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AIRCRAFT QUALITY HIGH TEMPERATURE VACUUM CARBURIZING

November 1990

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FINAL REPORT

Contract DAAG46-82-C-0034

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Prepared for

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In addition, a vacuum carburization procedure was investigated for the Vasco X2M alloy. Although a procedure for Vasco X2M was developed, it was not optimized. The data generated for this alloy is presented.

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SUMMARY

Development of a high temperature vacuum carburizing procedure for AISI 9310 gear steel was accomplished during this program. Use of this procedure significantly reduced processing time of gears, which can lead to a reduction in acquisition costs. The procedure was utilized to process surface contact fatigue, single-tooth bending fatigue, scoring, spur, and spiral bevel test gears. The data obtained from the testing and evaluation of these components was equal to or greater than similar data from conventionally carburized material. No significant variation in the vacuum carburize test data was observed from two mill heats of material. Following evaluation of these test gears, a spiral bevel input pinion gear was produced, vacuum carburized, and then tested in an actual helicopter transmission. Metallurgical evaluation of the tested gear showed that it met the same performance standards required of a conventionally carburized gear.

In addition, a vacuum carburization procedure was investigated for the Vasco X2M alloy. Although a procedure for Vasco X2M was developed, it was not optimized. The data generated for this alloy is presented.

PREFACE

This final contract report covers the work performed under contract DAAG646-82-C-0034 from April, 1982 to February, 1990 by Boeing Helicopters. The program was administered under the technical direction of Dr. Paul Fopiano (1982-1988) and Dr. Martin Wells (1988-1990), U.S. Army Materials Technology Laboratory, Metals Research Branch, Watertown, MA 02172.

The work was performed by Boeing Helicopters Materials Engineering Department. Phase I of this program was conducted under the technical direction of Mr. Gayle B. Wadsworth, former Manager of the Materials Engineering Department. Phases II, III, and IV were conducted under the technical direction of Mr. Roy J. Cunningham, Chief Metallurgist, Metallic Materials Engineering Department, and Mr. Ray Drago, Staff Engineer, Dynamic Systems Technology Department.

The major subcontractors for the program were C.I. Hayes, Inc., Cranston, RI, and Summit Gear Corporation, Plymouth, MN.

ACKNOWLEDGEMENTS

Acknowledgement is made to Mr. Stan Casper of C.I. Hayes for his cooperation and assistance in developing the vacuum carburizing procedures, as well as heat treatment, of certain test specimens.

Acknowledgement is also made to Messrs. Maurice Taylor and Kenneth Anderson of Summit Gear Corporation for their cooperation and assistance in the timely and efficient machining and heat treatment of the test specimens.

Acknowledgement is also made to the following people who participated in gathering and disseminating the data contained in this report.

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Mr. E. Slate
Mr. J. Kachelries
Mr. M. Brody
Mr. B. Johnson
Mr. G. Turk
Ms. P. Conyers

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1. INTRODUCTION

Carburization is one of the most costly and time consuming operations required in the manufacture of critical helicopter transmission components. The process provides a gear with a hardened tooth surface (after the teeth are cut) by the diffusion of carbon into the steel. After proper hardening, surface hardnesses of Rockwell C (R/C) 59-64 are obtained. The hard, carburized surface imparts excellent wear resistance properties as well as increases the load carrying capability of the component. Depending on the steel utilized, a degree of scoring and scuffing resistance is also attained. However, conventional endothermic carburizing processes require not only long process times of up to 35 hours (dependent upon the desired effective case depth*), but significant amounts of energy input in the form of both electricity and natural gas. Special masking techniques and atmosphere controls are also necessary.

Vacuum carburizing, which is a relatively new (1970's), advanced carburizing process, has been recognized as an energy and cost effective alternative to conventional endothermic carburization. It has permitted the use of higher carburization temperatures, which can reduce carburization cycle times from as great as two weeks to less than one day. Energy input can be reduced in proportion. Furthermore, gaseous atmospheres are not needed for subsequent hardening operations.

Despite these advantages the aerospace industry, in general, has not been sufficiently convinced that vacuum carburization could be applied to critical aircraft components. However, development of a high temperature technique in recent years has altered this thinking. Primarily through the efforts of the C.I. Hayes Company in Cranston, RI, a viable process has been developed which has been applied to commercial components. However, qualification of the process for aerospace applications by testing specimens and helicopter transmission gears had not yet been accomplished until this program was completed.

*Effective case depth is defined as the perpendicular distance from the surface to a depth below the gear tooth surface at which R/C 50 occurs.

Boeing Helicopters took a special interest in this program because of its use of advanced, state-of-the-art carburization and heat treating practices for processing high hot hardness alloys in its advanced helicopter transmissions. Boeing Helicopters has utilized the experience gained from such heat treating practices to implement the use of the advanced high hot hardness Vasco X2M material in the CH-47 D & E model helicopter transmissions. Boeing developed the heat treat procedures for carburizing X2M as well as numerous other high hot hardness alloy steels. In addition, they have been involved in the development of vacuum heat treating since its conception in the early 1970's, and have been highly interested in the advantages of this type of processing over the much slower endothermic process. In-house research and development (IRAD) programs showed the feasibility of vacuum carburizing both the 9310 and Vasco X2M alloys. Data obtained under these IRAD programs on several test slugs from various vacuum carburizing runs showed that uniform carburization may be obtained, and cycle times and energy usage could be decreased.

To make effective use of vacuum carburizing in processing aerospace gear materials, the process had to be qualified by evaluating various vacuum carburized gears, as was done in this program. Successful development of the vacuum carburizing procedure can reduce gear processing time, energy consumption, and the cost of Army helicopter transmissions.

Successful completion of this program led to the following:

(a) Generation of a high temperature vacuum carburizing procedure for AISI 9310 and Vasco X2M gear steels

(b) Data to qualify the process for aerospace components made from AISI 9310

(c) An implementation plan for deploying the vacuum carburization process into the production of helicopter transmission components.

