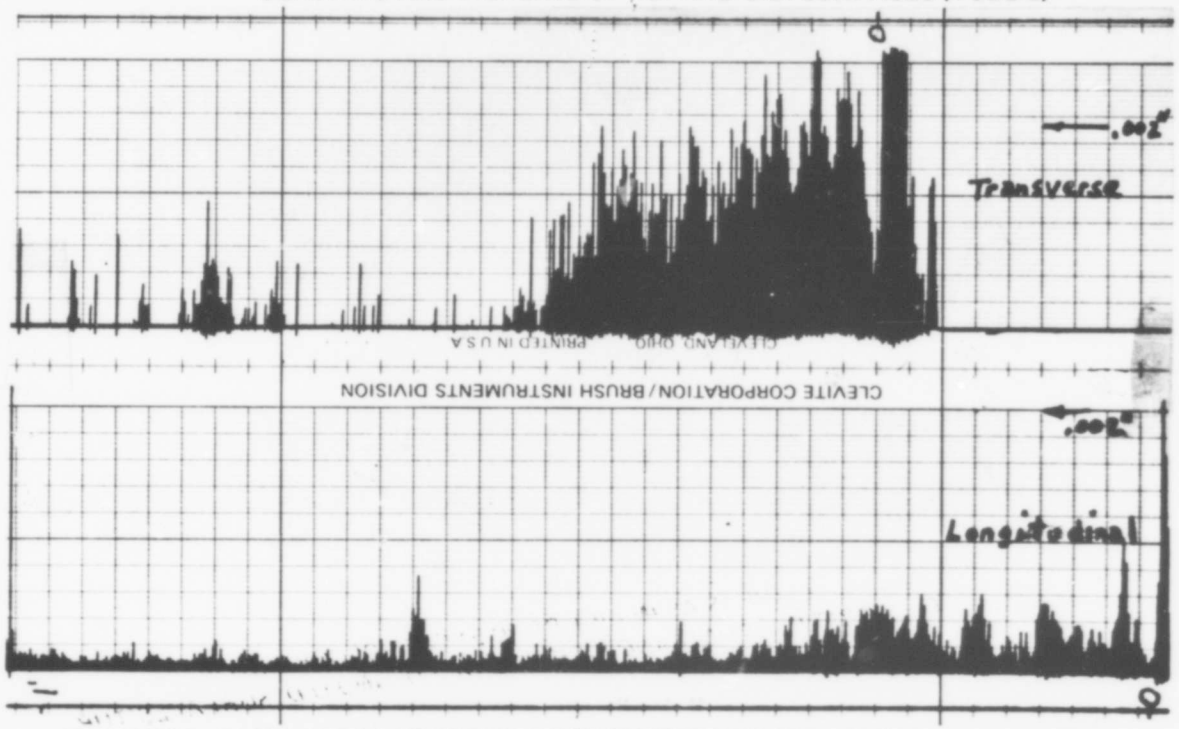


FIGURE 21.–SAME AREAS AS IN FIGURE 20 EXCEPT RECORDING PRODUCED AFTER GRIT BLASTING AND PICKLING OF I.D. AND O.D. SURFACES(TUBE 2)

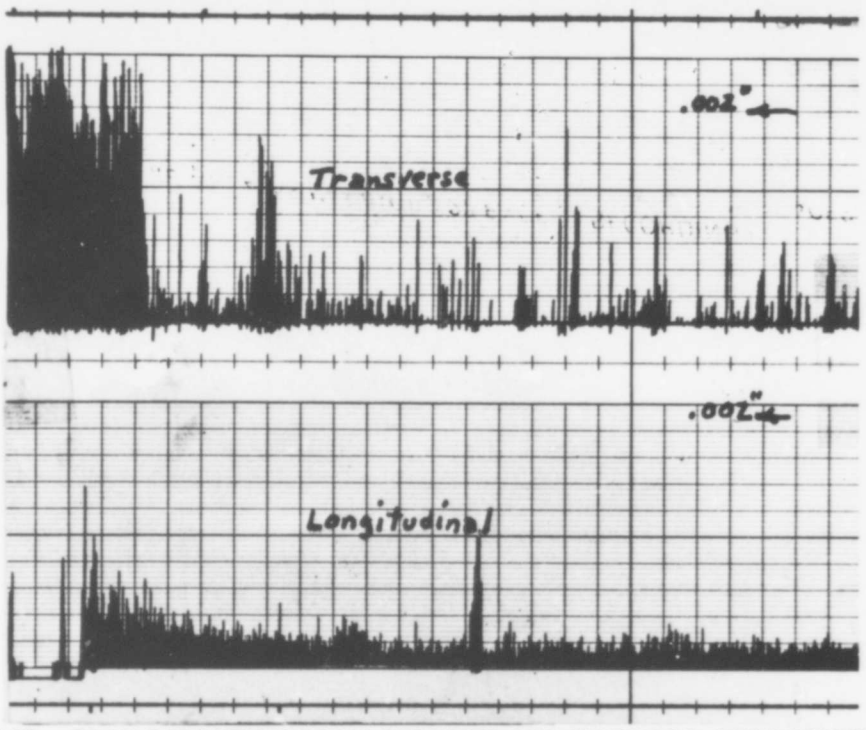


FIGURE 22. –SCAN DIRECTION FROM OPPOSITE END OF TUBE 2; RECORDING MADE BEFORE GRIT BLASTING AND PICKLING OF I.D. AND O.D. SURFACES

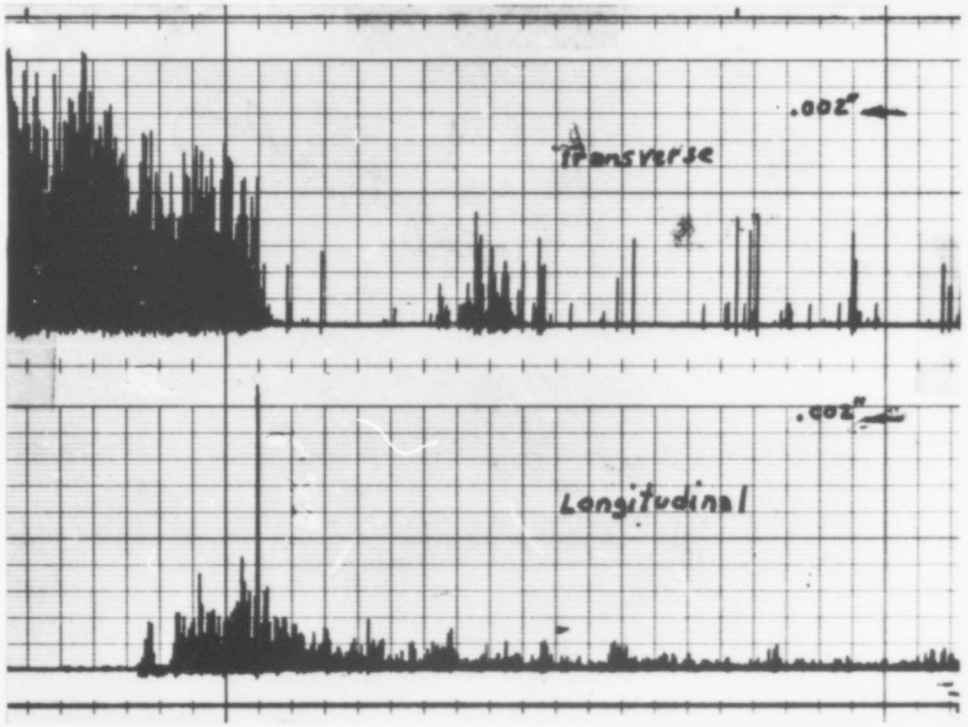


FIGURE 23.–SAME AREA AS IN FIGURE 22 EXCEPT RECORDING PRODUCED AFTER GRIT BLASTING AND PICKLING OF I.D. AND O.D. SURFACES (TUBE 2)

A definite change in response is noted for the surface finish attained by grit blasting. On the average the surface roughness was improved by grit blasting and light chemical etching from RHR 60-100 to RHR 16-32. As seen in figures 20 and 21, indications recorded on the strip charts were not completely obliterated by grit blasting of the tubing although they were minimized to an acceptable condition.

3.3.8.2 Effect of Chemical Milling (Etching) on Surface Finish and Defects

Figures 24 to 32 show the effects of chemically milling 0.002 inches of material from the surface of Ti-6Al-4V annealed tubing (ref. 25). It will be noted that defects are much reduced in size and surface finishes are greatly improved.

3.3.8.3 Effect of Defects on Fatigue Life

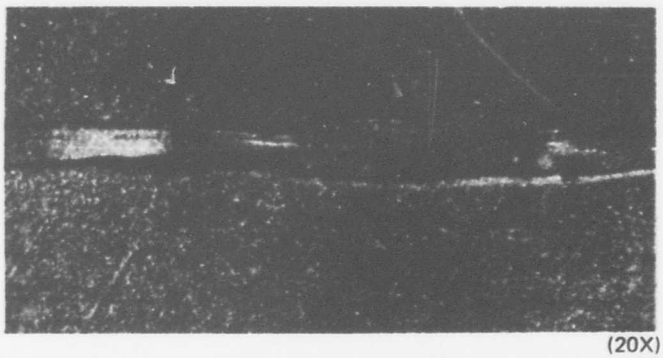
Two investigations have been performed on Ti-6Al-4V tubing to determine the effect of defects on fatigue life. They are as follows:

1. The first investigation covers the results of fatigue tests on six specimens made from 1½ x 0.110 x 30 in. long Ti-6Al-4V ELI tubing with a 120 -4D bend at mid-length (ref. 26). Testing was accomplished by first proof pressuring to 8000 psi, followed by pressure impulsing to a peak pressure of 6000 psi, and finally by rotary flexure while pressurized to 4000 psi. Results of the tests are shown in table 13.

TABLE 13.–THE FATIGUE BEHAVIOR OF FORMED Ti-6Al-4V TUBING. SOME TUBES CONTAINED SURFACE DEFECTS

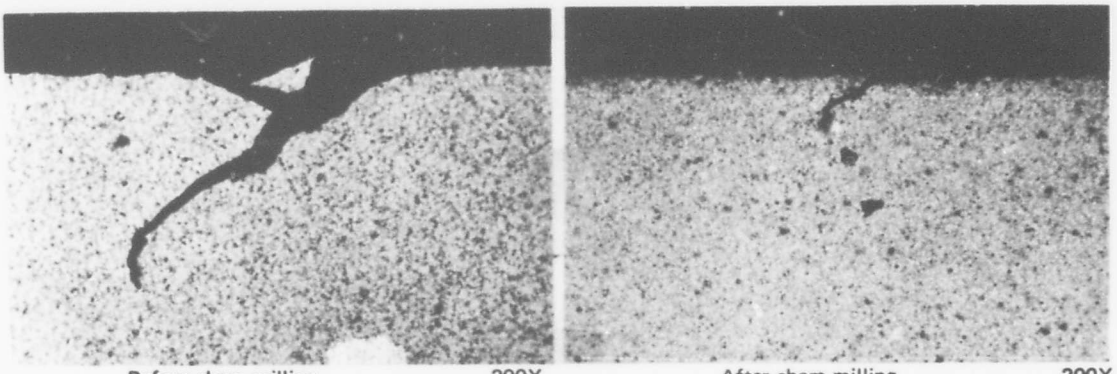
Specimen Number	Cycles in Press. Impulse	Deflection Double Amp. (Inches)	Cycles in Rotary Flexure	Type of Defect
BT 1.5 x 0.110 x 4000-1	70,951	–	–	I.D. lap
BT 1.5 x 0.110 x 4000-2	100,000	1.2	235,200	None
BT 1.5 x 0.110 x 4000-3	–	0.6	10×10^6	None
24 x 0.110 - 4000-4	–	0.9	1,478,400	Pit
24 x 0.110 - 4000-5	–	1.2	211,200	None
24 x 0.110 - 4000-6	–	1.2	1,459,200	None

Pressure impulse testing was conducted only on Specimens -1 and -2. Specimen -1 failed from an existing I.D. lap defect showing evidence of stress corrosion. It was found that a series of lap defects existing along the length of the specimen spaced intermittently about once every six inches. They varied in depth from 0.001-in to 0.010-in. and proportionately in length from about 0.003-in. to 0.030-in. A cross-section of these defects showed they contained branched cracking beyond the lap. The exact cause of stress corrosion beyond the laps is not known but is believed to have been caused by vendor processing during various stages of tube reduction.



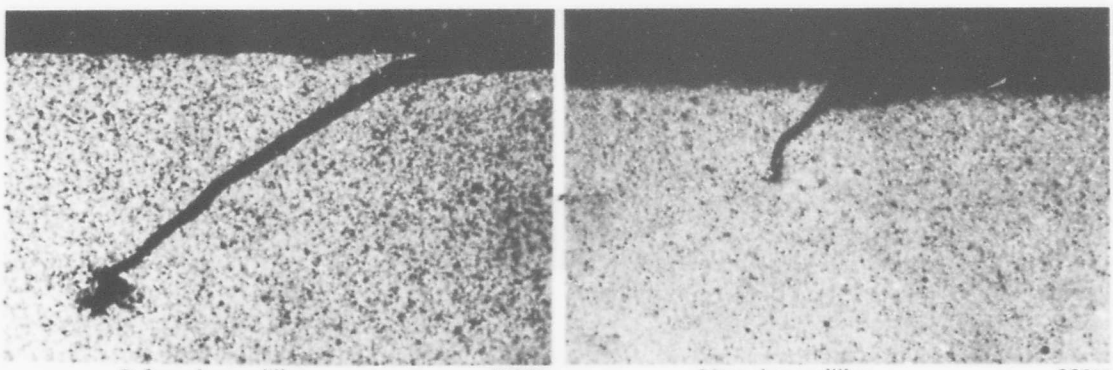
(20X)

FIGURE 24.—I.D. SURFACE FLAW ON BALL-SWAGED 1½ O.D. X 0.035 IN. TUBE; THE FLAW CONSISTS OF A (WEDGE-SHAPED) RIBBON AT THE SURFACE WITH A CRACK BENEATH IT



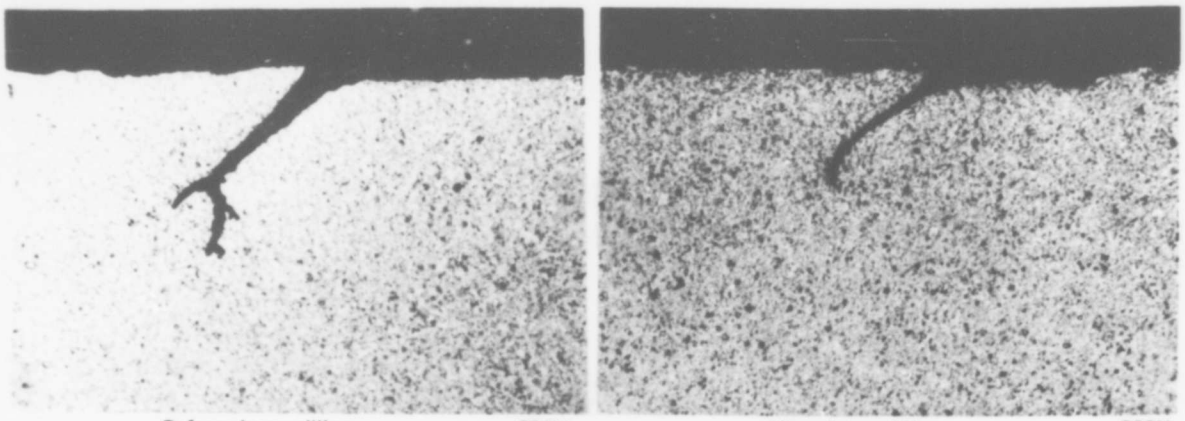
Before chem-milling 200X After chem-milling 200X

FIGURE 25.—CROSS-SECTION OF FLAW IN FIGURE 24 BEFORE AND AFTER CHEM-MILLING 0.002 IN. FROM THE SURFACE; DEPTH .0075 IN.BEFORE; .004 IN. AFTER



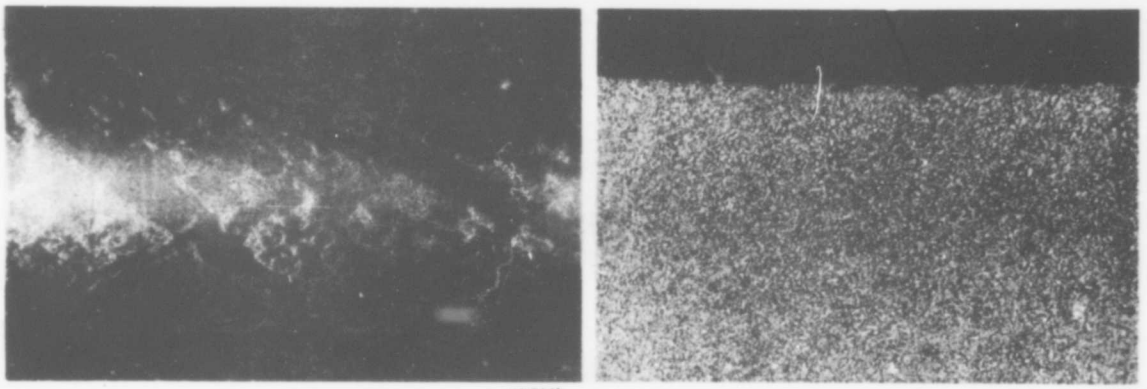
Before chem-milling 200X After chem-milling 200X

FIGURE 26.—SAME CRACK AS SHOWN IN FIGURE 24 EXCEPT AT DIFFERENT LOCATION. CHEM-MILLING 0.002 IN. DID NOT CAUSE FURTHER GROWTH OF CRACK. DEPTH .009 IN. BEFORE; .007 IN. AFTER



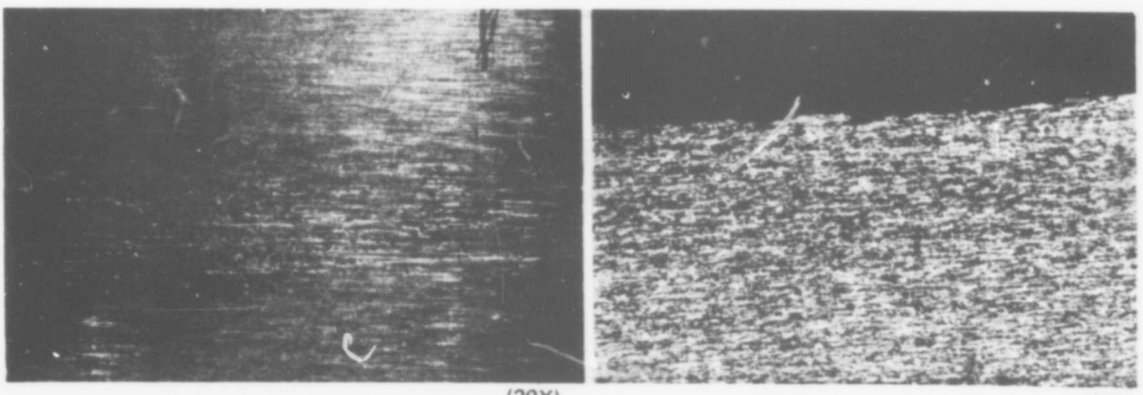
Before chem-milling 200X After chem-milling 200X

FIGURE 27.—ANOTHER SECTION OF THE CRACK SHOWN IN FIGURE 24 WHICH SHOWS THAT AN EXISTING CRACK WILL NOT GROW IN DEPTH DURING CHEM-MILLING; DEPTH .0075 IN. BEFORE; .005 IN. AFTER



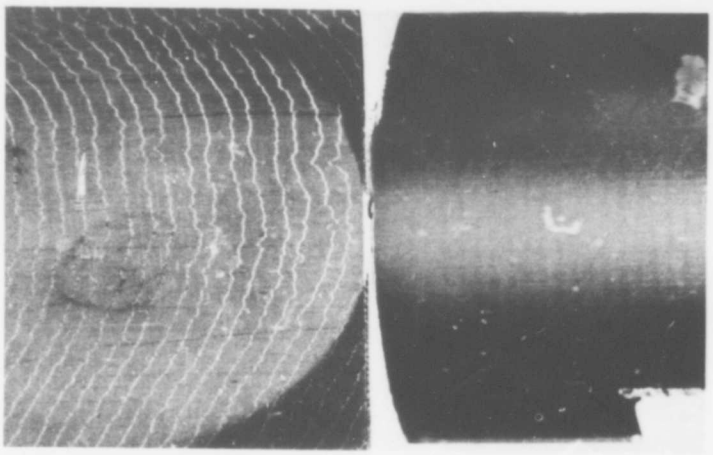
(20X) 100X

FIGURE 28.—SEVERE I.D. SURFACE ROUGHNESS SHOWN IN PLAN VIEW AT LEFT AND CROSS-SECTION AT RIGHT, THIS CONDITION WAS COMPLETELY REMOVED BY CHEM-MILLING 0.002 IN. OF SURFACE



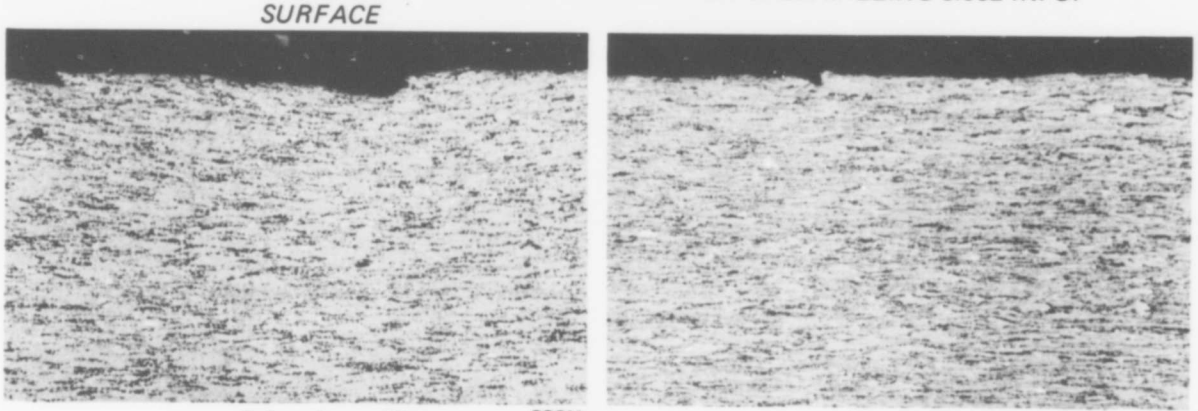
(20X) 100X

FIGURE 29.—SEVERELY SCRATCHED OR SCORED I.D.; (AS SHOWN IN FIG. 28) CONDITION COMPLETELY REMOVED BY CHEM-MILLING 0.002 IN. OF SURFACE



3X

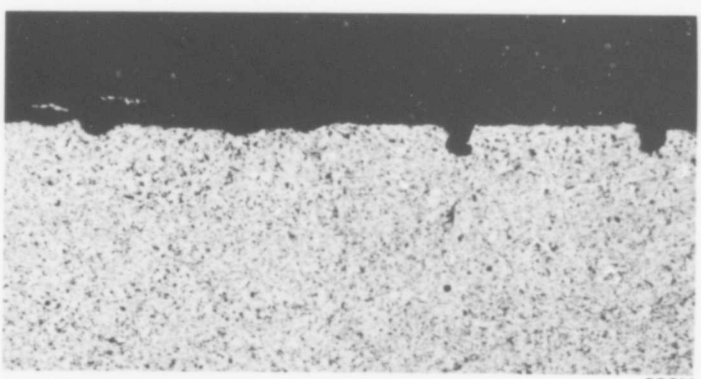
FIGURE 30.—VERY SEVERE I.D. ZIG-ZAG PIT MARKS; VIEW AT LEFT BEFORE CHEM-MILLING AND AT RIGHT AFTER CHEM-MILLING 0.002 IN. OF SURFACE



Before chem-milling 200X

After chem-milling 200X

FIGURE 31.—LONGITUDINAL CROSS-SECTION OF TUBE SHOWN IN FIGURE 30 BEFORE AND AFTER CHEM-MILLING. THE SURFACE ROUGHNESS IS SUBSTANTIALLY REDUCED.