2. OBJECTIVE

The objective of this program was to develop a high temperature vacuum carburizing technique for two gear materials which are presently being used in helicopter transmissions. Development, qualification, and incorporation of these procedures into production processing will result in significant cost savings through the use of higher carburization and heat treat temperatures that will shorten production process cycles. Accomplishing carburization and heat treatment under vacuum conditions will eliminate the need for pre-heating the part prior to heat treatment (necessary for high hot hardness gear steels) and will yield an energy savings due to lower usage of atmospheric gases.

3. SUMMARY OF TECHNICAL APPROACH

The program developed for the qualification of high temperature vacuum carburizing is graphically presented in Figure 1. This program was initially designed to be conducted in three phases. In Phase I, two heats of the AISI 9310 and VASCO X2M steel alloys were obtained, the vacuum carburization procedures were developed utilizing two vendors, and gear element testing was conducted. In Phase II, spur and bevel gears were produced and vacuum carburized using the procedures optimized in Phase I. The surface durability of these gears was then evaluated. In Phase III, a vacuum carburized input spiral bevel transmission gear was tested in a Boeing Helicopters CH-47C combining transmission, and a plan to implement the optimized vacuum carburization procedure into production was developed. However, during the course of the program, a fourth Phase was added in which further development of the vacuum carburization procedure for the X2M alloy was conducted. The original Phase I evaluations were not extensive enough to allow the vacuum carburization procedure for the X2M alloy to be fully developed and optimized. Unfortunately, the scope of the entire program did not allow for the complete optimization of the vacuum carburization procedure for X2M in Phase IV, nor for the subsequent component and full scale gear testing (Phases II and III) that was to be conducted in parallel with that done on the vacuum carburized 9310 material.

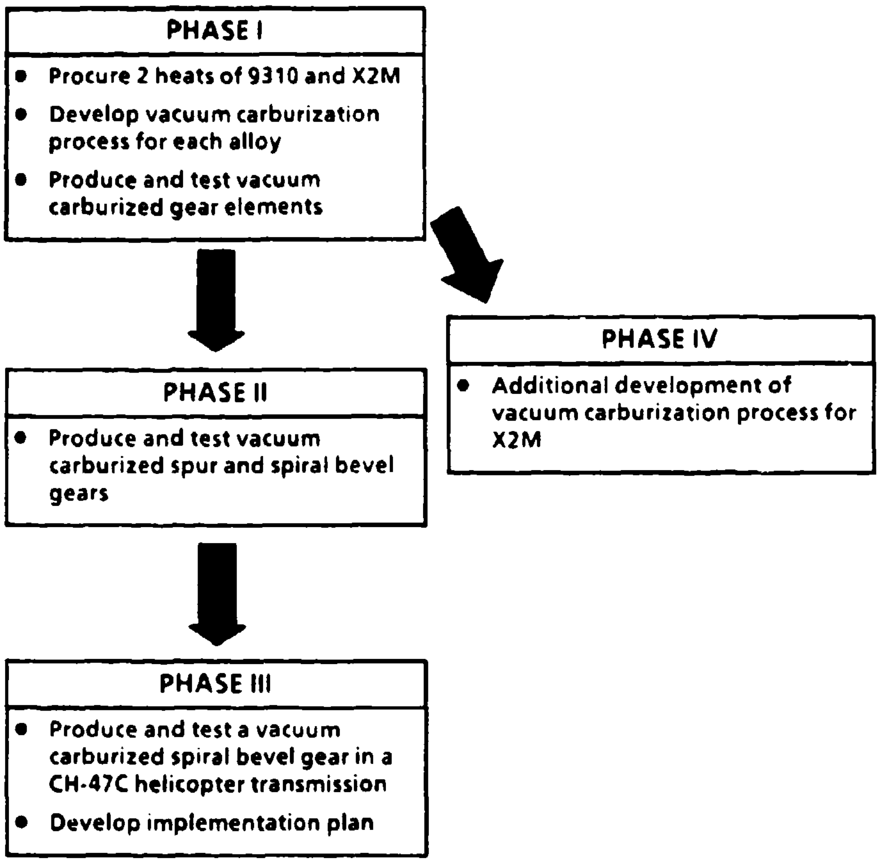


Figure 1. Overview of aircraft quality high temperature vacuum carburizing program.

4. EXPERIMENTAL PROCEDURES

4.1 VENDOR SELECTION

The prime vacuum carburizing vendor was the C.I. Hayes Company in Cranston, RI. C.I. Hayes has been in the forefront of vacuum heat treating technology due to its development of high quality vacuum carburizing furnaces. They are the recognized leader in the vacuum furnace industry and have been working on various high temperature vacuum carburizing procedures for many different materials. They developed a vacuum carburizing process for 9310 steel as well as the curves for the entire case thickness range. In addition, they have worked extensively with Boeing Helicopters in furthering the development of a vacuum carburizing procedure for the Vasco X2M material.

Summit Gear Company in Plymouth, MN was selected to machine all of the test gears for this program and perform various carburization heat treatments. They are a qualified source for manufacturing and heat treating aerospace gears. In addition, they have the latest C.I. Hayes Vacuum Seal Quench (VSQ) carburizing furnace available to industry, and are familiar with the 9310 and Vasco X2M alloys.

These two prime vendors, as well as the other vendors utilized in this program, are listed below with a brief description of the services provided by each:

VENDOR	SERVICES PROVIDED
C.I. Hayes, Inc. 800 Wellington Avenue Cranston, RI 02910	Development of Vacuum Carburize Cycles for Vasco X2M & 9310; Heat Treatment of Certain Test Specimens
Summit Gear Corp. 3131 Vicksburg Lane Plymouth, MN 55447	Machining of all Test Specimens and Heat Treatment of Certain Test Specimens
Teledyne Vasco P.O. Box 151 Latrobe, PA 15650	Raw Material - Vasco X2M
Carpenter Steel Company Reading, PA 19612	Raw Material - Vasco X2M and 9310

Stulen Machine Company 4693 Peoples Road Pittsburgh, PA 15237	Rough Machining of Billets
Litton Precision Gear Co. 4545 Western Avenue Chicago, IL 60609	Stabilization Heat Treatment of All Specimen Blanks

4.2 MATERIAL SELECTION

The materials evaluated in this program were AISI 9310 and Vasco X2M gear steels, both of which were double vacuum melted utilizing Vacuum Induction Melting-Vacuum Arc Remelting (VIM-VAR) processing. AISI 9310 gear steel was selected because it is one of the most common steel alloys that has been used for transmissions over the past many years. Vasco X2M was selected because it is an advanced high hot hardness alloy with exceptional properties for use in higher performance/temperature transmissions. The 9310 and X2M alloys were produced according to Boeing Helicopters specifications BMS 7-249, Type III, and BMS 7-223, Type III, respectively.

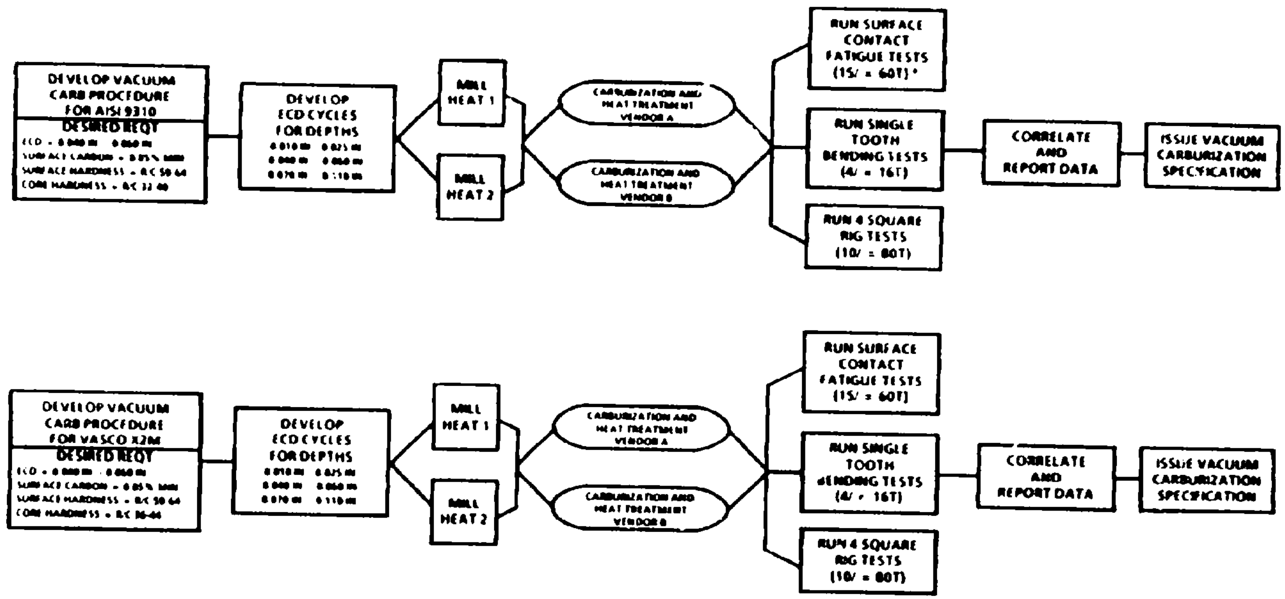
X2M is presently being carburized using Boeing Helicopters patented heat treat procedure (Reference 1) and is the only high hot hardness gear steel in use today which has been fully tested and qualified for use in helicopter transmissions. Presently, X2M is being used for all critical main drive system components in the CH-47D and E Model helicopters. The CH-47D and E programs involve the modification of more than 350 aircraft. It is noteworthy that vacuum carburizing the Vasco X2M material would eliminate the need for the proprietary preoxidation process (Reference 1) which must be accomplished to uniformly endothermically carburize the steel.

4.2.1 Material and Processing - Phases I and IV

A detailed schematic showing the test requirements for Phase I is shown in Figure 2.

The nominal chemistries of the two alloys used in the program, i.e., 9310 and X2M, are shown in Table 1. The mill certifications for these alloys are shown in Appendixes A through D.

HIGH TEMPERATURE VACUUM CARBURIZING – PHASE I



* Fifteen tests per mill heat and heat treat vendor for a total of 60 tests

Figure 2. Vacuum carburize program test requirements for Phase I.

TABLE 1. NOMINAL CHEMICAL COMPOSITIONS OF VASCO X2M AND AISI 9310 GEAR STEELS (WEIGHT PERCENT)

Material Composition (%)

Element	Vasco X2m	9310
Carbon	0.15	0.10
Silicon	0.90	0.27
Manganese	0.30	0.55
Sulphur	0.010 Max	0.010 Max
Phosphorus	0.015 Max	0.010 Max
Tungsten	1.35	--
Chromium	5.00	1.20
Vanadium	0.45	--
Molybdenum	1.40	0.19
Nickel	--	3.25

A detailed flow diagram showing the materials and procedures used to process test specimens for Phase I is shown in Figure 3. A schematic showing the sectioning pattern for the raw material with the grain direction noted for various specimens is illustrated in Figure 4. Table 2 details the mill heats, start and finish sizes of material, as well as the work ratio, i.e., the amount of work reduction of the ingot to billet used for all the Phase I material.

The raw material was shipped from Teledyne Vasco Co. or Carpenter Steel Co. to Stulen Machine Company, where it was machined into surface contact fatigue, single tooth bending fatigue, and rotating fatigue test specimen blanks.