200X

FIGURE 32.—TRANSVERSE CROSS-SECTION OF THE TUBE SHOWN IN FIGURE 30 BEFORE CHEM-MILLING. THE DEFECTS SHOWN HERE ARE DEEP PITS WHICH WERE CREATED DURING TUBE REDUCTION FROM THE EXTRUDED HOLLOW.

Specimen -3 was tested at a comparatively low circumferential stress of about 21,000 psi which is the probable reason for its surviving the 10,000,000 cycles in rotary flexure without failure. Specimen -4 failed in a low stress ares (opposite from the highest stressed area) of the tube; the crack starting from a deep (0.015 in) wedge-shaped pit or gouge. This O.D. surface defect was probably caused by a sharp object either during bending or testing. The deleterious effect of such surface nicks and gouges is serious and such discontinuities must be prevented if failures in service are to be avoided. Specimens -5 and -6 failed from cracks starting at the inside of the bend at the high stress area. The cracks initiated from the O.D. at about 45° to the tube length then rotated to fully transverse direction. There was no discernible existing defect to be attributed as cause of failure.

These tests confirmed that the deleterious effect of existing defects on the fatigue life of Ti-6Al-4V tubing is very significant.

2. A sample of 1½ x 0.086 in. Ti-6Al-4V seamless tubing was examined to determine the cause of a fatigue failure (ref. 27). Fatigue testing had been in rotary flexure at a stress of 21,000 psi plus an internal pressure of 3000 psi. Examination of the failure showed that two adjacent areas contained cracks. Two small O.D. cracks had penetrated into the tube to a depth of 0.050 and 0.020 inches. A third O.D. crack had completely penetrated the tube wall. There was a marked discoloration at the origin of the large crack which indicates it occured during the manufacture. Sections were taken through the nucleus of the small cracks which indicated that they were typical fatigue failures. No defects were associated with the orgins of these cracks.

   Adjacent to the large O.D. crack a small fourth crack was located which penetrated to a depth of about 0.005 inches. This crack is shown in figure 33 and appears to be a stress corrosion failure. This type of cracking has been noted previously in Ti-6Al-4V tube but has not been satisfactorily explained.

3.3.9 Methods of Chemical Milling

A 121 in. long x 0.5 in. O.D. Ti-6Al-4V tube was immersion etched in order to evaluate variations in gage reduction during the removal of a nominal 0.002 inches of material from the inside surfaces (ref. 28).

A. The following etching conditions were used:

Solution:	Nitric-hydrofluoric Acid per BAC 5753
Temperature:	130°F
Tube Orientation:	11° from horizontal
Solution Agitation:	Light air agitation. (Moderate to heavy agitation about midway along the tube inadvertently occurred during part of the etching.)

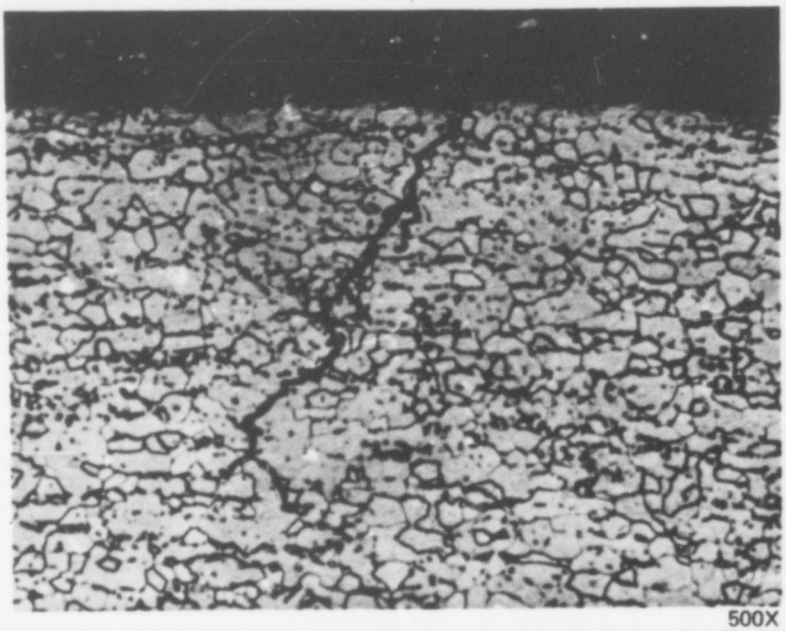


FIGURE 33.--APPARENT STRESS CORROSION CRACK IN Ti-6AI-4V TUBING

Solution Etch Rate:	0.0033 inch/surface/hour based on "standard" Q.C. control panel.
Immersion Time:	60 minutes

B. Portions of the tube were removed for measurement before and after etching, and the following noted:

Metal Removal, Outside Surfaces:	0.006 inch/surface
Metal Removal, Inside Surfaces:	0.002 inch/surface
Center Section:	0.015 inch/surface removed due to local solution agitation. Also, a thin area (0.006 in. wall thickness vs. 0.013-0.015 wall thickness for the rest of the center section) running the length of the center section was noted.
Tapering:	Slight tapering occurred within ½ inch of each end.
Wall Thickness:	0.028-0.030 inch before etching. 0.020-0.022 inch after etching (except for tube ends and center section).

On the basis of the above it is concluded that tubing can be procured 0.002 inch/surface oversize and etched as follows:

- Use a hot nitric-hydrofluoric acid solution per BAC 5753.
- Protect the outside of the tubing with chem mill maskant and etch the tube interior to remove 0.002 in. per surface. Process interiors by pumping the milling solution through the tube and continuously monitor metal removal with a Vidigage.
- Strip the maskant, place stoppers in the tube ends and etch the tube exterior to remove 0.002 in. per surface. Make wall thickness measurements and O.D. measurements every 12 inches before and after etching each tube.
- Masking and etching can be accomplished either by Boeing or by BMS 10-31 qualified chemical millers.
- Verify the adequacy of processing controls by milling sample parts prior to milling the actual tubes.

3.3.10 Minimum Wall Thickness Requirements

Regardless of strength requirements a minimum wall thickness of 0.020 inch for Ti-6Al-4V ELI per BMS 7-178 (ref. 2) for use on the SST was recommended (ref. 29) for the following reasons:

- To minimize damage caused during handling and fabrication, such as control of ovality and dents.
- To prevent arc blow holes caused during initiation of GTA fusion welds.
- To improve edge fit-up caused by misalignment.
- To reduce the effect of surface defects especially those produced during fabrication and in-service.
- To preclude the problems associated with etching (during cleaning) after heat treatment.

3.3.11 Preferred Method of Oxygen and Hydrogen Analysis

Oxygen content is considered critical for titanium hydraulic tubing applications and, therefore, must be carefully measured. Hydrogen content must also be carefully monitored as chemical milling is required as a final operation in XBMS 7-178. Thus is was considered imperative that these two gases be analyzed by accurate means to assure that the mechanical properties are not degraded.

In view of the foregoing, the oxygen content of titanium tubing was measured using only the neutron activation technique (ref. 4). Studies showed that this technique was more

reliable than the vacuum fusion method. Hydrogen content was determined using the hot extraction technique and a 0.3 gram minimum analytical sample. Evaluated studies have shown that the hot extraction technique gives a higher degree of confidence in results than does the vacuum fusion method.

3.3.12 Formability

The minimum and preferred bend radii of each size of tubing was determined by bending the tubing through a 120° bend. Five successive bends, without failure, at the minimum bend radius were required. Acceptability of each bend was determined by visual inspection (at 20X magnification) and penetrant inspection per the requirements of BAC 5423.

Formability data generated for Ti-6Al-4V annealed tubing is shown in table 14 (ref. 30). The hardness of formed tubing together with the degree of thinning is shown in table 15 (ref. 31).

Forming programs that have been undertaken to characterize Ti-6Al-4V tubing have shown the following to be true (ref. 30):

- Widmanstatten (Basketweave) microstructure is unacceptable in Ti-6Al-4V hydraulic tubing.
- The forming operation has no detectible effect on the microstructure of Ti-6Al-4V.

TABLE 14.–FABRICATION DATA FOR Ti-6Al-4V HYDRAULIC TUBING

Tube Size (O.D. x Wall Thickness) (Inches)	Bend Angle	Min. Bend Radius (R/D)	Preferred Bend Radius (R/D)	Thinning (%)	Min. Straight Length (in)	Angular Springback (°)
½ x 0.016	120°	2½	3	11.9	2	8
½ x 0.028		2	2½	19.2	2	14
5/8 x 0.016		2½*	3	11.9	2½	8
5/8 x 0.035		2	2½	19.6	2½	12
1 x 0.023		4*	5	8.5	4	8
1 x 0.057		3½	4½	14.7	4	14
1½ x 0.035		5	6			
1½ x 0.085		4*	5	25.5	6	12
½ x 0.016	90°	2	3	–	2	11
½ x 0.028		2	3	–	2	17
¾ x 0.020		2½	4	–	3	11
1¼ x 0.028		3	3¾	–	3¾	9
1½ x 0.035		4	4½	–	4½	9
1½ x 0.095		4	4½	–	4½	13

*Minimum bend radius obtained using a pressure boost on pressure die.

TABLE 15.–HARDNESS AND PERCENT THINNING OF Ti-6Al-4V TUBES AT THE APEX OF A 120° BEND (MIN. BEND RADII)

Tube Size (Inches)	Minimum Bend Radius (R/D)	Percent Thinning	Hardness (Rc)		
			Outside	Neutral Axis	Inside
½ x 0.016	5	11.9	33.2	35.4	32.0
½ x 0.028	4	19.2	38.2	40.0	34.7
5/8 x 0.016	4	11.9	30.8	33.0	32.0
5/8 x 0.035	3.2	19.6	32.8	31.1	35.8
1 x 0.023	4	8.5	32.2	33.8	32.2
1 x 0.057	3.5	14.7	29.1	29.1	28.0
1½ x 0.085	2.7	25.5	31.1	30.5	31.5

- Ground or sanded surfaces are unacceptable from both a forming and performance standpoint.

- When tooling and tubing are properly cleaned there should be no detrimental effect of the forming operation on surface condition.

3.4 ENGINEERING EVALUATION TESTS – Ti-3Al-2.5V COLD WORKED AND STRESS RELIEVED TUBING

3.4.1 Fatigue Performance (Failure Analysis)

A large number of fatigue tests have been performed on Ti-3Al-2.5V cold worked and stress relieved (CWSR) tubing to determine if this type of tube will meet STT performance requirements. Various types of surface defects were found to be the cause of virtually all premature fatigue cracks. Two investigations performed on failed Ti-3Al-2.5V tubes are reported below:

1. This report summarizes the fracture analysis work done on eleven Ti-3Al-2.5V CWSR tubing fatigue test speciments (ref. 32). The test conditions and test results are summarized in tables 16 and 17.

   The fractures in tubes 3 and 9 originated at longitudinal line type defects. The defects were determined to be laps which formed during the tube reduction process.

   The fractures in tubes 5 and 6 originated at transverse defects in the tubing. The defects were determined to be laps which formed during the tube reduction process. Tube 7 failed at a shallow longitudinal die mark that had a width to depth ratio (W/D) of 12. The fractures in tubes 2, 10 and 11 originated at finish grinding scratches not completely removed by subsequent processing.

   Tubes 1, 4 and 8 met predicted fatigue requirements. No defects were found associated with the failures in these tubes.

TABLE 16. –SUMMARY OF FATIGUE FAILURES IN Ti-3Al-2.5V CWSR HYDRAULIC TUBING

Spec. No.	Identification	Tube Size (O.D. x Wall Thickness) (Inches)	Pressure Impulse – Cycles x 1000					Total Cycles*	Rotary Flexure Cycles to Failure**
			RT	-50 °F	200 °F	350 °F	450 °F		
1	08040 Ft/3	½ x 0.040	25	10	25	40	0.01	100,010	144,420
2	08040 Ft/4	½ x 0.040	25	10	25	40	0.01	100,010	59,760
3	08040 Ft/5	½ x 0.040	25	10	25	32.3	–	92,300	–
4	08040 Ft/6	½ x 0.040	25	10	25	40	0.01	100,010	204,000
5	016080 Ft/1	1 x 0.080	25	10	25	8.6	–	68,600	–
6	016080 Ft/2	1 x 0.080	20.2	–	–	–	–	20,200	–
7	016080 Ft/3	1 x 0.080	25	10	25	20.8	–	80,800	–
8	024120 Ft/1	1½ x 0.120	25	10	25	40	0.01	100,010	698,340
9	024120 Ft/1	1½ x 0.120	25	10	25	40	0.01	100,010	37,000
10	BT24X120T1-1	1½ x 0.120	25	10	25	40	0.01	100,010	92,700
11	BT24X120T1-2	1½ x 0.120	25	10	25	40	0.01	100,010	135,960

*100,010 cycles required

**Predicted life is 10^5 - 10^6 cycles

TABLE 17. –SUMMARY OF Ti-3Al-2.5V CWSR HYDRAULIC TUBING FATIGUE FAILURES

Spec. No.	Identification	Tube Size (O.D. x Wall Thickness) (Inches)	Fracture Location and Orientation	Fracture Origin	Tube Ovality at Fracture %	Met. Analysis		Cause of Failure
						Chem	Micro	
1	08040 Ft/3	½ x 0.040	Inside radius of tube, at apex of bend almost transverse	OD Point	0.4	OK	OK	No defects found. Met fatigue requirements
2	08040 Ft/4	½ x 0.040	Inside radius of tube near apex of bend almost transverse	OD Point	0.0	OK	OK	Defect residual grinding scratch, transverse to axis
3	08040 Ft/5	½ x 0.040	Side of tube, 45° from apex, longitudinal fracture	ID Line	–	OK	OK	Line defect approximately 0.003 in. deep forming lap
4	08040 Ft/6	½ x 0.040	Side of tube about 45° from apex, longitudinal fracture	ID Point	–	OK	OK	No defects found. Met fatigue requirements
5	016080 Ft/1	1 x 0.080	Outside of tube, approx. 45° from apex of bend, longitudinal fracture	ID Point	–	OK	OK	Defect, transverse defect; forming lap
6	016080 Ft/2	1 x 0.080	Outside of tube at bend tangent, longitudinal fracture	OD Point	–	OK	OK	Defect, transverse defect; forming lap
7	016080 Ft/3	1 x 0.080	Outside of tube approx. 45° from apex of bend, longitudinal fracture	OD Line	–	OK	OK	Shallow longitudinal die mark
8	024120 Ft/1	1½ x 0.120	Side of tube at bend tangent propagated approximately 45° to axis	ID Line	–	OK	OK	No defects found. Met fatigue requirements

TABLE 17. –SUMMARY OF Ti-3Al-2.5V CWSR HYDRAULIC TUBING FATIGUE FAILURES (continued)

Spec. No.	Identification	Tube Size (O.D. x Wall Thickness) (Inches)	Fracture Location and Orientation	Fracture Origin	Tube Ovality at Fracture %	Met. Analysis		Cause of Failure
						Chem	Micro	
9	024120 Ft/6	1½ x 0.120	Outside of tube at apex of bend, longitudinal fracture	OD Line	–	OK	OK	Line type defect, forming lap
10	BT24X120T1-1	1½ x 0.120	Inside of tube at apex of bend, transverse	OD Line		OK	OK	Defect. Residual grinding scratches transverse to axis
11	BT24X120T1-2	1½ x 0.120	Inside of tube at apex of bend, transverse	OD Line		OK	OK	Defect. Residual grinding scratches transverse to axis

All of the tubes had acceptable chemistry and microstructure. See table 18.

The failures analyzed in the study showed two areas of difficulty with the tubing. The first is the surface finish. The failures in tubes 2, 10 and 11 were caused by residual surface grinding scratches not completely removed by subsequent tube processing. It has been found that titanium tubing is extremely sensitive to surface conditions, and defects as small as residual grinding scratches or draw marks can cause fracturing during plastic deformation or generate a fatigue sensitive condition. The second area of difficulty is the presence of forming defects. Tubes 3, 5, 6 and 9 failed at defects determined to be laps formed during the tube reduction process. The laps are probably the result of factors such as; 1)beginning with poor quality tube hollows, 2) improper processing of the hollows and 3) inadequate process control during the tube reduction stages.

TABLE 18.–CHEMICAL ANALYSIS OF TUBES

Specimen No.	Identification	Tube Size (O.D. x Wall Thickness) (Inches)	Element (Weight Percent)						
			Al	V	Fe	C	H(ppm)	O(ppm)	N(ppm)
1 thru 4	08040 Ft/3, 4, 5, & 6	½ x 0.040	3.47	2.39	0.10	0.015	22	995	24
5, 6, 7	016080 Ft/ 1, 2, & 3	1 x 0.080	2.81	2.36	0.12	0.03	33	932	37
8 thru 11	024120 Ft/ 1 & 6 BT24X120 T1/-1, -2	1½ x 0.120	2.85	2.38	0.11	0.005	31	975	25
	Specification BMS 7-203		2.5/ 3/5	2.0/ 3.0	0.30 max	0.05 max	150 ppm max	1200 ppm max	200 ppm max

2. This report summarizes the fracture analysis work conducted on six Ti-3Al-2.5V CWSR hydraulic tubing fatigue test speciments (ref. 33). The test conditions and test results are summarized in tables 19, 20 and 21.

Tube No. 1 failed by fatigue with the fracture initiating on the O.D. surface at a residual grinding scratch. Tubes 2 through 6 met predicted fatigue life. No defects were found associated with the fractures.

All of the tubes had acceptable chemistry and microstructure. See table 20.

TABLE 19. –SUMMARY OF FATIGUE TEST FAILURES IN Ti-3Al-2.5V CWSR HYDRAULIC TUBING

Tube No.	Identification	Tube Size (O.D. x Wall Thickness) (Inches)	Pressure Impulse Cycles X1000					Total Cycles	Flexure Fatigue Cycles to Failure*
			RT	-50	200	350	450		
1	016033 Ft/4	1 x 0.033	17.4	–	–	–	–	17,400	–
2	016033 Ft/5	1 x 0.033	25	10	25	40	0.01	100,010	108,150
3	016033 Ft/6	1 x 0.033	25	10	25	40	0.01	100,010	256,470
4	016033 Ft/7	1 x 0.033	25	10	25	40	0.01	100,010	179,220
5	016033 Ft/8	1 x 0.033	25	10	25	40	0.01	100,010	266,000
6	024049 Ft/2	1½ x 0.049	25	10	25	40	0.01	100,010	1.55×10^6

*Predicted life – 10^5-10^6 cycles

TABLE 20. –CHEMICAL ANALYSIS OF Ti-3Al-2.5V TUBES

Specimen No.	Identification	Tube Size (O.D. x Wall Thickness) (Inches)	Element (Weight Percent)						
			Al	V	Fe	C	H(ppm)	O(ppm)	N(ppm)
1 thru 5	016033 Ft/4 -Ft/8	1 x 0.033	2.99	2.38	0.12	0.02	36	1100	78
6	024049 Ft/2	1½ x 0.049	3.16	2.36	0.2	0.01	27	1260	97
Specification	BMS7-203	–	2.5/ 3.5	2.0/ 3.0	0.3 max	0.05 max	0.015 max	0.12 max	0.02 max

3.4.2 Surface Finish and Defects

3.4.2.1 Types of Defects

Based on experience gained during the Ti-3Al-2.5V CWSR development program the following types of defects were classafied. (ref. 34):

- I.D. longitudinal lap type. These defects have their long axis parallel to the tube centerline and intersect the surface with an included angle of 30° to 60°. These defects normally can be traced back to lap type defects in the extruded hollow. If they persist through to the finished tube they are normally intermittantly spaced along the tube.

- I.D. or O.D. helical lap type. These defects may occur singly or in pairs forming a chevron pattern. They generally lie parallel to a 45° helix and intersect the surface at an included angle of 30° to 60°. These defects occur during initial reduction of the tube hollow and, when encountered, are likely to be very widespread. Usually these defects are very short, significantly less than 1/8 inch in length.

TABLE 21. –SUMMARY OF Ti-3Al-2.5V CWSR HYDRAULIC TUBING FATIGUE FAILURES

Tube No.	Identification	Tube Size (O.D. x Wall Thickness) (Inches)	Fracture Location and Orientation	Fracture Origin	Tube Ovality at Fracture	Met. Analysis		Cause of Failure
						Chem	Micro	
1	016033 Ft/4	1 x 0.033	Transverse, outside of tube midway between apex and tangent point of bend	OD Line	–	OK	OK	Transverse grinding scratches on OD surface
2	016033 Ft/5	1 x 0.033	Longitudinal, outside of tube midway between apex and tangent point of bend	ID Point	2.0	OK	OK	Met fatigue requirements
3	016033 Ft/6	1 x 0.033	Transverse, inside of tube at apex of bend	OD Point	1.5	OK	OK	Met fatigue requirements
4	016033 Ft/7	1 x 0.033	Longitudinal, side of tube midway between apex and tangent point of bend	ID Line	1.6	OK	OK	Met fatigue requirements
5	016033 Ft/8	1 x 0.033	Transverse, inside of tube at apex of bend	OD Point	1.2	OK	OK	Met fatigue requirements
6	024049 Ft/2	1½ x 0.049	Longitudinal, side of tube midway between apex and tangent point of bend	ID Line	2.0	OK	–	Met fatigue requirements

- O.D. longitudinal lap. This defect is similar to its I.D. counterpart. It was not observed as frequently during the development program as the two earlier described defects.

- O.D. transverse. This defect may or may not be a lap type. It has been observed only infrequently and information on its characteristics is therefore limited.

3.4.2.2 The Effect of Surface Finish on Fatigue Properties

Preliminary fatigue testing of Ti-3Al-2.5V cold worked and stress relieved hydraulic tubing has shown that surface finish operations performed on the O.D. after the last mechanical reduction were of critical importance and could be responsible for premature fatigue failure (ref. 35). This program was initiated to evaluate various surface finishes and select those which would provide the best fatigue performance. Tubing for the test specimens was procured to BMS 7-203A. Six types of surface finishes (O.D.) were evaluated during the test. They were as follows:

- Sand (early process) + Chem Mill*
- Sand with 400 Grit + Chem Mill*
- Sand with 600 Grit + Chem Mill*
- Cork Belt Polish + Chem Mill*
- Chemically Milled*
- Sand with 240 Grit, Cork Belt Polish + Chem Mill*

Metallurgical analyses were conducted on 24 failed hydraulic tubing specimens representative of the various tubing groups (size/surface finish combinations) which experienced cracking during testing.

The fatigue data obtained to evaluate the six different surface finishes is presented in tables 22 and 23. The data will be discussed in the order of its presentation in the tables.

The ½ x 0.040in. Zirtech tubing was tested with three different surface finishes. None of the specimens with an as-reduced and chem-milled surface sustained failures during the test life. All specimens far exceeding the requirement of 1×10^6 cycles. Tubing that was sanded with 400 grit abrasive and chem milled showed an average fatigue life of 1.26×10^5 cycles.** Fracture analysis was conducted on three of the five tubes tested and showed that every failure was due to the surface condition of the tube (see table 22).

*Approximately 0.004 in. of material was removed from the O.D. during chem milling operations.

**All fatigue life averages listed are based on a disregard for the high data point and the low data point.

TABLE 22. – FATIGUE TEST RESULTS FOR Ti-3Al-2.5V CWSR HYDRAULIC TUBING

Tube Identification	Tube Description	*Pressure Impulse Cycles	Rotary Flexure Cycles to Failure
BT8X020Ti-1 -2 -3 -4 -5	Zirtech ½ O.D. x o.020 in. wall As reduced + sanded + chem milled	100,010	184,260 144,420 154,380 122,010 204,180 (100,000 goal)
BT8X040Ti/0-2 -3 -4 -5 -6	Zirtech ½ O.D. x 0.040 in. wall As reduced + chem milled	100,010	2.94×10^6 NF 3.75×10^6 NF 5.0×10^6 NF 5.0×10^6 NF 5.0×10^6 NF (100,000 goal)
BT8X040Ti/4-1 -2 -3 -4 -5 -6	Zirtech ½ O.D. x 0.040 in. wall As reduced + sanded (400 grit) + chem milled	100,010	104,580 59,760 129,480 154,380 156,870 136,950 (100,000 goal)
BT8X040Ti/6-1 -2 -3 -4 -5 -6	Zirtech ½ O.D. x 0.040 in. wall As reduced + sanded (600 grit) + chem milled	100,010 82,951** 100,010	5.0×10^6 NF 109,560 97,110 109,560 – 99,600 (100,000 goal)
BT16X033Ti-13A5 -14A5	RMI 1.0 O.D. x 0.033 in. wall Drawn + chem milled	100,010	2.59×10^6 NF 160,000*** (240,000 goal)
BT16X033Ti-4A3 -9A3 -11A3	RMI 1.0 O.D. x 0.033 in. wall Drawn + cork belt polish + chem milled	100,010	3.5×10^6 NF 2.76×10^6 NF 2.43×10^6 NF (240,000 goal)
BT16X033Ti-3A4 -7A4 -15A4	RMI 1.0 O.D. x 0.033 in wall Drawn + sanded + belt polish + chem milled	100,010	2.18×10^6 NF 1.72×10^6 NF 4.52×10^6 NF (240,000 goal)

TABLE 22. – FATIGUE TEST RESULTS FOR Ti-3Al-2.5V CWSR HYDRAULIC TUBING (continued)

Tube Identification	Tube Description	*Pressure Impulse Cycles	Rotary Flexure Cycles to Failure
Bishop -4 -5 -6	Bishop 1.0 O.D. x 0.031 in. wall Drawn + sanded + chem milled	100,010	2.48×10^6 NF 2.08×10^6 NF 3.06×10^6 NF (160,000 goal)
BT16X080Ti/142-1 -2 -3 -4	Zirtech 1.0 O.D. x 0.080 in. wall As reduced + chem milled	100,010	150,000-179,000 367,710 361,530 355,350 (170,000 goal)
BT16X080Ti/142A-1 -2 -3 -4	Zirtech 1.0 O.D. x 0.080 in. wall As reduced + sanded (400 grit) + chem milled	100,010 50,468** 100,010	83,430*** 204,940 – 342,990 (170,000 goal)
BT16X080Ti/143-1 -2 -3 -4	Zirtech 1.0 O.D. x 0.080 in. wall As reduced + sanded (600 grit) + chem milled	100,010	61,800*** 77,250*** 210,120 3.82×10^6 (170,000 goal)
BT24X049Ti/5-1 -2 -3 -4	RMI 1½ O.D. x 0.049 in. wall Drawn + chem milled	100,010	92,700*** 105,000-136,000 89,610*** 157,590 (100,000 goal)
BT24X049Ti/3-1 -2 -3	RMI 1½ O.D. x 0.049 in. wall Drawn + cork belt polish + chem milled	100,010	275,010 284,280 293,550 (100,000 goal)
BT24X120Ti-1 -2 -3 -5	Zirtech 1½ O.D. x 0.120 in. wall As reduced + sanded + chem milled	100,010	247,200*** 92,700*** 135,960*** 364,620 (330,000 goal)

NF – No failure, test discontinued

*Test schedule required 100,010 pressure impulse cycles on each test specimen prior to rotary flexure testing.

**Failed in pressure impulse testing.

***Failed to meet fatigue life goal.

TABLE 23. –SUMMARY OF FRACTURE ANALYSIS ON Ti-3Al-2.5V CWSR HYDRAULIC TUBING

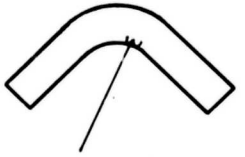
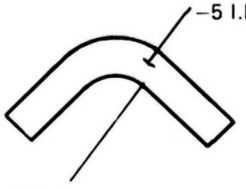
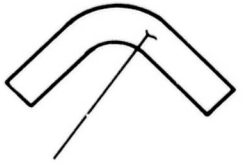
Tube Identification	Tube Description	Fracture Origin, Location and Orientation	Comments
BT8X040Ti /4-1 -2 -5	Zirtech ½ O.D. x 0.040 in. wall As reduced + sanded (400 grit) + chem mill (0.004)	 –1, –2, –5 O.D. Transverse	Origins coincides with residual sanding scratches on O.D. Ovality -2 = 0.3 Origins also occur in area of residual tensile stresses resulting from bending.
BT8X040Ti /6-3 -4 -5	Zirtech ½ O.D. x 0.040 in. wall As reduced + sanded (600 grit) + chem mill (0.004)	–3 I.D. Longit. –5 I.D. Longit.  –4 O.D. Transverse	-5 Origin at I.D. lap defect. Ovality -3 = 0.3; -5 = 0.5
BT16X033Ti -14A5	RMI 1.0 O.D. x 0.033 in. wall Drawn + chem milled	 –14A5 I.D. Longit.	Ovality = 2.6

TABLE 23. –SUMMARY OF FRACTURE ANALYSIS ON Ti-3Al-2.5V CWSR HYDRAULIC TUBING (continued)

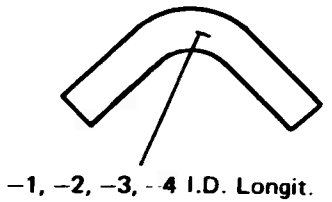
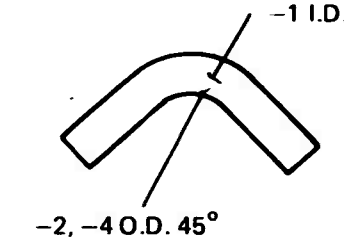
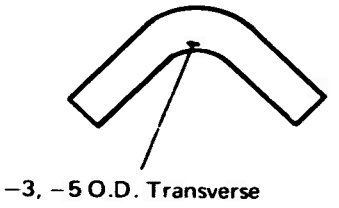
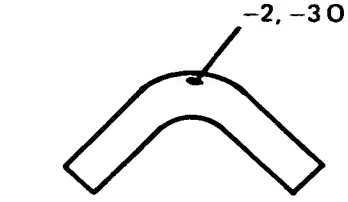
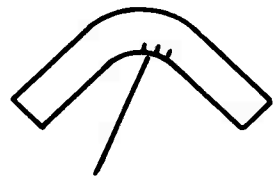
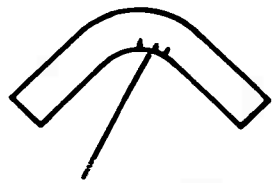
Tube Identification	Tube Description	Fracture Origin, Location and Orientation	Comments
BT24X049Ti /5-1 -2 -3 -4	RMI 1.5 O.D. x 0.049 in. wall Drawn + chem milled		Ovality of -4 = 1.2
BT24X049Ti /3-1 -2 -4	RMI 1.5 O.D. x 0.049 in. wall Drawn + cork belt polish + chem milled		-2, -4 origins at longitudinal forming marks. Ovality -1 = 0.6; -2 = 0.3; -4 = 0.9
BT24X120Ti -3 -5	Zirtech 1.5 O.D. x 0.120 in. wall As reduced + sanded + chem milled		-3 origin at sanding scratch; -5 origin at longitudinal defect on O.D. surface Ovality -3 = 2.6; -5 = 0.9
BT16X080Ti /142-2 -3	Zirtech 1.0 O.D. x 0.080 in. wall As reduced + chem milled		-3 origin at O.D. lap type defect

TABLE 23. –SUMMARY OF FRACTURE ANALYSIS ON Ti-3Al-2.5V CWSR HYDRAULIC TUBING (continued)

Tube Identification	Tube Description	Fracture Origin, Location and Orientation	Comments
BT16X080Ti /142A-1 -2 -4	Zirtech 1.0 O.D. x 0.080 in. wall As reduced + sanded (400 grit) + chem milled	 –1, –2, –4 O.D. Transverse	-1 origin at longitudinal defect on O.D. surface. Origins occur in area of residual tensile stresses resulting from bending.
BT16X080Ti /143-1 -3 -4	Zirtech 1.0 O.D. x 0.080 in. wall As reduced + sanded (600 grit) + chem milled	 –1, –3, –4 O.D. Transverse	-1 origin at longitudinal defect on O.D. surface. Origins occur in area of residual tensile stresses resulting from bending.

Tubing that was sanded with 600 grit abrasive and chem milled had an average fatigue life of 1.06×10^5 cycles. Fracture analyses were conducted on three of the tubes from this lot. The analysis showed that two of the failures originated at the I.D. surface and one on the O.D. surface but none of the failures appeared to be due to the surface condition.

Three different surface finishes were evaluated for the 1 x 0.033 in. tubing from RMI and one surface finish for a similarly sized Bishop tube. The finishes evaluated for the RMI tube were chem-milled; cork belt polished and chem milled; and sanded, cork belt polished, and chem milled. The Bishop tube was sanded and chem milled. Unfortunately only one specimen failed to achieve the maximum test life making it impossible to evaluate the relative fatigue sensitivity of the various finishes. The one low fatigue life specimen did not have crack initiation due to the surface condition.

Although the above data was not definitive between the as-drawn and chem-milled tubing it did demonstrate that the cork belt polished and sanded surface from Bishop was acceptable from a fatigue standpoint.

The 1 x 0.080 in Zertech tubing was tested with the same set of surface finishes as the ½ x 0.040 in. Zirtech tubing. The tubes with the chem milled surface finish had an average fatigue life of 3.58×10^5 cycles; tubes that had been sanded with 400 grit paper and chem milled had an average fatigue life of 1.43×10^5 cycles and tubes that had been sanded with 600 grit paper and chem milled had an average fatigue life of 1.44×10^5 cycles.

The 1½ x 0.049 in. RMI tubing was tested with either chem milled or cork belt polished and chem milled surface finishes. The average fatigue lives were 1.06×10^5 and 2.84×10^5 cycles respectively. Fracture analyses were conducted on each of the specimens tested. No failures were attributed to the surface finish.

Tests were also conducted on ½ x 0.020 in. and 1½ x 0.120 in. Zirtech tubing with sanded (not controlled) and chem-milled surfaces but no data was developed with which to compare the results. However, fracture analyses conducted on the larger tubes showed that three were directly attributable to the surface finish. Fracture analyses were not conducted on the ½ x 0.020 inch specimens.

The chemical composition of the various tubes was acceptable and is shown in table 24.

Conclusions that may be drawn from the investigation are as follows:

- Tubing finished by chemical milling or by a combination of cork belt polishing plus chemical milling generally has acceptable surface finish in terms of fatigue performance.

- Residual sanding marks in ½ inch O.D. Zirtech tubing appears to be detrimental to fatigue performance compared to tubing finished either without sanding or sanded with finer grit to produce a better surface finish.

- Sanded 1.0 inch Zirtech tubing had lower fatigue performance than unsanded tubing. However, the residual sanding marks did not appear to have an influence on the crack origin.

TABLE 24. –CHEMICAL ANALYSIS OF Ti-3Al-2.5V CWSR HYDRAULIC TUBING TEST SPECIMENS

Tube Identification	Element (Weight Percent)						
	Al	V	Fe	C	H(ppm)	O(ppm)	N(ppm)
BT8X040 Ti/4-1, -2, -5	2.62	2.4	0.11	–	24	1075	74
BT8X040 Ti/6-3, -4, -5	2.79	2.46	0.12	–	24	1079	83
BT16X033 Ti-14A5	3.35	2.41	0.14	0.14	21	1180	66
BT24X049 Ti/5 to -5 BT24X049 Ti/3-1, -2, -4	3.58	2.53	0.088	–	43	1140	75
BT24X120 Ti-3, -5	3.02	2.34	0.23	–	48	965	101
Specification BMS 7-203A	2.5/ 3.5	2.0/ 3.0	0.3 max	0.05 max	150 max	1200 max	200 max

- Sanding on 1.0 inch RMI and Bishop tubing did not appear to have an influence on fatigue performance.

- The somewhat erratic influence of sanding on fatigue performance suggests that other factors, such as residual stresses and crystallographic texture, may also have an important influence.

3.4.3 Shot Peening

Shot peening of exterior tube surfaces has been specified on some occasions for Ti-3Al-2.5V tubing although the latest revision of the Ti-3Al-2.5V CWSR tubing specification, BMS 7-234, did not allow this condition (ref. 3).

The shot peening intensity range for Ti-3Al-2.5V tubing has been called out (as of 1-30-70) as shown in table 25 (ref. 36).

Samples of seven different sizes (A,B,C,D,E,F,&G) of peened and unpeened Ti-3Al-2.5V hydraulic tubing per BMS 7-203A were evaluated to determine shot-peening parameters as a function of the residual hoop stresses generated (ref. 37). Residual hoop stress measurements were conducted using the Sach's boring out method. Techniques A and B were both used as explained in section 3.1.7. Data is presented for tubes A through F in figures 34 through 39 respectively. Data is tabulated in table 26.

Examination of the data indicates that in every case the shot peening generated a residual compressive stress of -60 to -80 ksi on the O.D. surface of the tube. The depth of the compression layer normally extended to about 0.005 inches. The interior portion of

TABLE 25.–SHOT PEEN INTENSITY RANGES SPECIFIED FOR Ti-3Al-2.5V HYDRAULIC TUBING

Nominal Wall Thickness (in.)	Almen Intensity Range No. 2 Gage
0.018	8-10N
0.019-0.024	11-13N
0.025-0.030	14-16N
0.031-0.036	17-19N
0.037-0.060	7-9A
0.061-0.095	8-10A
0.096-0.125	11-13A
0.126-0.188	13-15A

TABLE 26. –RESIDUAL HOOP STRESS, Ti-3Al-2.5V CWSR HYDRAULIC TUBING – SACH'S BORING OUT METHOD

Specimen Identification	Vendor	Tube Size (O.D. x wall thickness) (Inches)	Peening Parameters	Residual Stress at Outside Surface		Residual Stress at Inside Surface	
				Magnitude (ksi)	Depth (inch)	Magnitude (ksi)	Depth (inch)
A	RMI	1 x 0.052	Spec	-64	0.006	-22	0.015
B	RMI	¾ x 0.039	Spec	-80	0.004	+ 5	0.005
C	RMI	3/8 x 0.003	Spec	-64	0.006	+ 4	0.003
D	RMI	½ x 0.026	Spec	-77	0.006	-10	0.008
E	Bishop	3/8 x 0.020	Spec	-80	0.002	+ 6	–
F	Wolv.	3/8 x 0.020	Unpeened	+ 8	0.010	- 5	0.010
G-C	Zirtech	¾ x 0.045	Unpeened	+40	0.027	-36	0.016
G-1	Zirtech	¾ x 0.045	.005A2	-68	0.007	-16	0.007
G-2	Zirtech	¾ x 0.045	.008A2	-60	0.006	-10	0.005
G-3	Zirtech	¾ x 0.045	.012A2	–	0.012	- 8	0.004

each tube had a residual tensile stress which became either low tension or low compression at the tube inside surface. The unpeened tube F had a low tensile stress at the outside surface (+8 ksi) that became slightly compressive (-5 ksi) at the inside surface.

Another tube (G) was cut into four equal lengths. One length was retained for control data while the remaining three were peened at three shot-peen intensities: .005A2, .008A2 (specification value) and .012A2. The tubes were then examined for residual hoop stress using two methods.

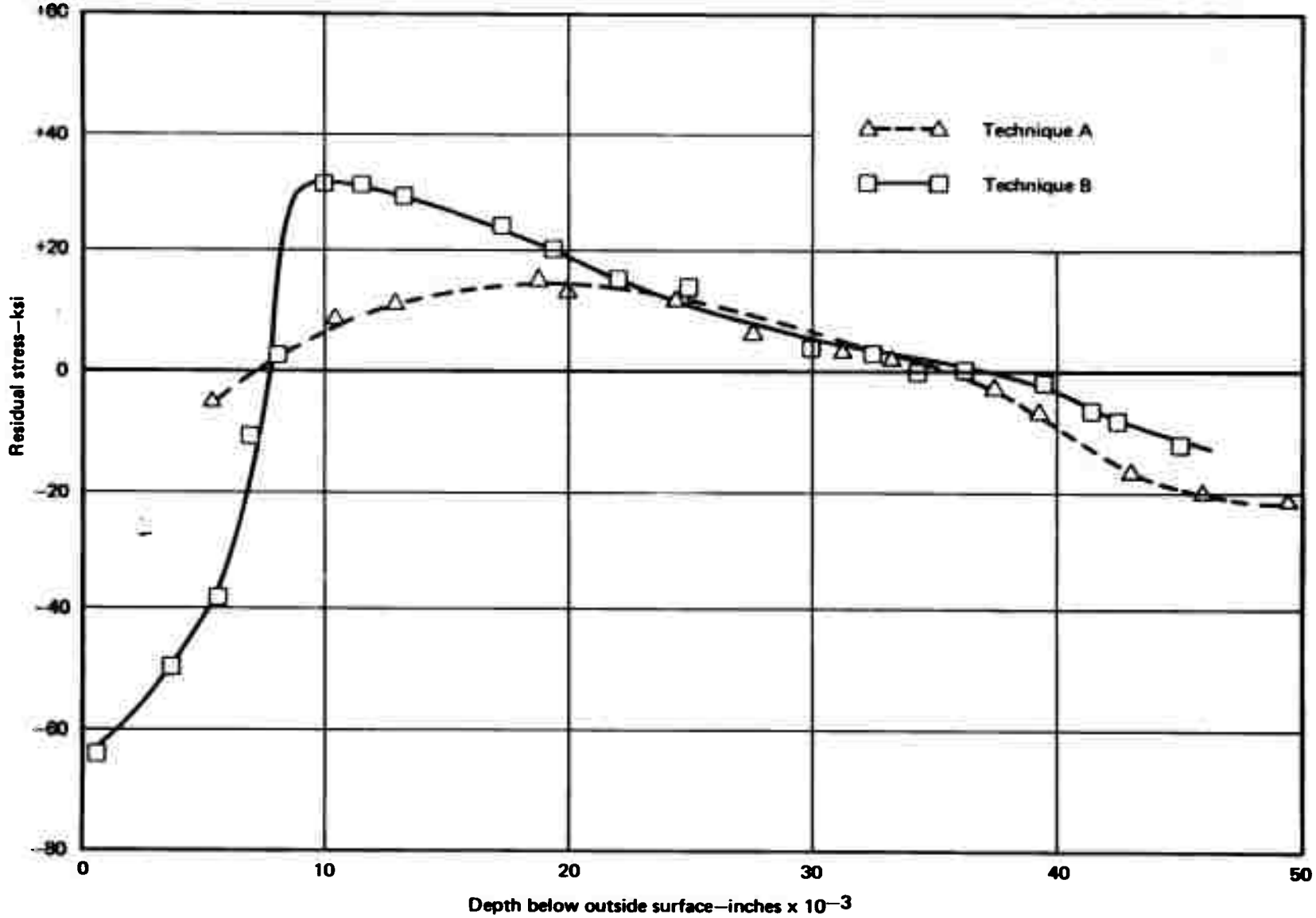


FIGURE 34.—RESIDUAL HOOP STRESS IN TUBE A (1 IN. X .052 IN.)