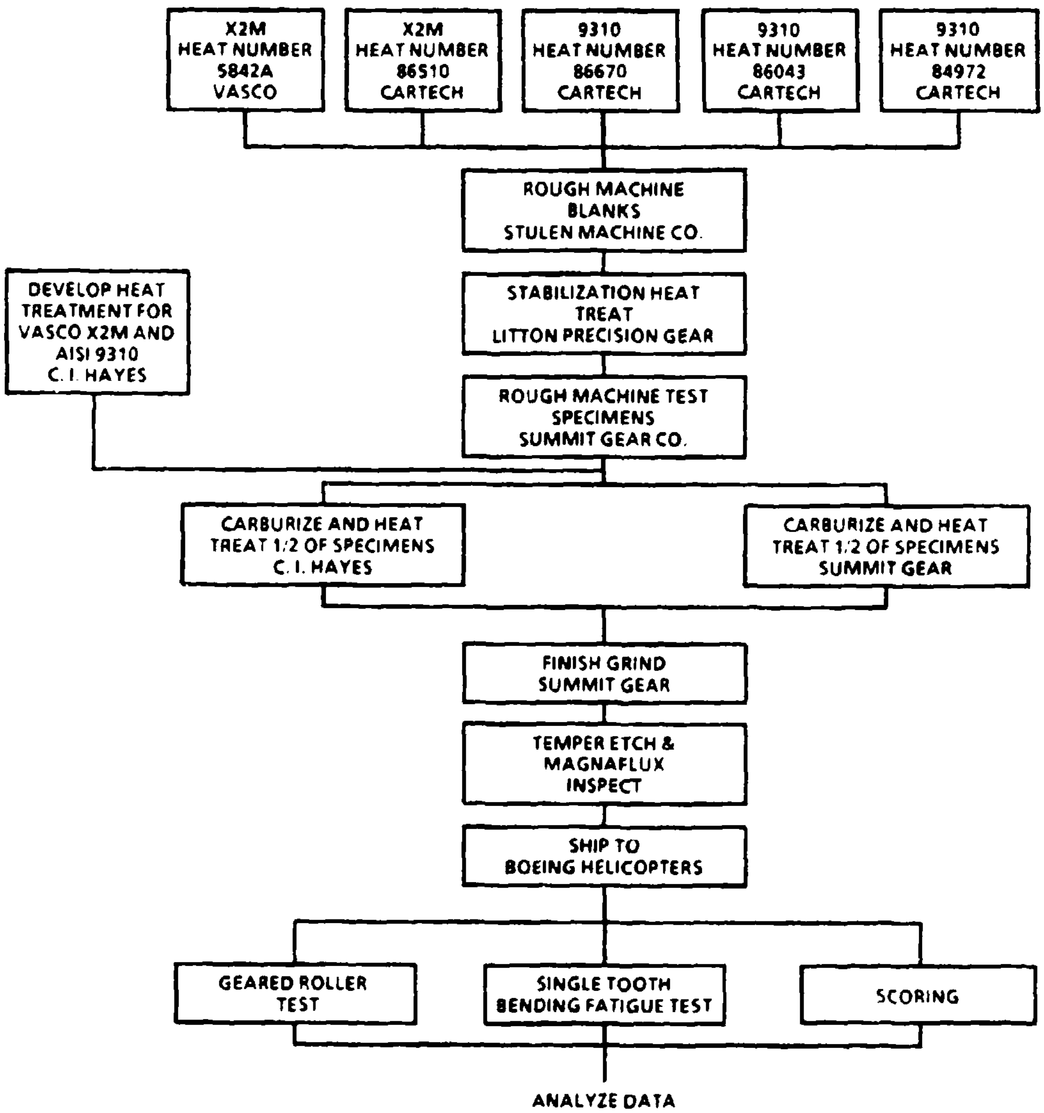


Figure 3 Process flow diagram for Phase I.

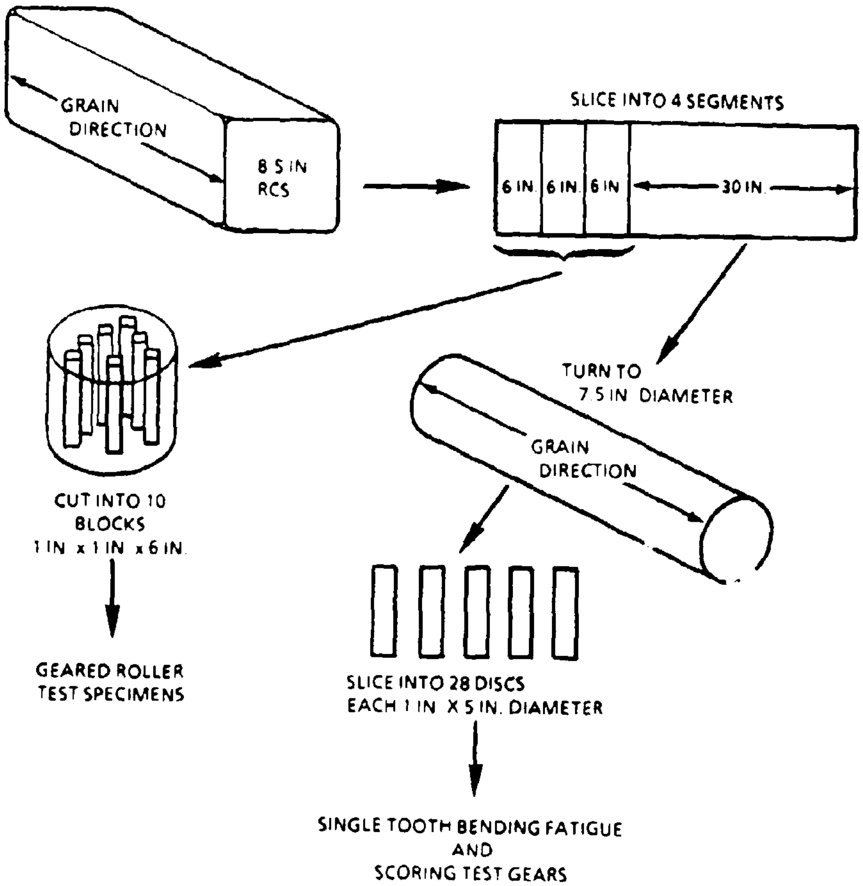


Figure 4. Sectioning pattern for raw material.

TABLE 2. DETAILS OF MATERIALS USED IN PHASE I

MATERIAL	MILL HEAT	START SIZE	FINISH SIZE	WORK RATIO	USED TO MAKE*	MATERIAL LABELED	DASH NO.
Vasco X2M	5842A (Teledyne Vasco)	20 in. Round	8.25 in. Round	5.8:1	30 GR 8 STBF 20 RF	A A A	-1
Vasco X2M	86510 (Carpenter Steel)	20 in. Round	8.5 in.	4.4:1 RCS	30 GR 8 STBF 20 RF	B B B	-2
9310	86670 (Carpenter Steel)	20 in. Round	8.4 in.	4.5:1 RCS	30 GR 8 STBF* 20 RF*	C C C	-3
9310	86043 (Carpenter Steel)	20 in. Round	8.5 in. Round	5.5:1	45 GR 8 STBF** 20 RF**	D D D	-4
9310	87885-2 (Carpenter Steel)	20 in. Round	8.5 in.	5.5:1	8 STBF 20 RF	F F	-10 -10

*GR: Gear Roller Test Specimen; STBF: Single Tooth Bending Fatigue Specimen;
RF: Rolling Contact Fatigue Life Specimen.