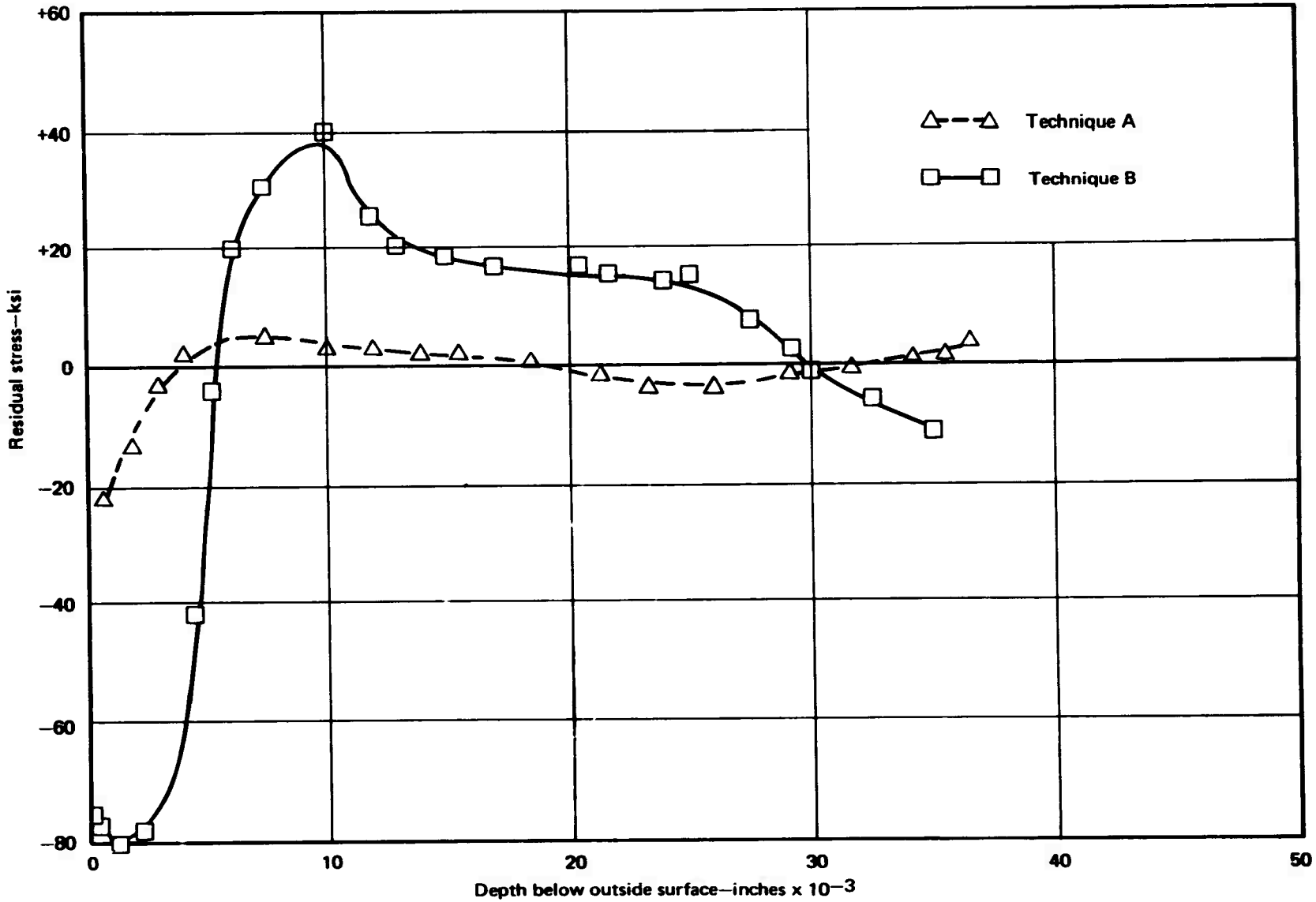


FIGURE 35.—RESIDUAL HOOP STRESS IN TUBE B (¾ IN. X .039 IN.)

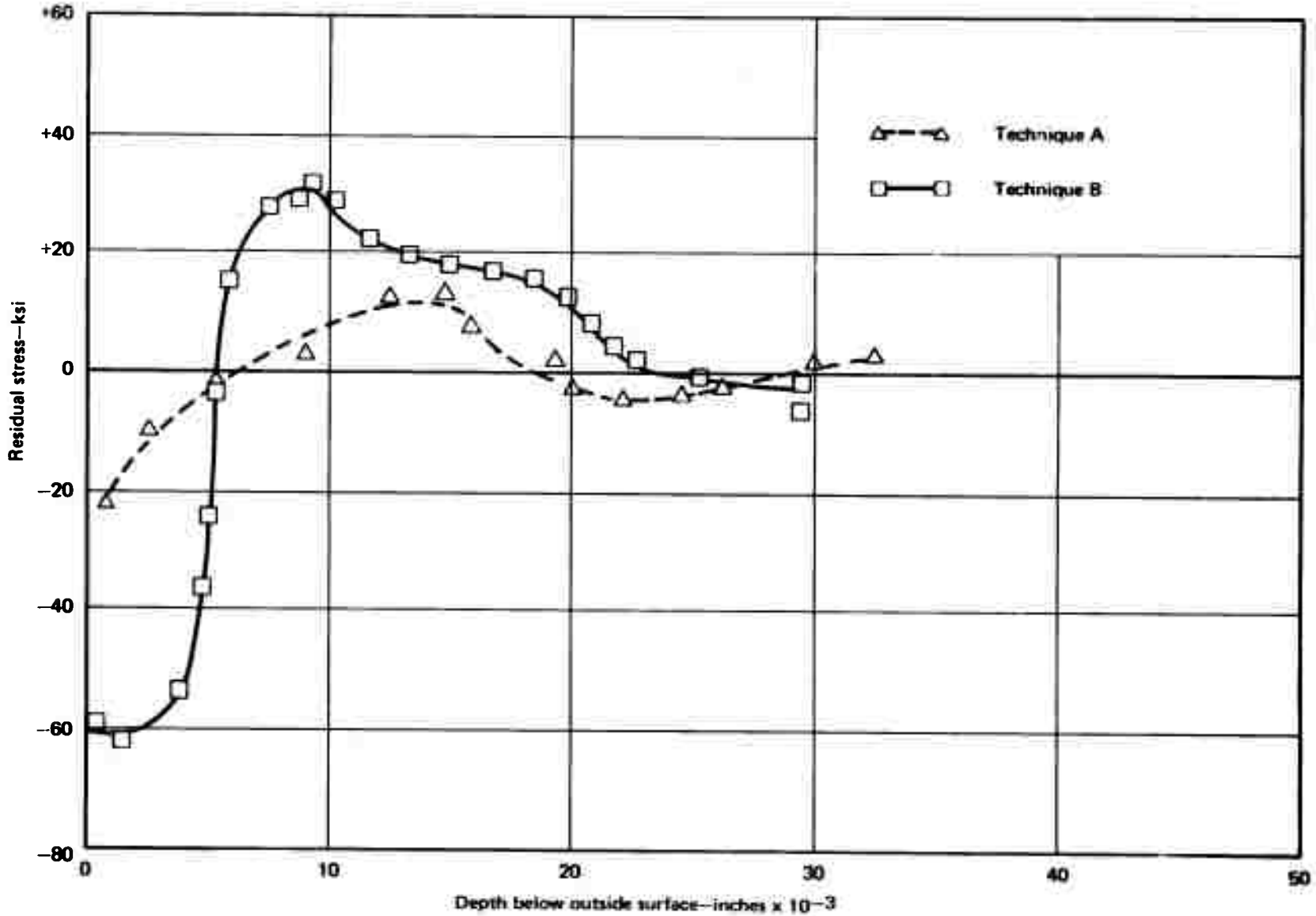


FIGURE 36.—RESIDUAL HOOP STRESS IN TUBE C (5/8 IN. X .033 IN.)

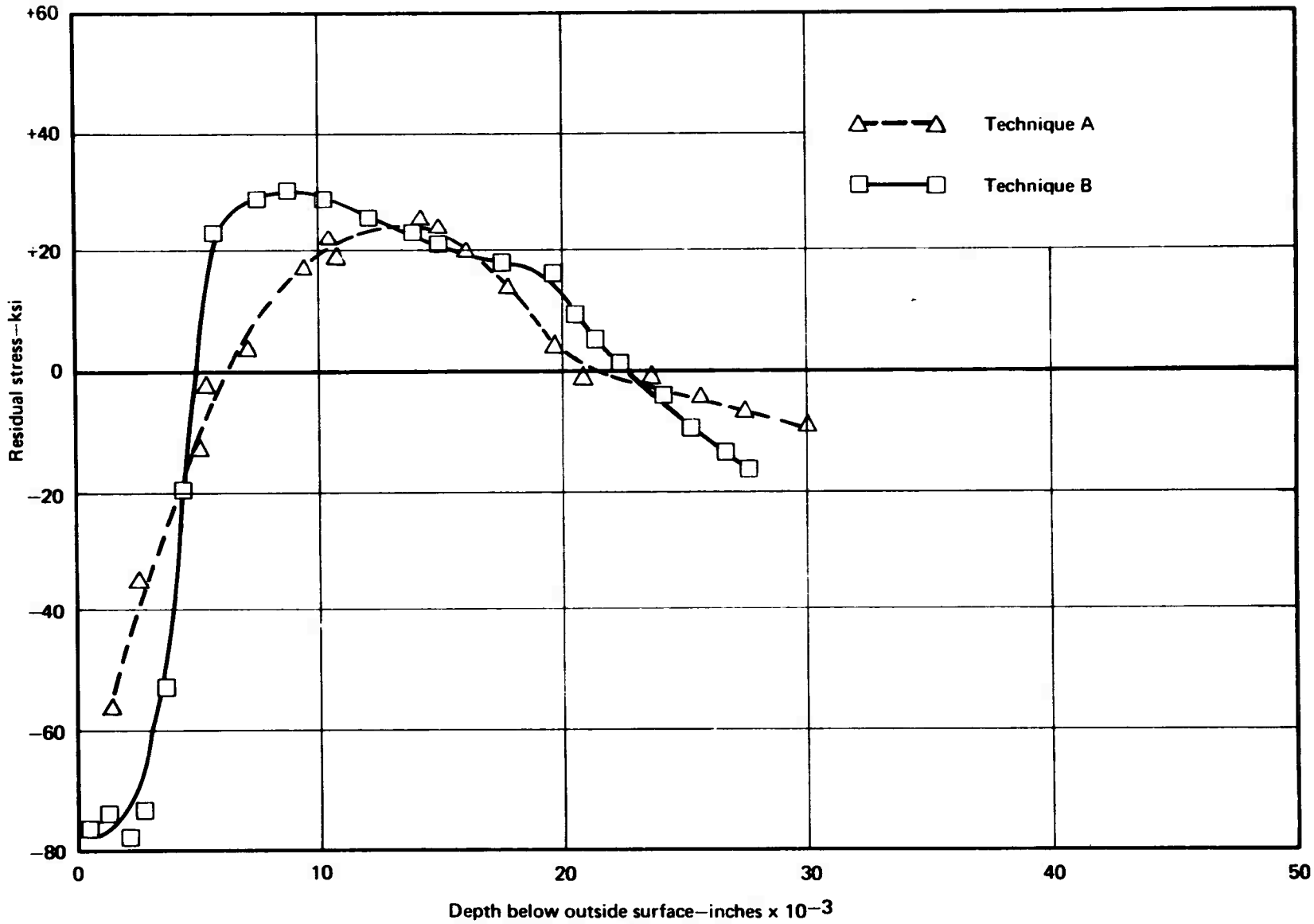


FIGURE 37.—RESIDUAL HOOP STRESS IN TUBE D (½ IN. X .026 IN.)

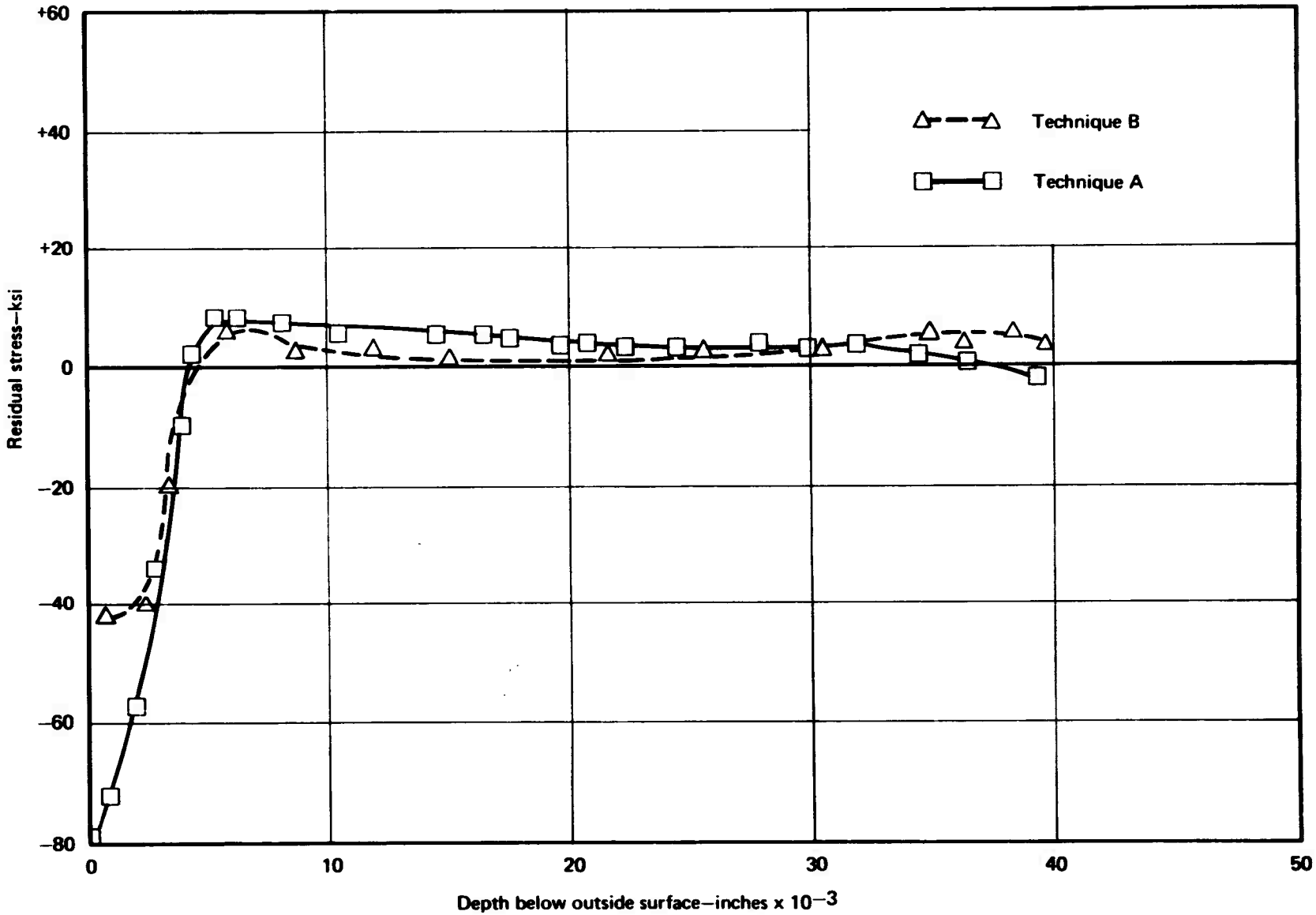


FIGURE 38.—RESIDUAL HOOP STRESS IN TUBE E (3/8 IN. X .020 IN.)

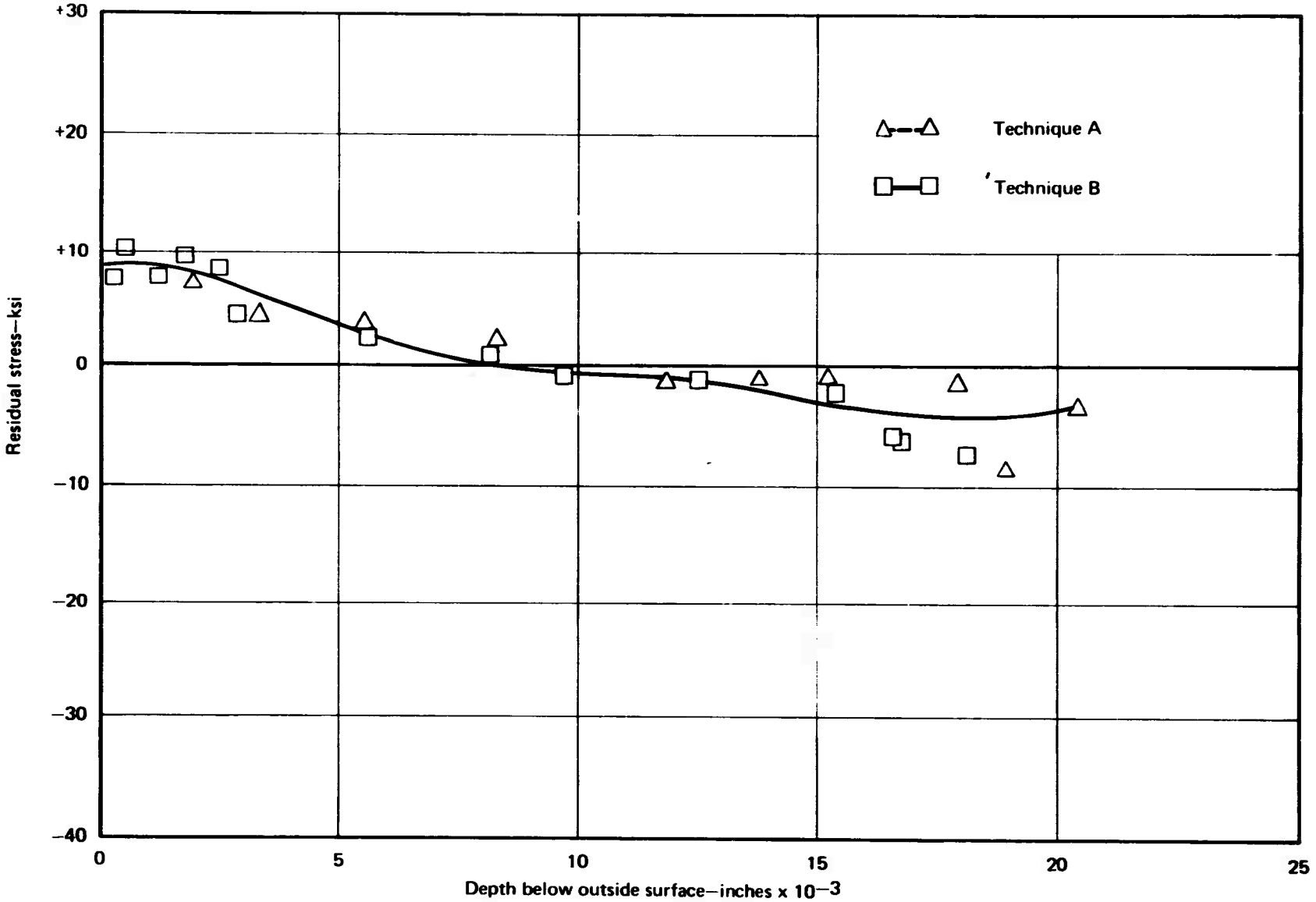


FIGURE 39.—RESIDUAL HOOP STRESS IN TUBE F (3/8 IN. X .020 IN.) UNPEENED

The first method involved making a lengthwise cut on a portion of the tubing (length = 3 times diameter) and noting the change in diameter after cutting. This method provides an average residual hoop stress determination. The data obtained is shown in table 27. An average tensile stress of +8.7 ksi was found on the unpeened tube and progressively greater compression stresses on the shot-peened tubes as the peening intensity increased.

The second method used was the Sach's boring out method, using Technique A (section 3.1.7). Residual stress curves obtained per this method are shown in figures 40 through 43 and the data is tabulated in table 26. Examination of the data shows a tensile stress of +40 ksi at the outside surface of the unpeened tube which becomes a compression stress of -36 ksi at the inside surface. The shot-peening operations resulted in a compressive stress of about -60 ksi in every case. However, as the peening intensity increased, the depth compression increased from 0.007 inch at .005A2 intensity to 0.012 inch at .012A2 intensity. It was further found that the compression stress at the inside surface was decreased but did not become tensile, even for the most severe peening intensity.

Shot-peening at the intensities specified in the procurement specification BMS 7-203A were found to be acceptable (.007A2, - .009A2) for tubing with wall thickness between 0.037 and 0.060 inches. It was noted however, that lower peening intensities than currently specified would normally produce an acceptable residual stress profile.

TABLE 27. –RESIDUAL HOOP STRESS, Ti-3Al-2.5V CWSR HYDRAULIC TUBING – TUBE CUTTING METHOD

Specimen Identification and Peening Intensities	Outside Diameter (inches)		Change in Diameter (inches)	Average Residual Stress (ksi)*
	Initial (D_o)	Final (D_f)		
G-C - unpeened	0.7517	0.758	+0.0065	+ 8.7
G-1 - .005A2	0.7517	0.743	-0.0087	-11.9
G-2 - .008A2	0.752	0.737	-0.015	-20.6
G-3 - .012A2	0.7525	0.733	-0.0195	-27.0

*Calculated using Crampton's method:

$$S = \frac{E}{1 - u^2} t \frac{D_f - D_o}{D_f D_o}$$

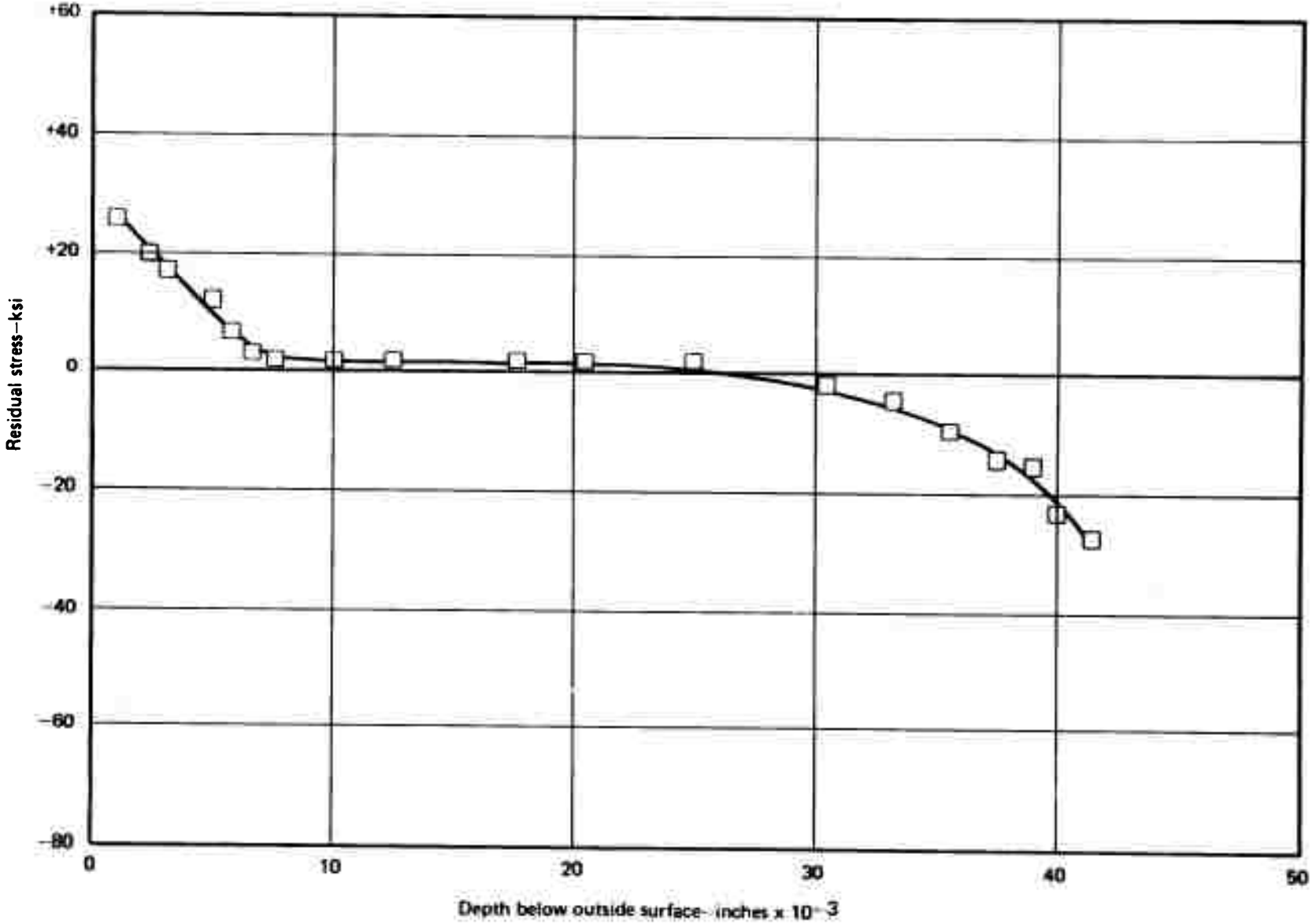


FIGURE 40.—RESIDUAL HOOP STRESS IN TUBE G-C (⅝ IN. X .045 IN.) AS RECEIVED FROM THE VENDOR

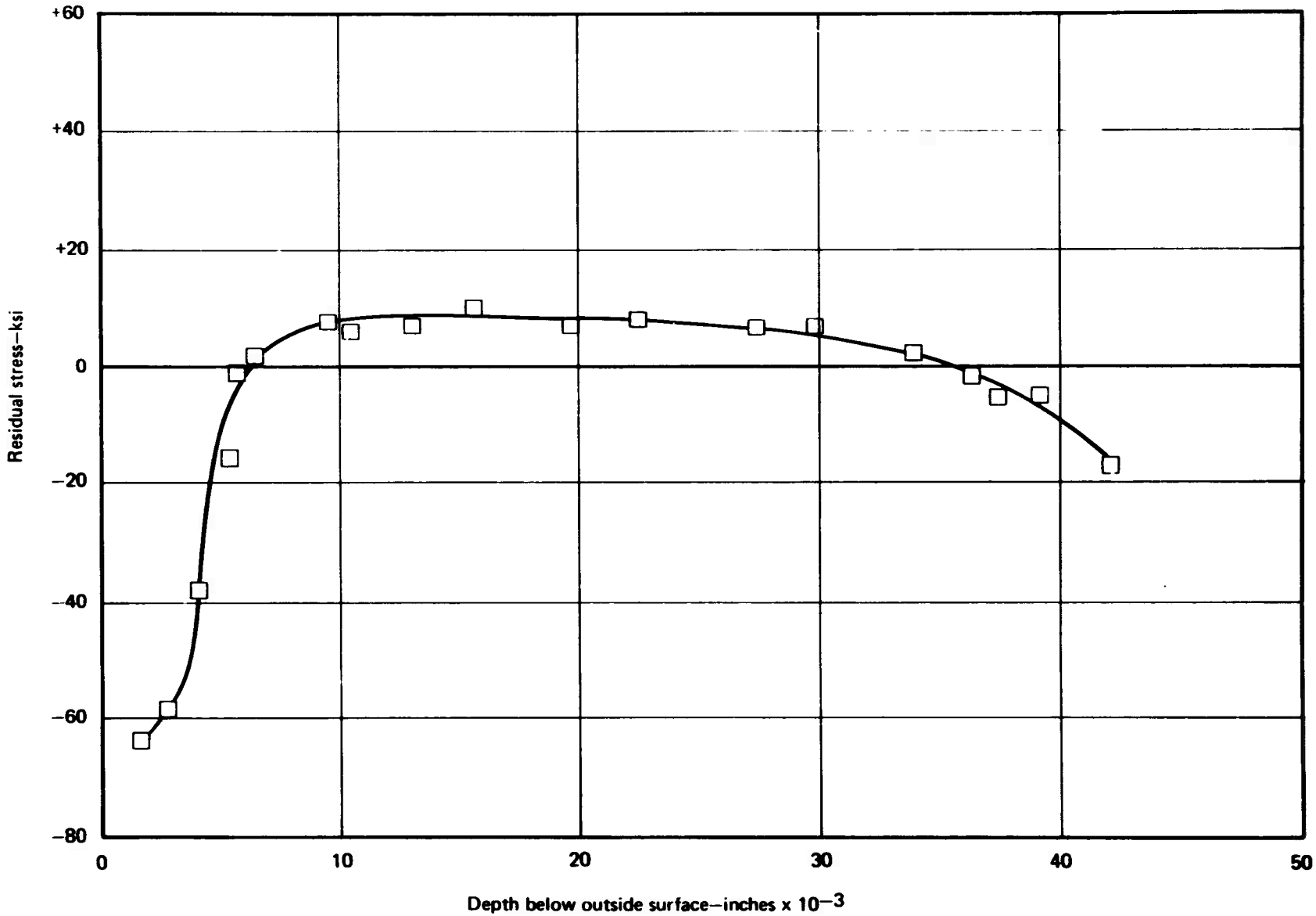


FIGURE 41.—RESIDUAL HOOP STRESS IN TUBE G-1 (¾ IN. X .045 IN.) PEENED TO 0.005A2

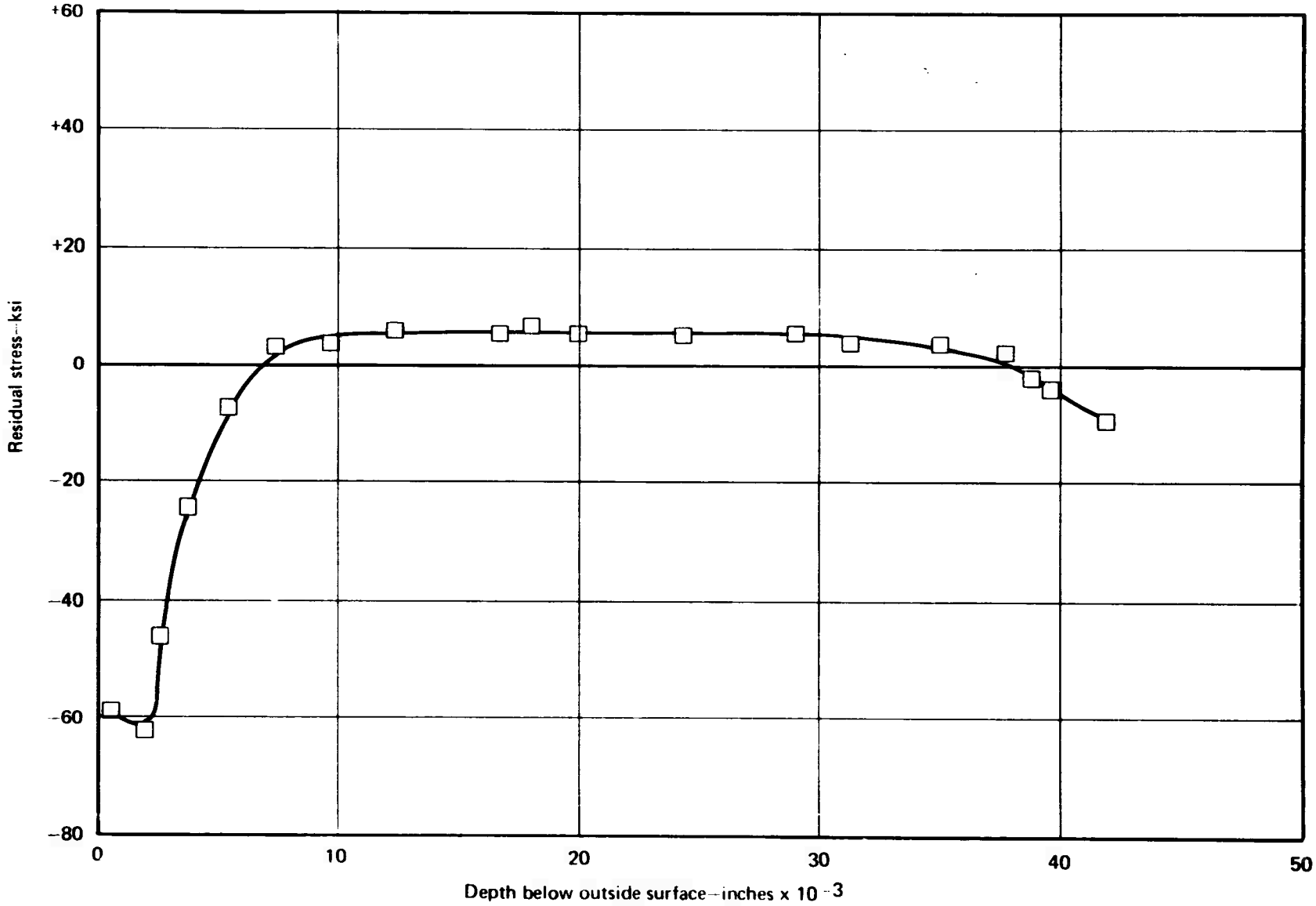


FIGURE 42.—RESIDUAL HOOP STRESS IN TUBE G-2 (¾ IN. X .045 IN.) PEENED TO 0.008A2

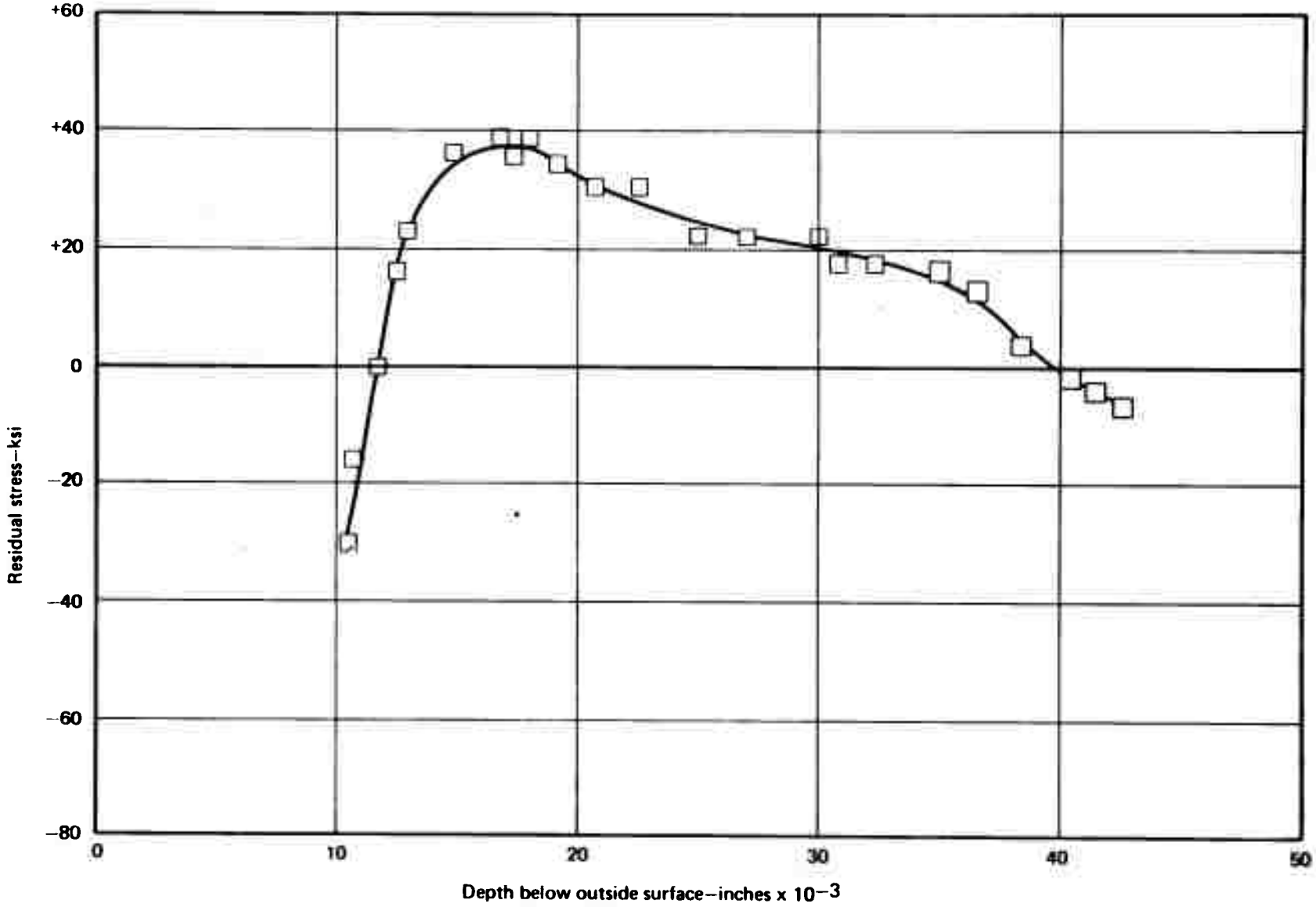


FIGURE 43.–RESIDUAL HOOP STRESS IN TUBE G-3 (¾ IN. X .045 IN.) PEENED TO 0.12A2

3.4.4 Formability

The forming characteristics and limitations for Ti-3Al-2.5V CWSR hydraulic tubing per BMS 7-203 were determined (ref. 38) and are as shown in the tabulation of data in table 28.

Samples of qualification tubing covered a wide range of diameters and wall thicknesses and were tested for minimum and preferred bend radii, angular and radial springback, minimum clamping distance and the percent of stretch determination. The tubes were bent using a Pines bending machine with a pressure boost die and one of the following types of mandrels; Ampco 1 ball, Ampco 3 ball, with plug mandrel and without a plug mandrel.

Measurements for ovality were taken in the plane of the bend and perpendicular to the plane of the bend. Ovality was then calculated using the following relationship:

$$\% \text{ Ovality} = \frac{\text{O.D. (max)} - \text{O.D. (min)}}{\text{O.D. (nom)}} \times 100$$

Measurements for wall thickness change were taken around the tube wall at the apex of the bend and compared with duplicate measurements made in an unbent region of the same tube.

3.4.4.1 Minimum and Preferred Bend Radii

Examination of the data showed that the Ti-3Al-2.5V CWSR tubing had a minimum bend radius of 3D regardless of tube size. The preferred bend radius for Ti-3Al-2.5V CWSR tubing is 4D.

3.4.4.2 Angular and Radial Springback

The Ti-3Al-2.5V CWSR tubing exhibited consistent angular springback characteristics of 12 ± 3 degrees. Springback in all of the bends fell within this range except the 1 x 0.080 in. tubing which had an angular springback of 16 degrees. Radial springback showed more variability but fell within the range of 0.20 ± 0.10 inch for all of the tube sizes except the 3/8 x 0.020 in. tubing which had an angular springback of 0.09 inch.

3.4.4.3 Percent of Stretch

The Ti-3Al-2.5V CWSR tubing showed approximately twenty percent stretch in the outer fibers regardless of the tube size when bent to the minimum band radius.

3.4.4.4 Ovality

The Ti-3Al-2.5V CWSR tubing had ovalities of 3 percent or less with the exception of the 3/8 x 0.020 in. Ti-3Al-2.5V CWSR tube, which had an ovality slightly greater than 4 percent. Ovality in bends is variable and is controlled by the quality of the forming equipment being used, tubing being formed, and forming techniques employed.

TABLE 28. –FORMABILITY OF Ti-3Al-2.5V CWSR TUBING

Tube Size (O.D. x wall thickness) (Inches)	Alloy	Supplier	Bend Rad.		Springback		Actual Bend Rad.	Ovality Percent	Wall Thickness		Bend Quality	Min. Clamp Length	Percent Stretch
			Die	R/D	Ang.	Radial			Thin.	Thicken.			
3/8 x 0.020	Ti-3Al-2.5V	Zirtech	0.50	1.3	–	–	–	–	–	–	Fract.	–	–
			0.75	2.0	–	–	–	–	–	–	Unaccept.	–	–
			1.00	2.7	10	0.0875	2.9	4.6	8.3	–	OK	1.125	19.
			1.50	4.0	10	0.227	4.6	2.4	4.4	3.8	OK	1.125	12.5
3/8 x 0.020	Ti-3Al-2.5V	Superior	0.50	1.3	–	–	–	–	–	–	Fract.	–	–
			0.75	2.0	–	–	–	–	–	–	Unaccept.	–	–
			1.00	2.7	11	0.0875	2.9	4.0	8.4	6.4	OK	1.125	19.
			1.50	4.0	11	0.227	4.6	1.8	3.9	2.9	OK	1.125	12.5
½ x 0.020	Ti-3Al-2.5V	Superior	1.00	2.0	–	–	–	–	–	–	Fract.	–	–
			1.50	3.0	12	0.150	3.3	2.2	6.3	3.1	OK	1.5	19.
			2.00	4.0	12	0.220	4.4	1.2	5.3	5.0	OK	1.0	19.
5/8 x 0.020	Ti-3Al-2.5V	Superior	1.50	2.4	–	–	–	–	–	–	Fract.	–	–
			1.75	2.8	11.5	0.150	3.0	3.0	–	–	Cracked	1.875	20.
			2.00	3.2	11.5	–	–	2.1	5.3	4.2	OK	1.875	19.
			2.50	4.0	11.5	0.212	4.3	2.0	4.8	3.0	OK	1.250	12.5
¾ x 0.060	Ti-3Al-2.5V	Zirtech	1.50	2.0	–	–	–	–	–	–	Fract.	–	–
			2.00	2.7	12	0.32	3.1	2.9	–	–	OK	3.00	21.
			2.25	3.0	15	0.25	3.3	1.3	6.8	12.7	OK	3.00	17.
			2.50	3.3	13	0.26	3.7	2.0	6.8	17.	OK	3.00	15.
			3.00	4.0	13	0.22	4.3	1.9	6.8	17.	OK	3.00	14.
1 x 0.033	Ti-3Al-2.5V	RMI	2.0	2.0	–	–	–	–	–	–	Fract.	–	–
			2.5	2.5	–	–	–	–	–	–	Fract.	–	–
			3.0	3.0	8	0.10	3.1	1.0	7.3	16.	OK	3.00	21.8

TABLE 28. –FORMABILITY OF Ti-3Al-2.5V CWSR TUBING (continued)

Tube Size) (O.D. x wall thickness) (Inches)	Alloy	Supplier	Bend Rad.		Springback		Actual Bend Rad.	Ovality Percent	Wall Thickness		Bend Quality	Min. Clamp Length	Percent Stretch
			Die	R/D	Ang.	Radial			Thin.	Thicken.			
1 x 0.080	Ti-3Al-2.5V	Zirtech	2.0	2.0	–	–	–	–	–	–	Fract.	–	–
			2.5	2.5	–	–	–	–	–	–	Fract.	–	–
			3.0	3.0	16	0.30	3.3	3.2	6.3	12.6	OK	2.00	18.7
1¼ x 0.041	Ti-3Al-2.5V	Zirtech	3.00	2.4	9	0.20	2.5	4.0	15.1	15.4	Cracked	3.75	21.
			4.00	3.2	9	0.20	3.3	1.8	5.8	5.6	OK	2.50	19.
			5.00	4.0	9	0.20	4.1	1.7	9.5	2.7	OK	2.50	12.5
1½ x 0.049	Ti-3Al-2.5V	RMI	3.00	2.0	–	–	–	–	–	–	Fract.	–	–
			4.00	2.7	13	0.20	2.8	1.6	11.7	11.1	OK	4.50	23.4
			5.00	3.3	13	0.24	3.5	2.5	11.1	7.	OK	4.50	15.6
			6.00	4.0	13	0.43	4.3	3.4	–	–	OK	4.50	12.6
1½ x 0.120	Ti-3Al-2.5V	Zirtech	4.00	2.7	13	0.13	2.9	2.3	8.1	10.2	OK	4.50	21.3
½ x 0.020	C.P.	Zirtech	0.875	1.75	2	–	1.76	4.3	–	–	OK	1.5	31.
			1.00	2.0	2	–	2.0	1.6	28.	20.	OK	1.0	27.
			1.50	3.0	2	–	3.0	1.0	–	–	OK	1.0	20.
½ x 0.020	C.P.	Wolverine	0.875	1.75	2	–	1.76	1.0	–	–	OK	1.5	30.
			1.00	2.0	2	–	2.0	1.6	–	–	OK	1.0	25.
			1.50	3.0	2	–	3.0	1.0	–	–	OK	1.0	20.
1½ x 0.030	C.P.	Zirtech	3.0	2.0	4	–	2.02	3.0	17.7	25.8	OK	3.00	30.

3.4.4.5 Wall Thickness Change

Selected bends for each size of the Ti-3Al-2.5V CWSR tubing were sectioned (2 specimens minimum for each size) at the apex of the bend and the wall thickness measured for thinning and thickening. The results obtained were compared with nominal wall thicknesses measured in unformed locations. The Ti-3Al-2.5V CWSR tubing had wall thinning of 7.5 ± 2.5% with the exception of the 1½ x .049 in. tubing which showed 11.7% thinning. Wall thickening was slightly greater, with an average of 9 percent, and more variable, ranging from 3.1% to 16% The wall thickness changes showed no relationship to the size of tubing.

3.4.5 Crystalographic Texture

Texture analysis was performed on three Ti-3Al-2.5V tubes using x-ray pole figure determinations (35). See figures 44, 45, and 46. The 1.00 in. x 0.033 in. tubing (RMI) demonstrated the strongest radial orientation of basal plans; (the pole of the basal plane is perpendicular to the surface of the tube for this texture.) The 1.5 x 0.120 in. tubing (Zirtech) possessed the second strongest radial orientation, and the ½ x 0.040 in. tube (Zirtech) the least preferred radial orientation. These texture differences are thought to result from the relative amount of wall to diameter reduction during processing.