**Not tested due to poor microstructure which developed at 1,900°F vacuum carburization temperature.

Mill certifications for all the material are shown in Appendixes A through D. All specimen blanks were shipped to Litton Precision Gear Company where each was stabilization heat treated as shown in Table 3.

TABLE 3. STABILIZATION HEAT TREATMENTS

Vasco X2M	9310
1,700°F - 2 Hours	1,700°F - 2 Hours
1,850°F - 1 1/4 Hours	1,525°F - 2 1/4 Hours
Oil Quench	Oil Quench
Draw 1,200°F - 3 Hours	Draw 1,000°F - 4 Hours

The primary purpose of this treatment is to produce a martensite structure in the material prior to machining to enhance machinability and to decrease distortion which could occur during subsequent carburizing and hardening.

After stabilization heat treatment, all specimen blanks were shipped to Summit Gear Company. Summit machined and ground all specimens to the SK drawing dimensions shown in Appendices E-H, and carburized and heat treated half of them. C.I. Hayes carburized and heat treated the remainder of the specimens. Several comments are given concerning the specimen machining.

a) The geared roller test rolls all had 0.010-inch of grind stock per side, while the test gears had 0.005-inch of grind stock per tooth surface.
b) All carburized surfaces, including the complete tooth profile, were ground to finish dimensions.
c) All components were temper etch inspected per Boeing Helicopters BAC 5436 requirements after final grinding.
d) After temper etching, all parts were tempered for four hours minimum at a temperature 50°F below the tempering temperature of the material.
e) All parts were magnetic particle inspected per Boeing Helicopters BAC 5424 requirements prior to testing.

f) Manufacturing plans were submitted to Boeing Helicopters by Summit Gear for all test components. Each plan was reviewed and approved as required.

The rough machining of test specimens from the blank pancake forgings was accomplished by hobbing all of the gear teeth. Teeth were then removed from the single tooth bending fatigue specimens as required.

Following vacuum carburizing and heat treatment, the gears were ground to final dimensions by Summit Gear, and then temper etch and magnetic particle inspected. The finished gears were then geometrically inspected and shipped to Boeing for testing.

Distortion due to heat treating was not excessive and consequently had little effect on the final grinding process. Temper etch inspection did not reveal any grinding burns on the gear teeth, indicating they were acceptable for use.

It is noteworthy that all of the processing of each component manufactured during Phase I of this program was accomplished in the same manner/procedure utilized for the production of CH-47D helicopter components. This was done such that all data obtained could be readily compared with previously obtained data and be applicable for future production transmission component processing.

4.2.2 Material and Processing - Phase II

In this Phase, spiral bevel and spur gears were produced and tested at Boeing Helicopters to evaluate the surface durability characteristics of the vacuum carburized gear tooth surfaces.

All of the gears in this phase were manufactured from the same billet material as those of Phase I. Test gear blanks were removed from the billets by Stulen Machine Co., after which they were processed as follows:

1. Forge material into individual blanks
2. Rough machine gear blank and stress relieve

3. Final machine gear blank (bore, faces, outside diameter)
4. Machine gear teeth
5. Vacuum carburize gear teeth, Summit Gear Corp
6. Heat treat (harden and draw), Litton Precision Gear
7. Finish grind bore and end faces, and grind gear teeth, Litton Precision Gear and Summit Gear Corp.
8. Bake
9. Perform final inspection (temper etch and geometric).

Litton final ground the spiral bevel gears, and Summit final ground the spur gears. The procedures used to test these gears is found in Experimental Procedures, Section 4. The results of testing are found in Results and Discussion, Section 5.

4.2.3 Material and Processing - Phase III

In this phase, two spiral bevel input gears, Part Number 114D5245-10, serial numbers M5373 and M5372, were produced from AISI 9310 steel. Gear S/N M5373 was tested at Boeing Helicopters in a CH-47C Combining Transmission. Gear serial number 5372 was held for possible future testing and evaluation. The two gears were selected from a group of standard production spiral bevel gears at Litton Precision Gear which were being readied for production by the conventional carburization method.

The two gears were rough machined at Litton with all of the others in the group, after which they were sent to Summit Gear for vacuum carburizing. The other gears in the group remained at Litton where they were conventionally carburized. The two vacuum carburized gears were then sent back to Litton where they rejoined the group of standard production gears from which they were selected. All of the gears were then hardened and ground to final dimensions. The grinding stock remaining on the vacuum carburized gears was the same as that specified for all of the other gears which were produced by conventional carburizing. Machining, hardening, grinding, inspecting, etc., these two gears in sequence with the group of gears from which they were selected ensured that the only variables in their manufacture was the carburization process.

The vacuum carburization and hardening processes used to produce these two gears are listed below. The hardening procedure is that which is used to harden all AISI 9310 parts which are found on Boeing's Helicopters (document D210-12023-1). The vacuum carburization records can be found in Appendix I.

Carburization - Vacuum Process

1. Copper plate all areas not to be carburized
2. Load furnace at room temperature
3. Carburize at 1,800°F for 65 minutes using propane-methane gas at 250 Torr to obtain an ECD of 0.035-0.055 inch
4. Diffuse at 1,800°F in a vacuum for 115 minutes
5. Quench using nitrogen gas
6. Subcritical anneal at 1,275°F for 150 minutes
7. Strip copper plate

Hardening

8. Nickel strike and copper plate at 0.003 inch all over
9. Heat to 1,150°F ±25°F for 3 hours
10. Heat to 1,400°F-1,500°F for 1 hour
11. Heat to 1,850 ± 25°F for 15-30 minutes
12. Quench in oil at 75-140°F
13. Cool to -100 to -120°F for at least 3 hours
14. Temper at 600°F for 2 hours
15. Air cool to room temperature
16. Temper at 600°F for 2 hours
17. Air cool to room temperature
18. Final grinding and other routine conventional processing

It should be noted that gear serial number M5372 was placed on a Rejection Report for Boeing Helicopters Materials Review Board (MRB) action due to case leakage. The leakage covered an area approximately 1.0 inch in diameter, and was located on the 2.40-inch diameter of the gear. The case leakage was the result of the copper plate which was too thin to prevent secondary carburization during hardening. Although case leakage is undesirable, it was determined that the extent and location of the leakage was not detrimental to the function of the gear, and it was released for final processing. However, to ensure that any minor or inconsequential effects of case leakage would not affect test results, the other gear, serial number M5373, was used for Phase III transmission test.

The vacuum carburized spiral bevel gear serial number M5373 was tested under Phase III of this program, and the test procedures and results are discussed in the Results and Discussion Paragraph 5.3.

4.3 DESCRIPTION OF PHASE I TEST PROCEDURES

4.3.1 Geared Roller Test

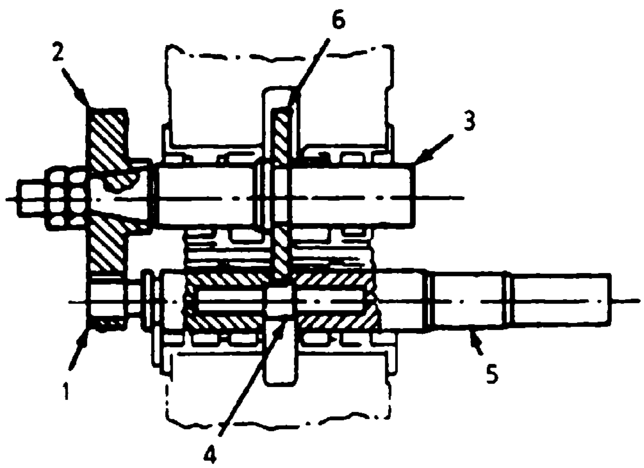
A geared roller test simulates the combined rolling and sliding conditions experienced by gears, cams, rolling element bearings, and similar machine components. It provides a means of testing materials, lubricants, and/or their interaction. The degree of sliding, the load, the lubricant temperature, and the rotating velocity are all controllable.

The heart of the geared roller test machine is a set of disks or rollers consisting of a 1-inch diameter test roll and a 5-inch diameter slave roll which are mounted on two parallel shafts and geared together in a 3.5:1 ratio. This combination of rollers and gears results in both rolling and sliding contact fatigue. The arrangement of shaft and gear is shown in Figure 5. The load is applied through a lever arrangement which is actuated by a pneumatic roto chamber.

Pressurized air from an external source controls the load to within ±3 percent. The actual load is determined by a calibrated strain gage while a pressure gage is used to check the stability of the load during periods of extended operation. The load is converted to a Hertzian stress by the relationships found in Reference 2.

The following parameters were employed during all testing:

a) Load - 450,000 psi Hertz compressive stress
b) Lubricant - MIL-L-23699 oil



ITEM	PART NAME	PART NUMBER*
1	LOWER SHAFT – GEAR END	201-C-086
2	UPPER SHAFT GEAR	201-C-114
3	UPPER SHAFT	201-C-144
4	TEST SPECIMEN (1-INCH DIAMETER)	201-B-047
5	LOWER SHAFT	201-C-058
6	SLAVE ROLL (5-INCH DIAMETER)	201-B-229

*ALL PART NUMBERS ARE THOSE LISTED IN THE TEST MACHINE BROCHURE FROM THE MANUFACTURER
GEARS 1 AND 2 WHICH HAVE 16 AND 56 TEETH, RESPECTIVELY, PROVIDE A 3.50:1 RATIO

Figure 5. Geared roller test setup

c) Rotating velocity - 900-1000 rpm

d) Test oil temperature - 200 ± 10°F.

To insure proper "break-in" of the lubricating system, a dummy specimen was run for a least 148 hours prior to the start of the first test. To renew the MIL-L-23699 oil during the test, one-half of a gallon of oil was changed for each 250 hours of total test time. A runout of any one specimen was considered to be the accumulation of 10×10^6 cycles without failure. None of the runout specimens were retested. Testing was accomplished by randomizing both the specimen tested and the test machine utilized. A total of three machines were employed for testing, serial numbers 3A437, 3A438, and 3A439.

Testing proceeded on a 24-hour basis. A failure was detected by a sensitivity switch which monitored the level of vibration of the test machine. When a spalling and/or pitting failure occurred, the vibration in the machine increased which resulted in machine shutdown. A time counter (hours) was connected to this sensitivity switch and became disconnected at machine shutdown.

The data recorded for the geared roller tests consisted of:

- part number
- serial number
- applied load
- test duration

A summary of these tests is discussed in paragraph 1.3.

4.3.2 Single Tooth Bending Fatigue Test

Before any new development can be incorporated into a helicopter gear box, it must be thoroughly evaluated from two viewpoints. Obviously, the first consideration is determining whether or not the specific advantage claimed is actually achieved. The second, and no less important, consideration is a determination of the side effects of the proposed new development. In the case of vacuum carburizing, one of these potential effects is the structural integrity of the gear teeth. Since the strength of gear teeth, in general, is a subject of great concern in the design of helicopter gear boxes, considerable testing of the strength of various gear designs and materials has been accomplished at Boeing Helicopters. Standardized test setups and methods have been developed and are routinely used for evaluating the strength of gear teeth. This standardized evaluation technique was applied to full sized test gears of two different materials (9310 and Vasco X2M) with tooth proportions typical of a final drive planetary system. Each gear was carburized by the vacuum process. The purpose of this testing was neither to confirm nor identify some advantage of the process. Rather, the goal was to insure that the cost, time, and consistency improvements obtained through the vacuum carburization process were not obtained at the expense of part strength.

With this background in mind, it is clear that a satisfactory test result is simply the identification of no statistical difference in the strength of identical parts carburized by either conventional or vacuum processes. Any gain which may be obtained in strength is purely a beneficial side effect.