3.5 MICROSTRUCTURE

The microstructure of Ti-6Al-4V and Ti-3Al-2.5V alloys has been found to have considerable influence on the formality, mechanical properties and fatigue properties of hydraulic tubes. The two microstuctural features that were noted to cause problems were 1) Widmanstatten structure and 2) alpha case. Several investigations have made note of these effects and are presented as follows:

3.5.1 Widmanstatten (Basketweave) Structure

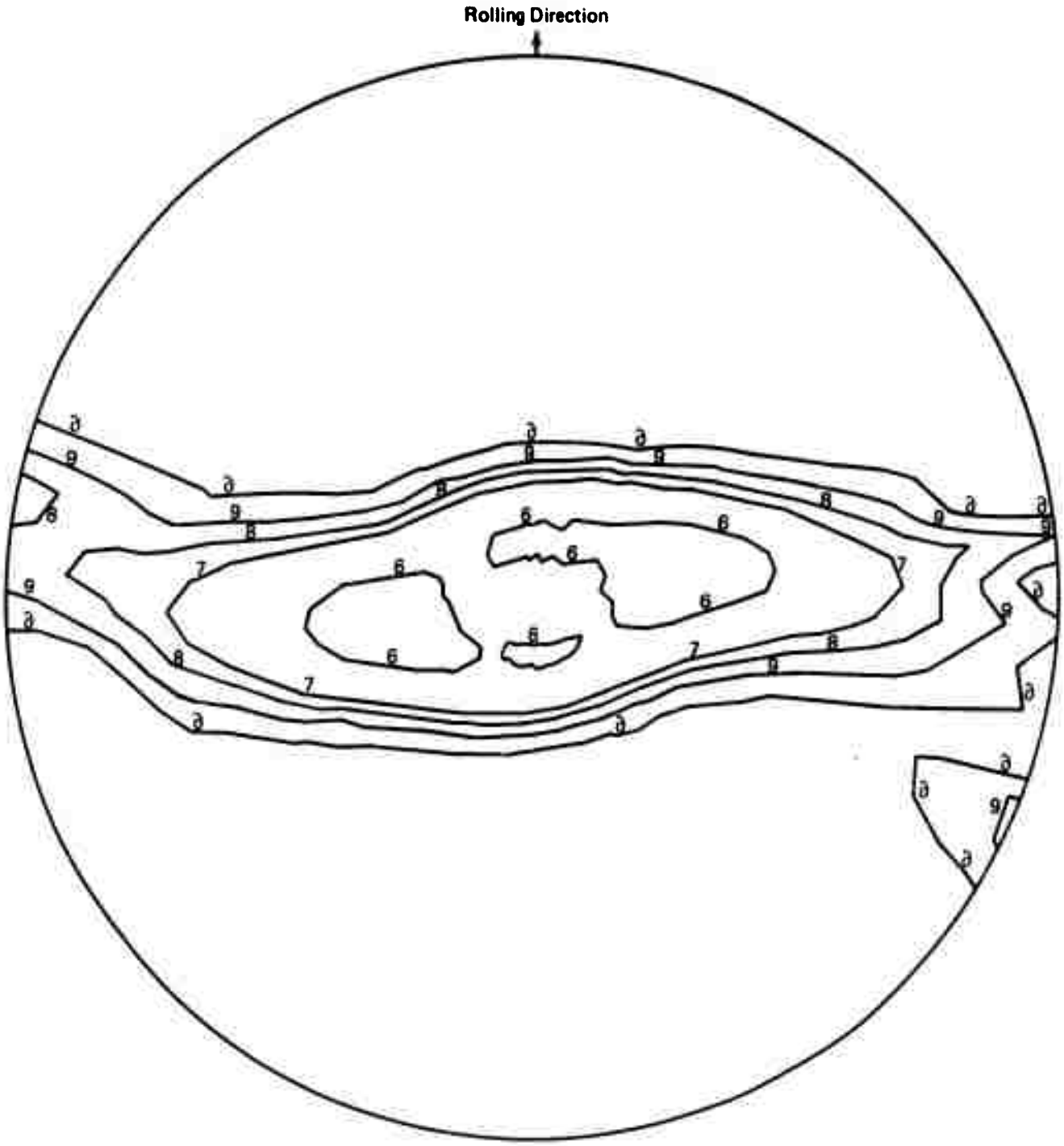
- Failure Analysis of a Brazed Ti-6Al-4V Tube (ref. 19)

  Specimen 2 in the referenced investigation failed when a fatigue crack formed in the tube at a distance of 1.5 inches from a blazed union fitting. This crack was unusually jagged which is typical of a very coarse Widmanstatten microstructure. (See figures 47 and 48.) The microstructure was not produced by the brazing operation but was a result of the manufacturing process.

  The fatigue crack initiated at the O.D. and progressed in a jagged manner. The fracture tended to zig-zag along the prior beta grain boundaries as well as martensite platelets. Similar failures have been ovserved in other tubes possessing a Widmanstatten microstructure.

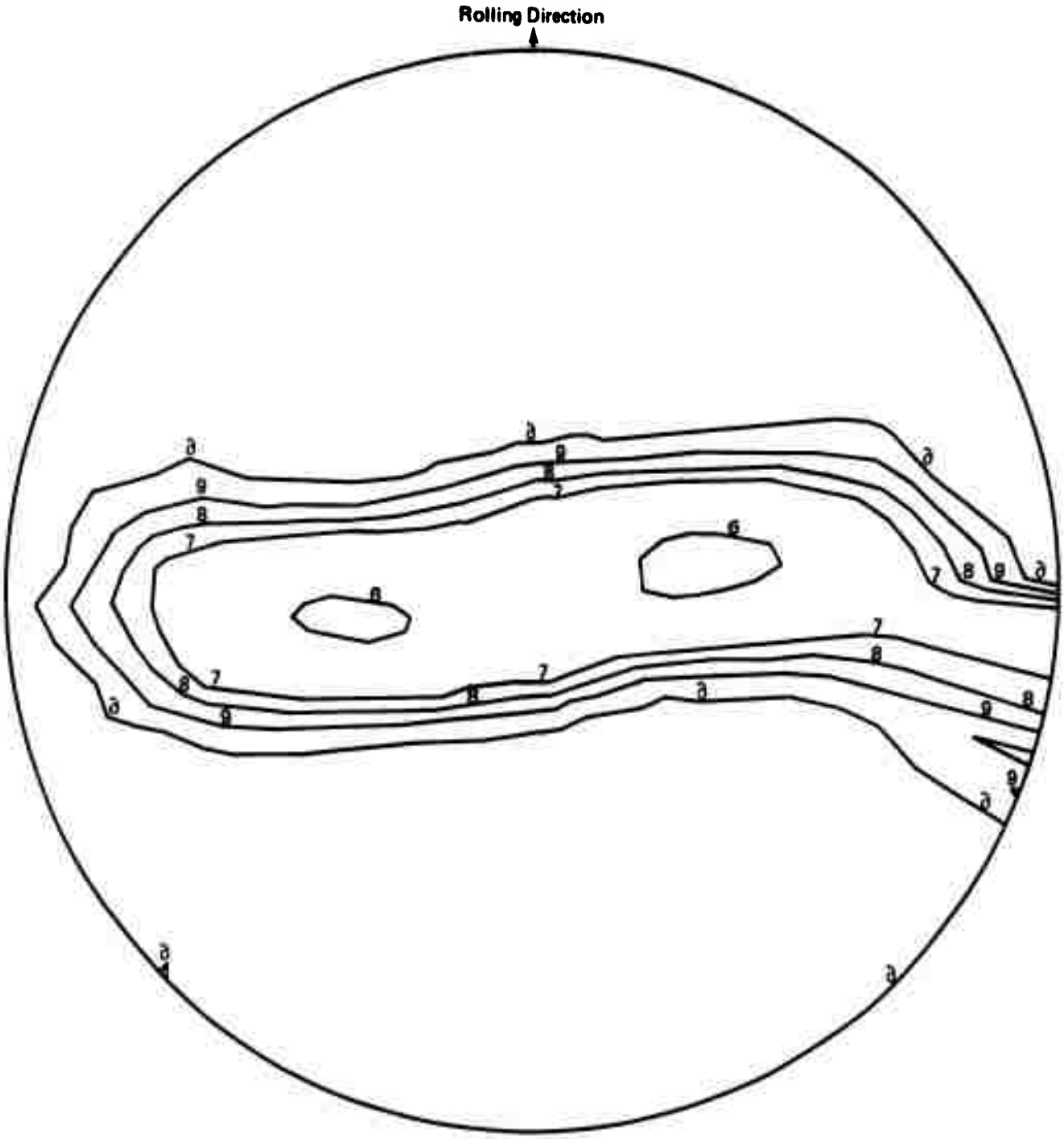
- Analysis of Formed Ti-6Al-4V Hydraulic Tubing (ref. 30)

  In the referenced investigation, a ½ x 0.028 in. tube was found to have a large grained Widmanstatten microstructure. This structure was produced in the tubing when it was it was heated above the beta transus during some phase in final processing. The material formed to the expected bend radius but due to the large grain size, the tube surface



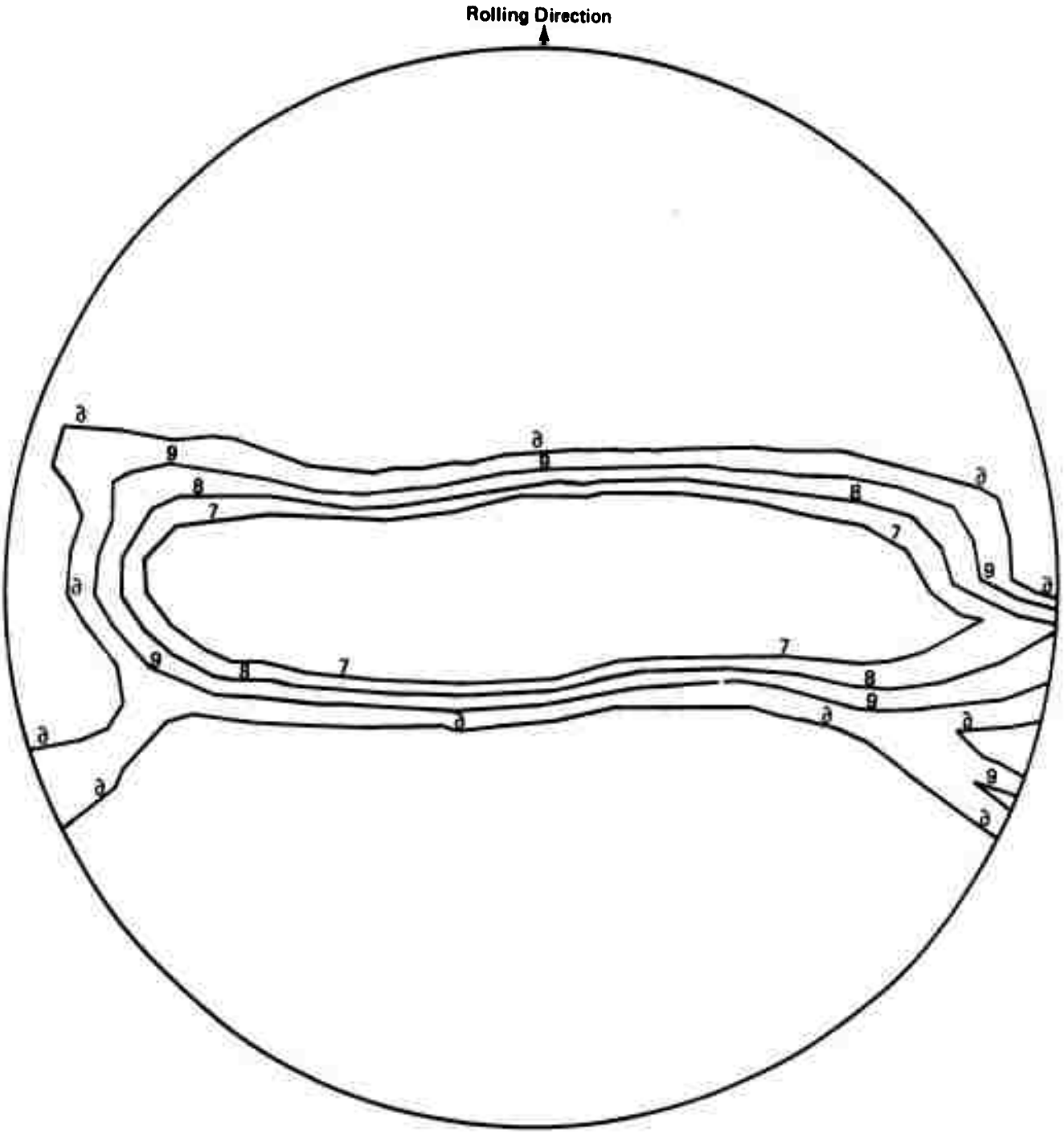
Contour lines	6	7	8	9	∂
Times random intensity	4.0	2.0	1.5	1.0	0.5

FIGURE 44.–POLE FIGURE SHOWING INTENSITY PROFILES OF BASAL PLANE REFLECTIONS FOR 1.0 IN. X 0.033 IN. RMI TUBING. DATA FOR THIS TUBING SHOWS THE STRONGEST RADIAL ORIENTATION IN COMPARISON WITH POLE FIGURES FOR THE OTHER TWO TUBING SAMPLES (FIGURES 45, 46)



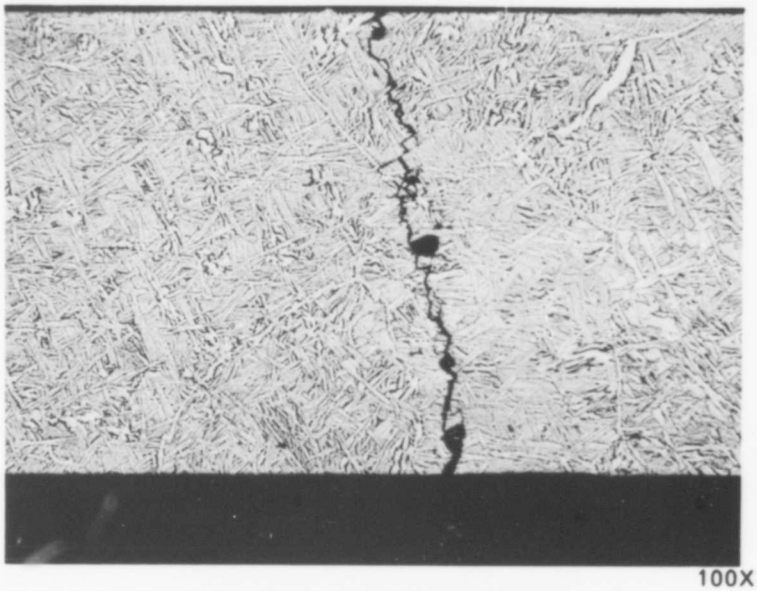
Contour lines	6	7	8	9	∂
Times random intensity	4.0	2.0	1.5	1.0	0.5

FIGURE 45.–POLE FIGURE SHOWING INTENSITY PROFILES OF BASAL PLANE REFLECTIONS FOR 1½ IN. X 0.120 IN. ZIRTECH TUBING. THE DATA SHOWS THE UNIT CELL AXES TO BE ORIENTED MORE STRONGLY IN THE RADIAL DIRECTION THAN FOR THE ½ IN. O.D. TUBING, (FIGURE 46) WITH PEAK INTENSITIES OCCURRING APPROXIMATELY 40°FROM A TRUE RADIAL DIRECTION



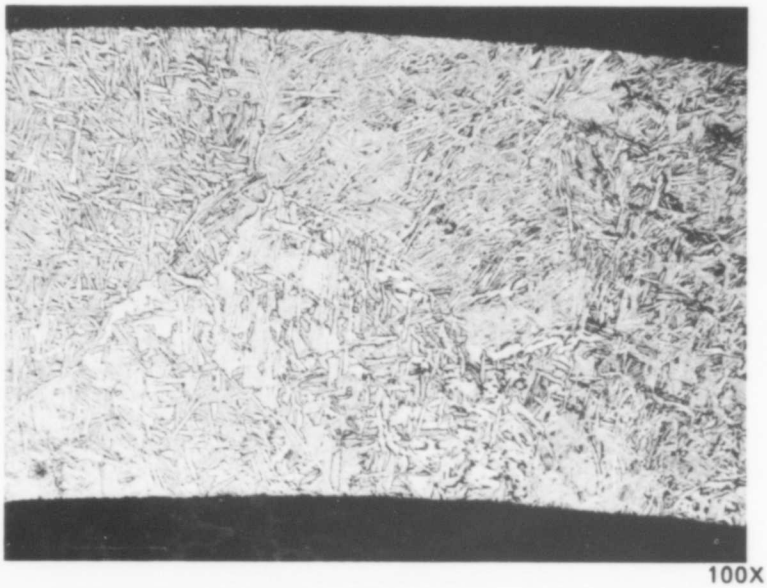
Contour lines	6	7	8	9	∂
Times random intensity	4.0	2.0	1.5	1.0	0.5

FIGURE 46.–POLE FIGURE SHOWING INTENSITY PROFILES OF BASAL PLANE REFLECTIONS FOR ½ IN. X 0.040 IN. ZIRTECH TUBING. THE DATA INDICATES THE AXES OF UNIT CELLS ARE DISTRIBUTED SOMEWHAT RANDOMLY BETWEEN A CIRCUMFERENTIAL AND A RADIAL ORIENTATION WITH A SLIGHT TENDENCY TOWARD A RADIAL ORIENTATION



100X

FIGURE 47. –PROFILE OF A CRACK WITH THE ORIGIN ON THE O.D.. THE CRACK IS VERY JAGGED AND TENDED TO FOLLOW PRIOR BETA GRAIN BOUNDARIES– NOTE THE CHANGE OF MICROSTRUCTURE AT RIGHT



100X

FIGURE 48. –COARSE WIDMANSTATTEN MICROSTRUCTURE–SECTION TAKEN FROM THE END OF THE TUBE AWAY FROM THE BRAZED JOINT

roughened severely (orange peel). The undesirable surface roughening characteristics and inherently less ductile nature of the Widmanstatten structure have resulted in a specification change to allow only a fine grained equiaxed alpha-beta structure. grained equiaxed alpha-beta structure.

- Fatigue Analysis of Failed Ti-6Al-4V Hydraulic Tubes (ref. 20)

  In the referenced report, a circumferential crack formed in Tube 5 and is shown in figure 49. Note the jagged appearance of the crack which is typical in tubing with a Widmanstatten microstructure. It is considered that the major factors which caused early failure, were the Widmanstatten microstructure and excessive wear at the edge of the tube due to fretting beneath a sleeve.

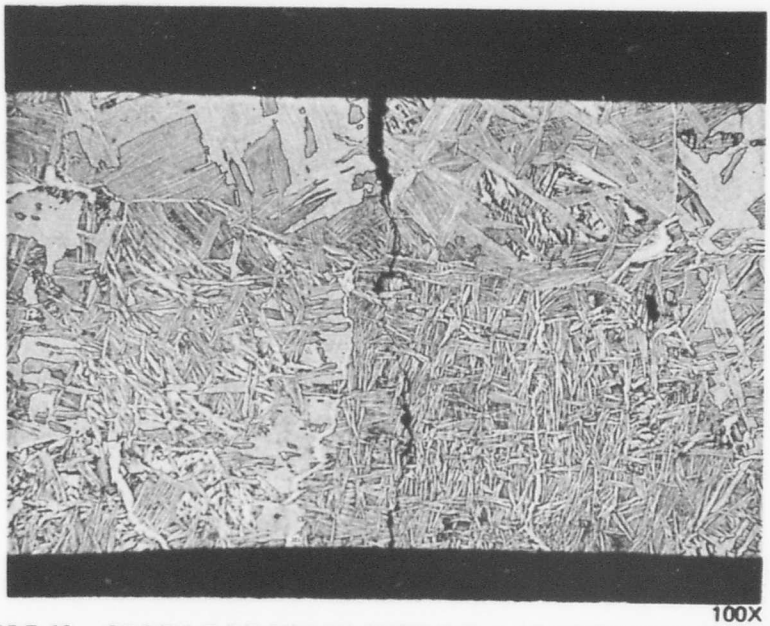
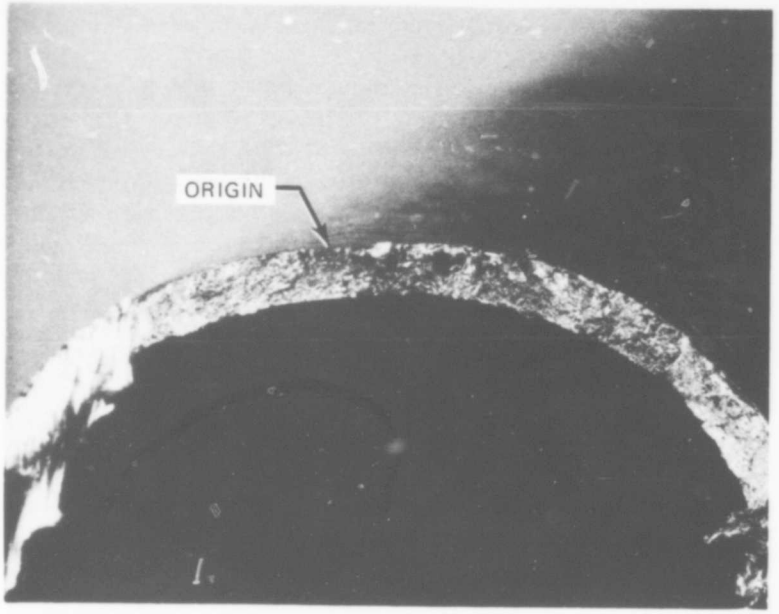


FIGURE 49. –PROFILE OF CRACK SHOWING A COARSE WIDMANSTATTEN STRUCTURE AND A JAGGED FRACTURE

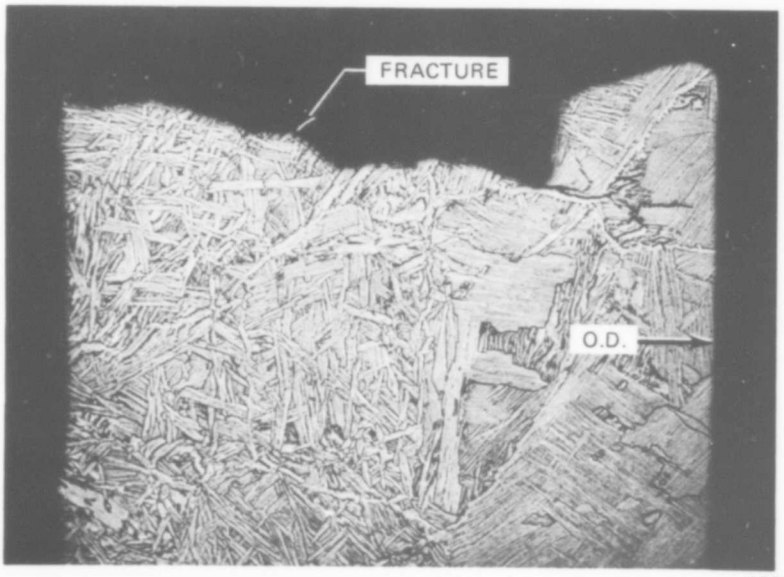
- Fatigue Analysis of Failed Ti-6Al-4V Hydraulic Tubes (ref. 15)

  Three failed tubes were examined in this investigation, and all showed a course grain Widmanstatten microstructure. The surface of the fatigue cracks were jagged and tended to follow along prior beta grain boundaries as shown in figures 50 and 51. A Widmanstatten microstructure is considered to produce lower tensile properties, including lower ductility, compared to a fine grain equiaxed microstructure. Failure of all three of the subject specimens is attributed to the course grain Widmanstatten microstructure, but could also have been affected by small surface defects.