4.3.2.1 Single Tooth Bending Fatigue Specimen Design - The design of the test gears (see Appendix G) utilized in this program is within the experience range of helicopter main transmission power gears in pitch diameters, diametral pitch, pressure angle, and profile modifications. All tolerances and records for the manufactured test specimens conformed to the appropriate Boeing Helicopters production specifications. Each dash number grouping of test gears (for instance SK29572-1 and SK29572-2 are two different dash number groups of the same basic part number) was heat treated in a single batch to minimize variations within batches.

The test gears were manufactured with a total of 32 teeth. However, for testing purposes, every other set of four teeth was removed to permit placement of the test specimen within the test fixture arrangement, thus allowing four gear teeth on each gear to be subjected to fatigue testing. The gear teeth selected for testing were spaced in such a manner as to eliminate any possible effects of previously incurred fatigue failures on adjacent test teeth. The processes used to manufacture these gears are discussed in Paragraph 4.2.1.

4.3.2.2 Test Apparatus - The gear specimens were tested on a nonrotating single tooth bending fatigue test fixture (Figure 6) designed by Boeing Helicopters for use on a Baldwin-Lima Hamilton IV-20 Universal Fatigue Machine. The test machine is capable of developing total loads up to 16,000 pounds (8,000 pounds steady and 8,000 pounds alternating load) at a frequency of 1,200 cycles per minute.

The test fixture was specifically designed to conduct nonrotating bending fatigue testing, and permits application of a cyclic load to one gear tooth at a time. Present analytical methods established by the American Gear Manufacturers Association (AGMA) rate the maximum bending strength of a gear at the critical section when loaded at the Highest Point of Single Tooth Contact (HPSTC).

The design of the fixture is such that the test gear tooth is loaded at the highest point of single tooth contact (HPSTC), which is based on a one-to-one gear ratio. The location of the load anvil at the HPSTC is maintained during setup for each gear tooth by maintaining a constant static height (with a load of approximately 100 pounds) on the load anvil, thus assuring loading through the load angle at the HPSTC due to the geometry of the test fixture.

Load on the test gear tooth was transferred from the test machine to the gear tooth through a load link. All load links were instrumented with strain gages and connected to an oscilloscope to permit monitoring of the gear tooth load during testing.

4.3.2.3 Testing Technique - The test specimen was mounted in the gear fatigue fixture in the manner shown in Figure 6. The height of the load anvil was adjusted to the required position, as determined by gear and fixture geometry, and the reaction anvil was then moved into position on the reaction tooth. Load anvil height was rechecked with a compressive load of approximately 100 pounds. The specimen was then ready for test load application if the load anvil height was found to be within the correct tolerance.

The steady load was maintained approximately 100 pounds above the alternating load during all test runs so that impact loading of the test tooth was

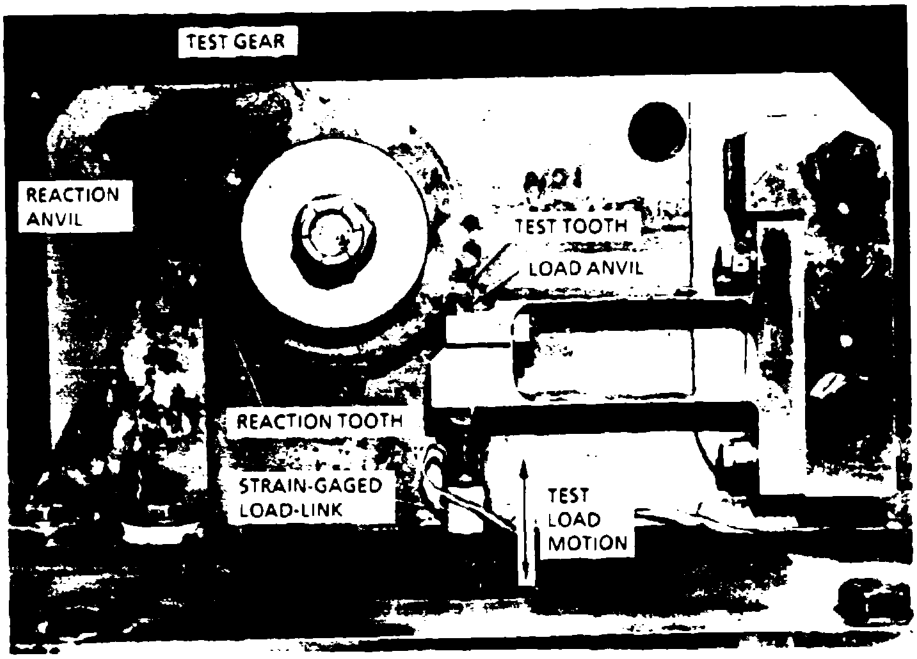


Figure 6. Single-tooth bending fatigue test fixture.

avoided. The load was unidirectional in all cases as would be typical of a simple gear mesh. The 100 pounds preload maintained on the gear teeth during testing represents less than 2 percent of the total load on the gears and was therefore considered a zero load.

Since the test gear teeth were loaded at a rate of approximately 1,200 cycles per minute, no localized heat buildup was noticeable in the fillet area of the test gear tooth due to the constant cycling of stress. Heating of the fillet did not occur throughout the entire loading range, no matter how long or how little a particular gear tooth was cycled before failure. The constant temperature maintained by the test gear specimens during testing precluded the effect of gear tooth root fillet temperature increase on the test results.

A small amount of moly grease was applied to the load and reaction anvils at the tooth contact points but no other lubrication was provided.

To insure accurate data, one tooth in each group of test gears was instrumented with a strain gage located at the critical section in the tooth fillet region. A calibration curve was then developed so that tooth bending stress could be measured directly.

Each specimen was run continuously until failure or runout (6×10^6 cycles), whichever occurred first. Failure is defined as a crack length of approximately 0.25-inch. Testing was terminated either manually by the test technician upon observance of a crack or occurrence of a runout, or automatically (during unattended running) by limit switches. The 0.25 inch crack length was chosen as a failure criteria to be consistent with the previously acquired data with which the current data was compared.