10X

FIGURE 50. –VERY JAGGED FRACTURED SURFACE.



150X

FIGURE 51. –VERY COARSE WIDMANSTATTEN MICROSTRUCTURE, ESPECIALLY TOWARDS THE O.D. ON THE RIGHT–NOTE HOW FRACTURE FOLLOWS ALONG PRIOR BETA GRAIN BOUNDARIES

3.5.2 Alpha Case

- Analysis of Ti-6Al-4V Hydraulic Tubing That Had Cracked During Forming (ref. 39)

  In the referenced study a microstructural examination showed evidence of an alpha case on both the I.D. and O.D. extending to a depth of greater than 0.001 inches. Microhardness tests were conducted at both surfaces which further verified the presence of an alpha case. The results were as follows:

Distance From Surface-inches	Outside Diameter		Inside Diameter	
	KHN*	Rc	KHN*	Rc
.0004	433	43	412	41
.004	360	36	330	33

*100g load

The microstructure beneath the alpha case was a fine equiaxed alpha-beta structure typical of Ti-6Al-4V. The tube also experienced poor formability which is considered to be due to the contaminated layer. The contaminated layer was also responsible for a low total elongation that was measured in tensile tests.

4.0 ANALYSIS OF TEST RESULTS

This analysis of test results was made with regard to the combined findings on both the Ti-6Al-4V annealed and Ti-3Al-2.5V CWSR alloys.

4.1 SURFACE CONDITION

The numberous failure analysis and evaluation tests that were performed on Ti-6Al-4V annealed and Ti-3Al-2.5V CWSR hydraulic tubes showed conclusively that the surface condition of tubes can materially influence performance. Two areas of primary concern were formability and fatigue life.

Surface finishes evaluated were:

- As cold reduced
- Ground
- Sanded
  - Unspecified grit
  - 400 grit
  - 600 grit
- Chemically milled
  - 0.0005 removed/surface
  - 0.002 removed/surface
  - 0.004 removed/surface
- Grit blasted
- Shot peened
- Alpha case contamination
- Polished
- Buffed

The data showed that grinding in any form should be prohibited. Grinding marks acted as crack starters during the cold forming of tubes and/or during fatigue cycling. The severity

of the grinding marks showed a loose correlation with the degree of property degradation but all grinding operations appeared to be unacceptable. Chemical milling of ground surfaces often improved the forming and fatigue performances of tubes but in a significant number of cases this operation did not improve the situation. Therefore, it was accepted as a general rule that ground surfaces cannot be reliably improved by secondary finishing operations.

Sanded surfaces were extensively evaluated in a major Ti-3Al-2.5V tubing program and in numerous smaller programs. The findings of these tests indicated that sanded or sanded and chemically milled surfaces were sometimes, but not always detrimental to forming operations and/or fatigue life. Unspecified grit papers, 400 grit, and 600 grit sanding papers used alone were often found to have had a detrimental effect on fatigue properties.

Chemical milling of surfaces was evaluated to some extent and, in general, improved the service performance of titanium hydraulic tubes. Chemical milling tends to improve surface smoothness and reduce the effects of grinding or sanding scratches. The removal of 0.0005 inch of metal/surface, rather than 0.002 inch, was briefly evaluated and was found to give properties equivalent to the latter amount, although this would not seem to be a realistic expectation for all cases one might consider. It has similarly been suggested that up to 0.008 inch of metal be removed per surface although it would seen that processing costs and wall thickness tolerances would suffer considerably for this situation.

Grit blasting of surfaces was included in some specifications and excluded from others, but did not receive a complete and satisfactory evaluation. It would seem that this process might offer some improvements in surface characteristics.

Shot peening of O.D. surfaces improved the fatigue performance of tubes to a considerable extent in some instances, but not in all. This lack of a consistently improved performance was due to fatigue cracks originating on the I.D. surfaces of many tubes.

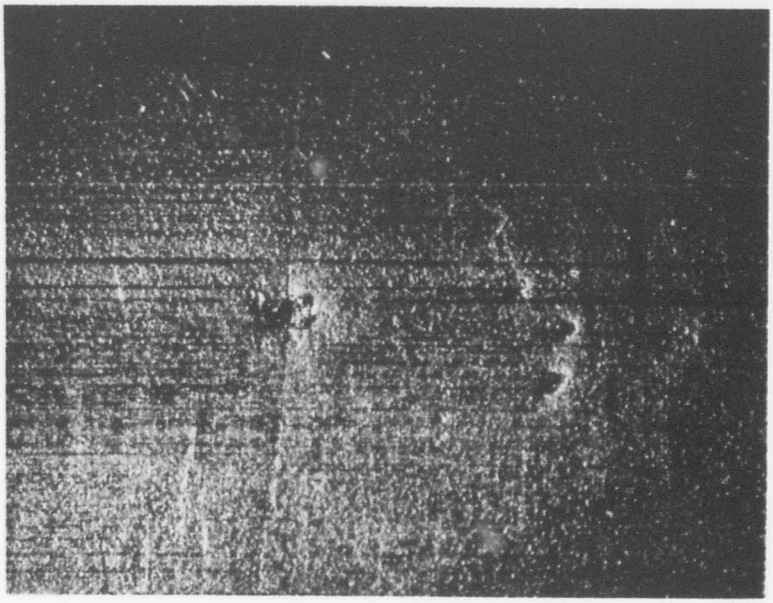
Alpha case on the surface of tubing caused a severe reduction in ductility and thus the ability of the tube to be formed. This surface condition cannot be tolerated.

Polishing and buffing of tubes did not cause any property degradations and may improve fatigue properties. These conditions have generally been allowed in Boeing's material specifications.

4.2 DEFECTS

Defects were the greatest point of concern with respect to the quality of titanium Ti-6Al-4V and Ti -3Al-2.5V tubing. A large number of defect types were noted, some arising from the starting stock and some from manufacturing processes. Those defects that are on the surface or protrude to the surface were normally the ones that caused manufacturing or service problems. Cracks, laps, laminations, tears and pits were the types of discontinuities usually noted. An example of a pit type defect is shown in figure 52.

Often surface defects opened during forming operations and caused the tube to perforate or fracture.



~20X

FIGURE 52.–A PIT TYPE DEFECT WHICH HAS ACTED AS A FATIGUE CRACK ORIGIN

In many cases, surface defects caused premature formation of fatigue cracks and thus early failure. These crack starter type defects may be either on the O.D. or I.D. surfaces and may be oriented transverse, longitudinal, or 45° to the tube axes.

Most defects could divided into four general categories as noted in section 3.4.2.1. They are:

- A longitudinal I.D. lap type defect that intersects the surface at an angle of 30 - 60°. These defects are thought to be carried through from the starting stock (tube hollows) and are usually intermittent.

- Helical I.D. or O.D. lap type defects that interest the surface at an angle of 30 - 60°. These defects often lie parallel to a 45° helix and sometimes occur in pairs that form a chevron pattern. These defects are usually quite short (<0.12 in.) but may be encountered in large numbers.

- A longitudinal O.D. lap defect similar in character to its I.D. counterpart. This type of defect has not been ovserved as frequently as the I.D. variety.

- A transverse O.D. defect that may or may not be a lap. This defect type was infrequently observed.

4.3 MICROSTRUCTURE

The experience gained on titanium sheet, plate, extrusion, and bar material together with the studies performed on the present Ti-6Al-4V and Ti-3Al-2.5V tubing evaluation program showed conclusively that metallurgical structure is vitally important to the satisfactory performance of titanium hydraulic tubing. The two microstructural conditions of prime concern are an alpha case on the surface of the material and a coarse Widmanstatten structure.

Alpha case arises from oxygen contamination on the surface which has the effect of stabilizing the alpha phase. This condition is ususally brought about by improper heat treating atmospheres. An alpha case on Ti-6Al-4V and/or Ti-3Al-2.5V tubing causes the ductility and forming characteristics of the material to be lowered very substantially.

A Widmanstatten microstructure is caused by heating of the titanium above the beta transformation temperature. The ductility of the tube is impaired by this condition and a roughened surface known as "orange peel" is often noted after forming operations. The fatigue properties of titanium with a Widmanstatten microstructure are thought to be impaired and fatigue cracks often follow the prior beta grain boundaries.

4.4 CRYSTALOGRAPHIC TEXTURE

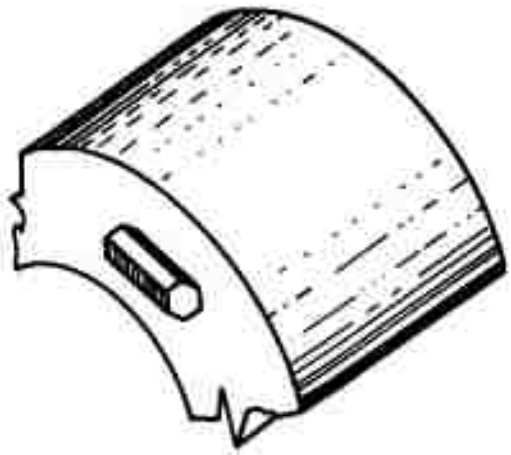
It has long been known that the crystalographic texture of titanium has a great influence on mechanical and physical properties. This is particularly true with respect to strength, ductility, and modulus of elasticity. The texture of titanium tubing has been shown to be influenced by the relative amount of wall to diameter reduction during processing. See figure 53. The greater the ratio of wall to diameter reduction, the greater the tendency toward a radial orientation of the basal plane poles. The influence that radial orientation of basal plane poles has on mechanical properties is to give better formability and less wall thinning during cold deformation. On the other hand, a circumferential orientation of poles is thought to contribute to I.D. roughness and longitudinal type defects. This orientation will give the best hoop strength properties however.

The importance of crystalographic texture on the properties of titanium tubing is considered to substantial and future investigations are planned in this area.

SINK (Diameter Reduction Only)

$(T < 1)^*$

- I.D. Roughness, Longitudinal Defects
- Best hoop strength
- Unit cell tends toward circumferential orientation



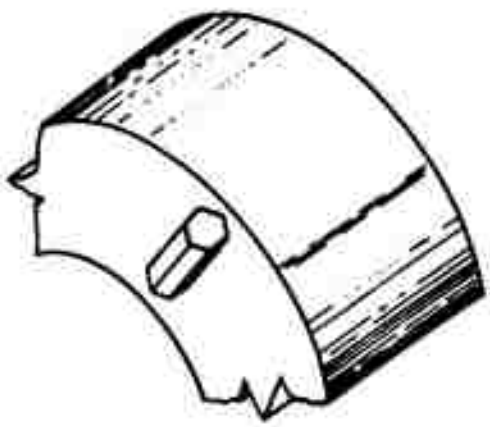
COMBINATION SINK AND WALL REDUCTION

$(T \approx 1)^*$

WALL REDUCTION

$(T > 1)^*$

- Unit cell tends toward radial orientation
- Resists wall thinning during tension deformation



$$^*T = \frac{\frac{\Delta W}{Wo}}{\frac{\Delta I.D.}{I.D.o}}$$

FIGURE 53.—EFFECT OF PROCESSING ON TEXTURE AND PROPERTIES OF TITANIUM TUBING

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5.0 CONCLUSIONS

Several conclusions can be drawn from this investigation on **Ti-6A-4V annealed and** Ti-3Al-2.5V cold worked ans stress relieved tubing. They are as follows:

- The alloy Ti-6A1-4V, annealed, is the most structurally efficient material of those considered for hydraulic tubing applications.
- The quality of Ti-6Al-4V annealed tube steadily improved furing the course of the vendor-Boeing development program but is not yet at a point of satisfactory reliability for application to the SST program.
- Ti-6A1-4V annealed tubing development was sufficient to indicate that satisfactory aircraft quality material can be developed with additional time and funding.
- The surface finish characterisitics and defect levels in Ti-6A1-4V tubing are the most troublesome problem areas to be solved.
- Ti-3Al-2.5V, cold worked and stress relieved tubing, is the most structurally efficient material that can currently be procured for production applications. It is approximately 2% heavier that a Ti-6Al-4V annealed tubing system for the SST.
- Ti-3A1-2.5V cold worked and stress relieved tubing is produced by several vendors, each using somewhat different manufacturing methods. These various processing methods result in tubes of somewhat different characteristics and quality.
- Ti-3A1-2.5V cold worked and stress relieved tubing can be produced to current aircraft specification requirements with relative ease but important secondary properties such as fatigue behavior still have considerable inconsistency.
- More development work is yet required on Ti-3Al-2.5V cold worked and stress relieved tubing before it can be considered wholly satisfactory for aircraft applications. Surface condition, defect levels, and crystalographic texture are items that are in particular need of further developmental work.

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6.0 RECOMMENDATIONS

1. Further development of Ti-6Al-4V annealed hydraulic tubing should be undertaken as this system is more structurally efficient than any other tubing system now in use. The progress made during the SST program strongly indicates that tubing made from this alloy can be brought to a state of commerical and military aircraft readiness.

2. The development of alloy Ti-3Al-2.5V cold worked and stress relieved tubing for hydraulic applications should be continued. This sytem is currently at a state of commercial readiness but can be considerably upgraded in a number of areas. These areas are as follows:

   - Quality of tube hollows (starting stock)
   - Refinement of NDI methods for defect detection
   - Optimization of surface condition
   - Reduction of flaws introduced during manufacturing or from starting stock
   - Texture control to improve strength, forming characteristics, and fatigue properties.

These areas of study have been incorporated into a Department of Transportation follow-on program being conducted by The Boeing Company at the present time. This contract is entitled Titanium Hydraulic Pressure Supply and Distribution Systems; Number DOT-FA-SS-71-12, Phase I, task 6.

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APPENDIX A

DEVELOPMENT OF SPECIFICATIONS

The development of materials specifications to control the quality of Ti-6A1-4V and Ti-3A1-2.5V hydraulic tubing procured by The Boeing Company was a continuous process over the duration of the SST contract. Specifications were continuously modified and up-data in order to reflect new test date, service experience, vendor capability and such like. Three basic Boeing Material Specification (BMS) numbers were used for Ti-6A1-4V and Ti-3A1-2.5V hydraulic tubing; 7-178, 7-203, and 7-234. The primary original issues and revisions of these specifications and the material and conditions which they covered are listed in table A-1. Several additional variations of these specifications were approved but these reflected minor modifications rather than basic changes. At the conclusion of the SST program substantially all titanium hydraulic tubing was being procured to XBMS7-234*.

TABLE A-1.–PRIMARY ORIGINAL ISSUES AND REVISIONS OF Ti-6A1-4V AND Ti-3Al-2.5V BOEING MATERIAL SPECIFICATIONS

Specification Number	Author	Date	Alloy and Heat Treatment		
			Ti-6A1-4V annealed	Ti-3A1-2.5V cold worked and stress relieved	Ti-3A1-2.5V annealed
XBMS 7-178	H. Clark	1-18-66	✓		✓
XBMS 7-178	J. Davies	1-19-68	✓		
XBMS 7-203	J. Davies	3-25-68		✓	
XBMS 7-178	D. Apodaca	9-19-68	✓ (ELI)		
BMS 7-203A	J. Davies	12-17-68		✓	✓
BMS 7-203B	R. Stewart	5- 7 -70		✓	✓
XBMS 7-234	L. Clark	10- 7 -70		✓	
BMS 7-203B	L. Clark	11-10-70			✓

*X indicates preliminary

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1. SCOPE

a. This specification covers seamless round tubing made from Ti-6Al-4V ELI and mill annealed suitable for use in high-pressure hydraulic systems operating to a maximum temperature of 450°F.

b. This specification requires qualified products.

2. REFERENCES

Except where a specific issue is indicated, the issue of the following references in effect on the date of invitation for bid shall form a part of this specification, to the extent indicated herein.

a. AMS 2249 - Chemical Check Analysis Limits - Titanium and Titanium Alloys

b. ASA B46-1 - Surface Texture (Surface Roughness, Waviness and Lay)

c. ASTM B338 - Specification for Seamless and Welded Titanium Tube for Condensers and Heat Exchangers

d. BAC 5439-2 - Inspection, Ultrasonic, of Thin Wall Tubing

e. BAC 5492 - Machining and Cutting of Titanium

f. Federal Standard No. 184 - Identification Marking for Aluminum, Titanium, and Magnesium

g. Federal Test Method Standard No. 151 - Metals, Testing Methods

3. CONDITION

Tubing shall be furnished in the mill annealed condition (MA) as specified by contract or purchase order. The annealing temperature shall be 1275 F to 1450 F. Stress relieving shall be performed as a final thermal treatment on all tubing prior to shipment. The stress relieving temperature shall be 1100 ± 50 F.

4. MATERIAL REQUIREMENTS

4.1 GENERAL

a. This specification requires product qualification prior to acceptance of production orders.

b. The tubing shall be of uniform quality and free from cracks, seams, laps, laminations, tears, pits and other defects detrimental to fabrication or performance.

c. Material used to manufacture tubing shall be produced by multiple consumable electrode melting practice. At least one of the melting stages shall be under vacuum. One stage may be melted using an inert gas atmosphere under a slight positive pressure.

4.2 CHEMICAL COMPOSITION

Chemical composition shall be of extra low interstitial (ELI) and shall conform to the requirements of Table I when analyzed per Section 8.5. Hydrogen analysis shall be conducted and certified for each tubing lot.* Check analysis shall be per AMS 2249.

TABLE I - CHEMICAL COMPOSITION
(WEIGHT PERCENT)

ELEMENT	WEIGHT, PERCENT
Aluminum	5.5 - 6.75
Vanadium	3.4 - 4.5
Iron (max.)	0.25
Carbon (max.)	0.08
Hydrogen (max.)	0.0125 (125 ppm)
Oxygen (max.)	0.1300 (1300 ppm)
Nitrogen (max.)	0.03 (300 ppm)
Other Elements (max.)	0.40 [1]
Titanium	Remainder

[1] Need not be reported. An individual element shall not exceed 0.10 percent.

*A lot is defined as tubing of the same outside diameter and wall thickness made from one heat of material and processed in a similar manner.

4.3 MECHANICAL PROPERTIES

The room temperature longitudinal tensile properties of the tubing shall conform to the requirements specified in Table II when tested in accordance with Section 7.8.

TABLE II - MECHANICAL PROPERTIES

ULTIMATE TENSILE STRENGTH (ksi)	YIELD STRENGTH AT 0.2% OFFSET (ksi)	ELONGATION IN 2 INCHES %
130 min.	120 min.	10 min.

4.4 FLARE TEST

When flare tested per Section 7.7 the tubing shall be capable of being flared to a minimum expansion of 15% of the internal diameter. The flared zones shall be uniform, smooth and free from cracks and other defects when examined at magnifications of 3 to 5 diameters.

4.5 HYDROSTATIC PRESSURE RESISTANCE

When the tubing is tested per Section 7.9 there shall be no leaking, cracking or permanent set exceeding .002 inch per inch of diameter.

4.6 MICROSTRUCTURE

The metallurgical condition of the finished tubing shall be a fine-grained equiaxed microstructure with no evidence of widmanstatten as determined by the method per Section 7.1.

4.7 SURFACE CONDITION

a. Outside and inside surface of finished tubing shall be free from a brittle layer (alpha case) as determined by the test in Section 7.2.b.

b. Belt sanding of the O.D. and grit blasting of the ID is recommended. Grinding with a hard wheel of the outer surface shall not be employed. The finishing operation shall conform to BAC 5492.

c. After the final mechanical abrasive treatment, all tubes shall be chemically etched a minimum of 0.002 inch on all surfaces to wash out sharply reentrant defects such as scratches and strike marks from belt sanding. Surface roughness of the tubing shall not exceed RHR 63 on inside surfaces and RHR 32 on outside surfaces.

4.7 (Continued)

d. Finished tubing shall not contain defects greater than those noted in Table III as determined per Section 7.5.

TABLE III - ULTRASONIC SIZE OF DEFECTS

Wall Thickness, in.	Depth, in.	Length, in.	Inspection Class per BAC 5439-2
0.020 to 0.050	0.002	0.060	Class A-2
0.051 and above	0.003	0.125	Class B-3

4.8 TOLERANCES

a. Wall Thickness

Wall thickness tolerances shall be nominal ± 5%

b. Ovality

Ovality tolerance shall be ± 1% when measured per Section 7.3.

c. Outside Diameter

Outside diameter tolerances for tubing shall be as specified in Table IV when measured per Section 7.4.

TABLE IV - OUTSIDE DIAMETER TOLERANCES

Nominal O.D. (inches)	Tolerance (inches)
0.187 to 0.625	+0.003 -0.000
0.626 to 1.000	+0.005 -0.000
1.001 to 1.500	+0.007 -0.000
1.501 to 2.500	+0.010 -0.000

d. Straightness

Tubing shall not deviate from straightness by more than 0.025 inches per foot, and more than 0.125 in any 5 foot length.

5. QUALIFICATION

a. All requests for qualification shall be directed to the Material Department of The Boeing Company which will request certified test data and specimens.

b. Certified test data shall be submitted by the supplier desiring product approval indicating compliance with the requirements of this specification for the tubing outside diameter and nominal wall thickness for which qualification is desired.

c. After review of supplier and Boeing test data, the supplier will be advised whether product approval has been granted. Products which have been qualified will be listed in the Boeing Qualified Products List.

d. No significant changes in raw material or methods of manufacturing which are not in conformance with this specification shall be made without notification and prior written approval by the division of The Boeing Company granting the original approval. Requalification of a revised material and/or process will be required.

6. QUALITY CONTROL

6.1 SUPPLIER QUALITY CONTROL

a. Unless otherwise stated on the purchase order, the supplier shall furnish three copies of a test report containing actual test results showing conformance to the requirements of Sections 4.2, 4.3, 4.4, 4.5, 4.6, 4.7 and 4.8.

b. The test report shall also include the Purchase Order number, this Material Specification number, heat number, lot number, size and quantity of tubes from each lot, and a statement that all requirements of this specification have been met.

c. An internal quality control system which outlines procedures followed to assure compliance with this specification is required. The system must include, but is not limited to the following: (1) a plan for periodic equipment calibration and certification with record control; (2) an in-process control plan and record system for processes subsequent to the final tube reduction stage; and, (3) an end item inspection and testing plan and record system. Records indicating compliance with this system will be made available for review by a qualified representative of The Boeing Company.

6.2 PURCHASER QUALITY CONTROL

a. Purchaser Quality Control Department shall insure conformance to the requirements of this specification.

b. Purchaser Quality Control Department shall review supplier test reports and conduct additional tests as deemed necessary to assure that tubes meet the requirements of this specification.

c. Complete records shall be maintained by Purchaser Quality Control Department and will be made available to The Boeing Company upon request.

7. MATERIALS TEST METHODS

7.1 MICROSTRUCTURE

One specimen from each of three tubes for each lot shall be examined metallographically in full circumferential cross-section at a magnification of 50X or above to ascertain presence of an equiaxed microstructure.

7.2 SURFACE CONDITION

a. Each tube shall be visually inspected for compliance with surface condition requirements per Section 4.1.c.

b. Same as Section 7.1 above except use a magnification of 50X or above to check for evidence of brittle layer (alpha case). The same micro used in 7.1 may be used to perform this check.

c. The finish of the inside and outside surfaces of each tube shall conform to Section 4.7.b as defined by ASA B46-1.

7.3 MEASURING OVALITY

The percent ovality shall be determined by measuring the minimum and maximum O.D. around 360° in one plane across the tube; it is calculated by using the following relationship:

$$\frac{\text{O.D. max.} - \text{O.D. min.}}{\text{O.D. Average}} \times 100 = \% \text{ Ovality}$$

7.4 MEASURING O.D. DIMENSIONS

The outside diameter (O.D.) of every tube shall be measured every two feet or fraction thereof using a calibrated micrometer or equivalent for compliance with Section 4.8.b and averaging the high and low points throughout 360 degrees at each location.

7.5 ULTRASONIC INSPECTION

Tubing shall be 100% ultrasonic inspected for inside and outside diameter defects per the requirements of BAC 5439-2 Class A-3 or B-3 to meet the requirements of Section 4.7.c.

7.6 CHEMICAL ANALYSIS

Each heat shall be sampled for the requirements of Section 4.2 in accordance with Federal Test Method 151, Method 111.1 (Chemical Analysis) and Method 112.1 (Spectrochemical Analysis). The tubing supplier may use the raw material certification except for oxygen, hydrogen and nitrogen analysis which must be determined after final processing.

7.7 FLARE TESTS

One specimen from each of three tubes from each lot shall be flared per ASTM B338 to meet the minimum requirements of Section 4.4. On these tests, the end of the tube to be flared shall be cut square, with the cut end smooth and free from burrs but the corners not rounded. The tube shall be forced axially at a steady pressure over a hardened and polished steel pin having a 60° included angle until the tube at the mouth of the flare has expanded the required amount. Lubrication shall be used. Surfaces of flares shall be examined at magnifications of 3 to 5 diameters for freedom from cracks and other defects.

7.8 TENSION TESTS

One specimen from each of three tubes for each lot shall be tension tested in accordance with Method 211.1 of Federal Test Method 151. The strain rate shall be 0.003 - 0.007 in/in/min through 0.2% offset plastic strain and then increased to 0.075 - 0.125 in/in/min to failure. If a dispute occurs between the purchaser and supplier over the yield strength values, a referee test shall be performed on a machine having a strain rate pacer, using a rate of 0.005 in/in/min through the yield strength. All tension tests shall meet the requirements of Section 4.3.

7.9 PRESSURE TESTS

Hydrostatic pressure tests will be conducted on three specimens from each lot to meet the requirements of Section 4.5. Specimens for testing shall be at least 12 inches long and shall be hydrostatic pressure tested to a pressure tested by the following formula:

$$P = Fty \frac{D^2 - d^2}{D^2 + d^2}$$

where P = hydrostatic test pressure in psi

d = maximum permissible inside diameter (D less twice the minimum permissible wall thickness in inches)

D = maximum permissible outside diameter (Nominal O.D. plus tolerance in inches)

Fty = minimum yield strength per Table II

Each specimen shall be pressurized for at least 2 minutes while maintaining the calculated pressure.

8. REJECTION AND RETEST

Failure of a specimen to meet the test requirements shall be cause for rejection of the lot.

At the discretion of the supplier, retest will be permitted. A retest sample of five specimens shall be tested to replace each failed specimen of the original sample.

If one of the retest specimens fails, the lot shall be rejected with no further retesting permitted.

9. MATERIAL IDENTIFICATION

9.1 TUBING

Tubing shall be marked with the following information which shall be grouped and shall be repeated at intervals not to exceed two (2) feet.

a. Specification number and letter

b. Nominal tube diameter and wall thickness

c. Heat number and lot number

d. Vendor's name or trademark

9.2 MARKING MATERIAL

The marking fluid shall not be soluble in water or oil, but shall be removable in a hot alkaline cleaning solution without rubbing. The marking shall be sufficiently stable to withstand normal handling and shall have no deleterious effect on the tubing or its performance. Esterbrook (Cad.) Flo-master Ink or an equivalent halogen-free marking ink is recommended.

10. PACKAGING AND MARKING

a. The article container shall be legibly marked with the following:

(1) Vendor's name

(2) Contents

(3) Number of articles

(4) Purchase Order Number

(5) Specification number and letter

(6) Heat number and lot number

b. Packaging shall be suitable for storage and shall be adequate to assure safe delivery.

c. Each tube shall be individually packaged in such a manner that it will not make contact with any other tube. A polyethylene sleeve is recommended.

1. SCOPE

a. This specification covers Ti3Al-2.5V seamless tubing in the cold worked and stress relieved condition. The tubing is intended for use in hydraulic systems at a maximum temperature of 550°F.

b. This specification requires qualified products.

2. REFERENCES

Except where a specific issue is indicated, the issue of the following references in effect on the date of invitation for bid shall form a part of this specification to the extent indicated herein.

PRELIMINARY SPECIFICATION

a. AMS 2249 - Chemical Check Analysis Limits, Titanium and Titanium Alloys

b. ASA B46-1 - Surface Texture (Surface Roughness, Waviness and Lay)

c. ASTM E-8 - Tension Testing of Metallic Materials

d. ASTM E-120 - Methods of Chemical Analysis for Titanium and Titanium Alloys

e. ASTM E-146 - Chemical Analysis of Zirconium and Zirconium Base Alloys

f. BAC 5439-2 - Ultrasonic Inspection of Tubing

3. CONDITION

All tubing shall be cold reduced and stress relieved at a minimum temperature of 600°F for not less than 30 minutes.

4. TYPES

a. Type I

After final reduction the tubing shall be chemically milled to remove a minimum of 0.002 inches from the O.D. surface. No abrasive treatment shall be applied.

Code Ident. No. 81205

BY [signature] 10/6/70	TITANIUM 3Al-2.5V SEAMLESS TUBING FOR HYDRAULIC SYSTEMS, COLD WORKED AND STRESS RELIEVED	X BMS 7-234
CHECKED [signature] 10/6/70		
ENGINEERING [signature]		
QUAL. CONTROL [signature]	BOEING MATERIAL SPECIFICATION	PAGE 1 of 10
MATERIEL [signature]		

ORIGINAL ISSUE 10-7-70 (CAG)

4. (Cont'd)

b. Type II

After final reduction the tubing shall be cork belt polished. Sanding is not allowed. Tubing shall be final chemically milled to remove a minimum of 0.002 inches from the O.D. surface.

c. Type III

After final reduction the tubing shall be finish sanded with 400 or finer grit. Sanding with grit coarser than 240 is not allowed as a preliminary step. Tubing shall be final chemically milled to remove a minimum of 0.002 inches from the O.D. surface.

5. MATERIAL REQUIREMENTS

5.1 GENERAL

a. Tubing shall be of uniform quality and condition and shall be free from cracks, seams, laps, laminations, tears, pits, and other defects which do not conform to the limits given in Section 5.9.

b. Material used to manufacture tubing shall be produced by multiple melting consumable electrode practice. At least one stage shall be melted in vacuum. One stage may be melted in inert gas under slight pressure.

c. Preparation procedures and inspection criteria for tube hollows shall be reviewed and approved by The Boeing Company.

d. The metallurgical condition of each tube shall be fine grained equiaxed microstructure with no evidence of Widmanstatten structure as determined by the method in Section 8.1.b.

5.2 CHEMICAL COMPOSITION

Chemical composition shall conform to the requirements of Table I when analyzed per Section 8.3. Hydrogen, oxygen, and nitrogen shall be certified for each lot [1]. Check analysis shall be per AMS 2249.

[1] A lot is defined as tubing of the same diameter and wall thickness made from one heat of material, processed in a similar manner and stress relieved together.

5.2 (Cont'd)

TABLE I - CHEMICAL COMPOSITION

ELEMENT	WEIGHT PERCENT
Aluminum	2.5 - 3.5
Vanadium	2.0 - 3.0
Iron	0.30 (Max.)
Carbon	0.05 (Max.)
Hydrogen	0.015 (Max.)
Oxygen	0.12 (Max.)
Nitrogen	0.02 (Max.)
Other Elements, Total	0.40 (Max.) ▷2◁
Titanium	Remainder

▷2◁ Need not be reported. Any individual element shall not exceed 0.10%.

5.3 MECHANICAL PROPERTIES

The room temperature tensile properties of tubing shall be determined on one specimen per 1000 feet of tubing in each lot with a minimum of three specimens per lot. Testing shall be done using full cross-section of the tubing to conform to the requirements of Table II when tested in accordance with Section 8.4.

TABLE II - MINIMUM TENSILE PROPERTIES

ULTIMATE TENSILE STRENGTH (KSI)	YIELD STRENGTH AT 0.2% OFFSET (KSI)	ELONGATION IN 2 INCHES (%)
125	105	10

5.4 FLARE TEST

One specimen for each ten (10) tubes in each lot with a minimum of five (5) specimens taken from different tubes shall be tested per Section 8.5. The tubing shall be capable of being flared to a minimum of 1.2 times the original diameter without cracking or tearing of the material.

5.5 HYDROSTATIC PRESSURE RESISTANCE

Three (3) specimens from each lot shall be tested per Section 8.6. The tubes shall exhibit no leaking, cracking, or permanent set exceeding 0.002 inch per inch of diameter.

5.6 FLATTENING TEST

One specimen for each ten (10) tubes in each lot with a minimum of five (5) specimens taken from different tubes shall be tested per Section 8.7. The tubing shall show no evidence of cracking or tearing when examined at 5X magnification.

5.7 BENDING TEST

One specimen per 1000 feet of tubing in each lot with a minimum of three (3) specimens per lot shall be tested per Section 8.8. The tubing shall show no evidence of cracking, open sanding striations or tearing when examined at 5X magnification.

5.8 RESIDUAL STRESS

Three specimens from each lot of tubing shall be tested per Section 8.9. The tubing shall not have more than 15 KSI residual hoop stress.

5.9 SURFACE CONDITION

a. One specimen from each of ten (10) tubes from each lot shall be tested per Section 8.1.b. If there are fewer than 10 tubes in the lot, each tube shall be examined. Outside and inside surfaces of tubing shall be free from a brittle layer (alpha-case).

b. Surface roughness of tubing shall not exceed 63 RHR on the inside surface or 32 RHR on the outside surface. Grinding of the surface is not acceptable. Sanding, buffing or polishing with a soft backing is acceptable as permitted by Section 4. A minimum of 0.002 inch shall be removed by chemical milling from the O.D. surface after sanding, polishing, and buffing.

c. Depth of defects shall be in conformance with a Class A-2 standard per BAC 5439-2 for wall thicknesses 0.046 and under and Class B-3 standard for wall thicknesses greater than 0.046.

5.10 TOLERANCES

5.10.1 Wall Thickness Tolerances

Wall thickness tolerances shall not exceed ±7.5% or ±0.002 whichever is greater

5.10.2 Outside Diameter Tolerance

Outside diameter tolerances for tubing shall be as specified in Table IV. These tolerances include ovality.

TABLE IV

O.D. TOLERANCES

Nominal Outside Diameter (Inches)	Diametral Tolerances (Inches)
up to .093	+ .002, - .000
.094 to .187	+ .003, - .000
.188 to .499	+ .004, - .000
.500 to .999	+ .005, - .000
1.000 to 1.499	+ .007, - .000
1.500 to 2.000	+ .010, - .000

5.10.3 Straightness Tolerances

Tubing shall not deviate from straightness by more than 0.025 inch per foot length nor more than 0.125 inch in any 5 foot length.

6. QUALIFICATION

a. All requests for qualification shall be directed to a Materiel Department of The Boeing Company, which will request data and samples when desired for qualification purposes.

b. After review of supplier data or Boeing tests, the supplier will be advised as to whether product approval has been granted. Qualified products will be listed in the BMS Qualified Products List.

c. No changes in raw material or methods of manufacture shall be made without notification and prior written approval. Requalification of the revised material may be required and a revised supplier designation may be requested. Qualified products will be listed in the BMS Qualified Products List.

7. QUALITY CONTROL

7.1 SUPPLIER QUALITY CONTROL

a. Unless otherwise stated on the purchase order, the supplier shall furnish three (3) copies of a test report containing actual test data showing conformance to the requirements of Sections 5.2 and 5.3 of this specification.

b. The test report shall also include the purchase order number, Boeing Material Specification number (including revision letter), heat number, lot number, size and quantity of tubes from each lot and a statement that all requirements of this specification have been met.

c. The supplier shall maintain processing records for not less than five (5) years for all material including starting stock certification, number and amount of each tube reduction, Quality Control inspection and any other information which may influence the quality of the end product.

Non-proprietary processing information shall be made available to The Boeing Company on request.

7.2 PURCHASER QUALITY CONTROL

a. Purchaser Quality Control shall insure conformance to the requirements of Sections 5.9.c and 5.10.

b. Purchaser Quality Control Department shall review supplier test reports and may conduct additional tests as deemed necessary to assure that tubes meet the requirements of this specification.

c. Complete records shall be maintained by Purchaser Quality Control Department and will be made available to The Boeing Company on request.

8. TEST METHODS

8.1 SURFACE CONDITION

a. Each tube shall be visually inspected for compliance with surface condition requirements per Section 5.1.a.

b. Specimens shall be examined in full cross section metallographically at a magnification of 500-750X for microstructure and evidence of a brittle layer (alpha case). The specimens shall be etched in an aqueous solution containing 1 volume percent hydrofluoric acid.

c. The finish of the inside and outside surfaces of each tube shall conform to the requirements of Section 5.9.b as defined by ASA E46-1.

8.2 ULTRASONIC INSPECTION

a. Finished tubing shall be 100% ultrasonic inspected for inside and outside deflects per the requirements of BAC 5439-2 to meet the requirements of Section 5.9.c. Inspection shall be performed with the tube run in one direction and then run in the opposite direction if only two transducers are used, one each for longitudinal and transverse defects. If four transducers are used and the transducers are positioned from opposite directions, then the tubes need be run in only one direction.

b. Standard notches shall be class A-2 per BAC 5439-2 for wall thicknessess less than 0.046 and Class B-3 for wall thicknesses 0.046 inch and greater.

8.3 CHEMICAL ANALYSIS

a. Each heat shall be analyzed for conformance to the requirement of Section 5.2. The tubing supplier may use raw material certification except for oxygen, hydrogen, and nitrogen analysis which must be determined after final processing of the tube.

b. Chemical composition for all elements except hydrogen shall be determined using ASTM E-120. Analysis for hydrogen shall be performed using the hot extraction method described in ASTM E-146. Limits for check analysis shall be according to AMS 2249. Any other analysis having equivalent or better accuracy and precision than the above methods may be used provided they are approved by The Boeing Company, Quality Control Department. Analysis for oxygen content shall be performed by a technique having an accuracy of 50 ppm.

8.4 TENSION TESTS

The specimens shall be tension tested in accordance with ASTM E-8. The strain rate shall be .003 - .007 inch/inch/minute through 0.2% offset plastic strain, and then increased to .075 - .125 inch/inch/minute to failure. If a dispute occurs between the purchaser and supplier over the yield strength values, a referee test shall be performed on a machine having a strain rate pacer, using a strain rate of .005 inch/inch/minute through the yield strength. All tension tests shall meet the requirements of Section 5.3.

8.5 FLARE TEST

The specimens shall be flared per ASTM B338 to meet the minimum flaring requirements specified in Section 5.4.

8.6 PRESSURE TESTS

a. Hydrostatic pressure tests shall meet the requirements specified in Section 5.5. Specimens for testing shall be at least 10 inches long and shall be hydrostatic pressure tested to a pressure determined by the formula:

$$P = f_{ty} \frac{D^2 - d^2}{D^2 + d^2}$$

in which P = hydrostatic test pressure (p.s.i)

d = maximum permissible inside diameter (D less twice the minimum permissible wall thickness, in inches)

D = maximum permissible outside diameter (Nominal O.D. plus diametrical tolerance, in inches)

f_{ty} = minimum yield strength per Table II.

b. Each specimen shall be subjected to two (2) pressure applications with the calculated pressure to be maintained for at least two (2) minutes during each cycle.

8.7 FLATTENING TESTS

Flattening tests will be conducted to meet the requirements of Section 5.6. Specimens with length equal to twice the diameter shall be flattened at room temperature between parallel plates until the distance between the plates does not exceed fourteen (14) times the nominal thickness.

8.8 BENDING TESTS

Bending tests will be conducted to meet the requirements of Section 5.7.

The specimens shall be bent through 180 degrees at room temperature about a suitable bending block having a tube centerline radius three times the outside diameter of the tube. An appropriate mandrel or tube filler shall be provided to restrict flattening to a value that does not exceed 5% of the nominal outside diameter.

8.9 RESIDUAL STRESS

Residual stress measurements shall meet the requirements specified in Section 5.8. Specimens for testing shall be at least 3 times the tube diameter in length.

8.9 (Cont'd)

The specimen diameter shall be measured before (D_o) and after (D_1) making a longitudinal saw cut normal to the measured diameter. The cut shall be made using a sharp hack saw blade. The residual stress shall then be determined using the following formula:

$$S_r = \frac{E}{1-\mu^2} \, t \left(\frac{1}{D_o} - \frac{1}{D_1} \right)$$

where: $E = 14.1 \times 10^6$ psi

$\mu = 0.31$

t = wall thickness

D_o = O.D. before splitting

D_1 = O.D. after splitting

9. REJECTION AND RETEST

a. Failure of a specimen to meet the test requirements shall be cause for rejection of the lot which it represents.

b. At the discretion of the inspector a retest may be permitted. One specimen from each of five (5) different tubes shall be tested to replace each failed specimen of the original sample.

c. If any of the retest specimens fails to meet the applicable test requirements, the entire lot which is represented shall be rejected with no further testing permitted.

10. MATERIAL IDENTIFICATION

10.1 MARKING MATERIAL

The marking fluid shall not be soluble in water or oil, but shall be removable in a suitable hot alkaline cleaning solution without rubbing. The marking shall be sufficiently stable to withstand normal handling, and shall have no deleterious effect on the tubing or its performance. Esterbrook (Cado) Flo-Master ink or an equivalent halogen-free marking ink is recommended.

10.2 TUBING

Tubing shall be marked with the following information, which shall be grouped and shall be repeated at intervals not to exceed two (2) feet.

a. Boeing Material Specification number, including the applicable revision letter.

AMS 1402 8-61

10.2 (Cont'd)

b. Nominal tube diameter and wall thickness (in inches)

c. Heat Number

d. Lot Number

e. Supplier's name, trademark, or other designation

11. PACKAGING AND MARKING

a. The article container shall be legibly marked with the following:

(1) Supplier's name

(2) Description of contents. (Dimensions in inches)

(3) Quantity of tubes

(4) Purchase order number

(5) Boeing Material Specification number, including the applicable revision letter.

(6) Heat Number

(7) Lot Number

b. Packaging shall be suitable for storage and shall be adequate to assure safe delivery.

c. Each tube shall be individually packaged in such a manner that it will not make contact with any other tube.

ORIGINAL ISSUE 10-7-70
REV. "A" 2-22-71

MATERIAL CLASSIFICATION	SUPPLIER PRODUCT DESIGNATION	SUPPLIER	QUALIFYING DIVISION	DATE	
	3/4 thru 1-1/2 inch diameter All Wall Thicknesses	Reactive Metals Inc. 1000 Warren Avenue Niles, Ohio 44446	Commercial Airplane Group	9-1-70	
	3/8 thru 5/8 inch diameter All Wall Thicknesses	Superior Tube Company 1938 Germantown Avenue Norristown, Pennsylvania 19404	Commercial Airplane Group	9-1-70	R
	3/8 thru 1 inch diameter All Wall Thicknesses	Bishop Tube Company Route 30 and Malin Road Frazer, Pa. 19355	Commercial Airplane Group	9-15-70	
	3/8 thru 1-1/4 inch diameter All Wall Thicknesses	Zirconium Technology Corporation P. O. Box 947 Albany, Oregon 97321	Commercial Airplane Group	2-2-71	R

BY L.P. Clark
ENG K. Clark 2/3/71

BOEING MATERIAL SPECIFICATION QUALIFIED PRODUCTS LIST

X BMS 7-234

VENDOR QUALIFICATION

Throughout the SST development program, it was usual practice to require titanium tube producers to pass certain qualification tests before they were permitted to bid on material to be procured. This qualified list of producers was known as a QPL (Qualified Producer List) and was specified for several reasons:

- The manufacture of Ti-6A1-4V annealed and Ti-3A1-2.5V cold worked and stress relieved tubing was a relatively new technology and was considered to require a particularly close tie between vendors and Boeing engineering. As Boeing engineering groups determined who was on the QPL list, this close tie was established.

- This procedure afforded Boeing engineering the opportunity to assess the technical capabilities and the production methods of potential sources.

- This assured that a "low bid" from a questionable source would not be accepted and possibly lead to production stoppages because of vendor non-performance.

- The quality control procedures to which incoming tubing was subjected were made somewhat simpler because all tubing was procured from suppliers that had a proven capability.

There were several drawbacks to the use of a QPL, however, and these should be noted.

- The procurement of material was somewhat more complicated because QPL lists were often in a state of flux and this meant that more coordination than normal was required.

- New specifications and revisions to old specifications were continuously being set forth which meant that vendors qualified to the obsolete specifications must demonstrate their compliance to the added requirements.

During the course of the SST development program, The Boeing Company has dealt primarily with six titanium tube making companies. They are as follows:

- Bishop Tube Company
  Route 30 and Malin Road
  Frazer, Pa. 19355

- Reactive Metals Inc.
  1000 Warren Avenue
  Niles, Ohio 44446

- Superior Tube Company
  1938 Germantown Avenue
  Norristown, Pennsylvania 19404

- Whittaker Corporation
  Nuclear Metals Division
  West Concord, Mass. 01781

- Wolverine Tube Division
  17200 Southfield Rd.
  Allen Park, Michigan 48101

- Zirconium Technology Corporation (Zirtech)
  P.O. Box 947
  Albany, Oregon 97321

Most of these companies possessed special capabilities in one or several of the tube products required for the SST, none having a clear superiority in all areas. Some were not on the Qualified Producer List (QPL) at the time of the SST contract termination but did display consistent and significant improvements in their titanium tube making capabilities during the time period of their involvment.

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