4.3.2.4 Gear Stress Calculations - The gear stresses presented in this report were calculated by a computer program based on AGMA standards for rating the strength of spur gear teeth. Calculation of the geometry factor for the test gear was based on an assumed gear ratio of one-to-one.

Based on the AGMA standards, the equation for calculating the bending stress at the critical section of a gear tooth when loaded at the highest point of single tooth contact is:

$$S_t = (W_t P_d)/(FJ) \tag{1}$$

where: S_t = Calculated tensile stress at critical section, PSI

W_t = Transmitted tangential load, pounds

P_d = Diametrical pitch

F = Face width, inches

J = Geometry factor

AGMA methods include factors to account for dynamic loading, misalignment, etc. In these analyses, all of these factors were taken as unit. By utilizing the engineering drawing (Appendix G) data for the test gears, equation 1 can be reduced to a function of tangential tooth load as follows:

$$S_T = 27.14\, W_t \tag{2}$$

The above stress calculations are provided for reference only, since actual tooth bending stresses were measured during the test program using strain gages. Additional information concerning the statistical method for analyzing this data is shown in Appendix J.

4.3.2.5 Test Data - The data recorded for the single tooth bending fatigue tests consisted of:

- Part Number
- Serial Number

- Test Tooth Number
- Applied Load, Steady and Alternating
- Cycles to Failure (or Runout)
- Crack Length
- Failure Mode

A summary of the single tooth bending fatigue data is discussed in Paragraph 5.1.4.

4.3.3 Scoring Test

As was the case with the single tooth bending fatigue strength, the scoring capacity of vacuum carburized gears must also be evaluated to insure that the process did not, somehow, produce an unknown side effect which reduces the ability of the gears to resist failure by scoring.

Scoring is a very significant problem in the design of helicopter gear systems. Under conditions of high speed and heavy load, the thin oil film which normally separates the mating gear tooth surfaces is sometimes destroyed. When this happens, the asperities of the tooth surfaces come into contact and generate enough heat to allow them to instantaneously weld together on a microscopic scale. Continued rotation of the gear causes these micro welds to be pulled apart and the resulting sliding motion along the tooth flanks produces the scratches which typify a scoring failure. Scoring is not a fatigue phenomena. If it is to occur at all, it will occur in a very short time (usually 10 or 20 minutes) of operation. If it does not occur within 10 or 20 minutes it will never occur as long as the operating conditions remain constant. Several theories have been proposed to explain this phenomena for aerospace gears which are operating with synthetic oils. The critical temperature theory, first proposed by Blok (Reference 3), shows the greatest correlation with actual test results. This theory states that the instantaneous temperature of the contact point at any time is a function of the material properties of the gears and the oil, as well as the combination of sliding and contact pressure which exists at that point on the tooth surface. When the instantaneous contact temperature due to these combined effects reaches a critical or "flash" temperature, the film of oil is destroyed and scoring occurs. The parameter used to evaluate the scoring behavior is thus known as the flash temperature.

The relative scoring behavior of various materials and lubricants is a key factor in the design of helicopter transmissions. Because this behavior is a key factor, considerable score testing has been accomplished at Boeing Helicopters, where standardized test machines and methods have been developed and are routinely used for such test programs.

This standardized evaluation technique was applied to full sized gears in this program which were carburized by the vacuum process. The tooth proportions were typical of a final drive planetary system. The purpose of this testing was neither to confirm nor identify some advantage due to the process. Rather, the goal was to insure that the cost, time, and consistency improvements obtained through the vacuum process were not obtained at the expense of the scoring capacity of the parts.

With this background in mind, it is clear that a satisfactory test result is simply the identification of no difference in the scoring behavior of identical parts carburized by either conventional or vacuum processes. Any gain which may be obtained in this area is purely a beneficial side effect.

4.3.3.1 Scoring Test Specimen Design - As with the single tooth bending fatigue test specimens, the design of the scoring test gears (Appendix H) utilized in this program is within the experience range of helicopter main transmission power gears in pitch diameter, diametrical pitch, pressure angle, and profile modifications. All tolerances and records for the manufactured test specimens conformed to the appropriate Boeing Helicopters production specifications. Each dash number grouping of test gears (for instance, SK29571-1 and SK29571-2 are two different dash number groups of the same basic part number) was heat treated in a single batch to minimize variations within batches.

These test gears were designed to simulate a typical first stage planetary system sun-planet mesh for the final drive of a medium to large helicopter. By way of comparison, they are quite representative of that set on either the

CH-46 or CH-47 helicopter. The processes used to manufacture these gears are defined in Paragraph 4.2.1.

4.3.3.2 Test Apparatus - The score testing was conducted in the Boeing Helicopters Gear Research Test Facility, Figure 7, which is located in the Transmission Assembly and Test Building. This facility is designed to test full sized, representative, test specimens. It will accommodate spur, helical, and spiral bevel gears. There are two identical test rigs in the facility, each of which may be easily configured for a wide variety of test programs. The standard scoring test configuration (6 inch center distance, 1/2 inch face width, overhung mounted gears with isolated oil supply) was used for this program, Figure 8. This setup incorporates provisions for controlling center distance, speed, oil temperature, torque, and oil flow. The system is a regenerative (four-square) design using one gearbox as the slave unit and one gearbox as the test unit. Gear mountings were designed to be rigid and stable under all loading conditions, with through-bored housings for maximum accuracy.

To facilitate short-term operation for scoring tests, the test stand design provides for testing outboard of the main gear housing and allows for rapid assembly and removal of the test specimens and good accessibility for frequent visual inspection of the test gears, as Figure 9 shows. This test stand arrangement has a separate lubricating system for the test housing with heating and cooling capabilities and direct oil flow measurement. Lubrication is directed to the test gears by individual, externally cooled oil jets which can be directed on the in-mesh side, the out-of-mesh side, or both sides simultaneously. This configuration also permits control of the oil flow rate, oil inlet temperature and operating torque while maintaining a constant speed. Power is supplied by an electric motor driving the input shaft through a toothed belt arrangement.

All test parameters as well as the general test stand operation are monitored continuously from the test stand control center, which is located just outside of the test cell.

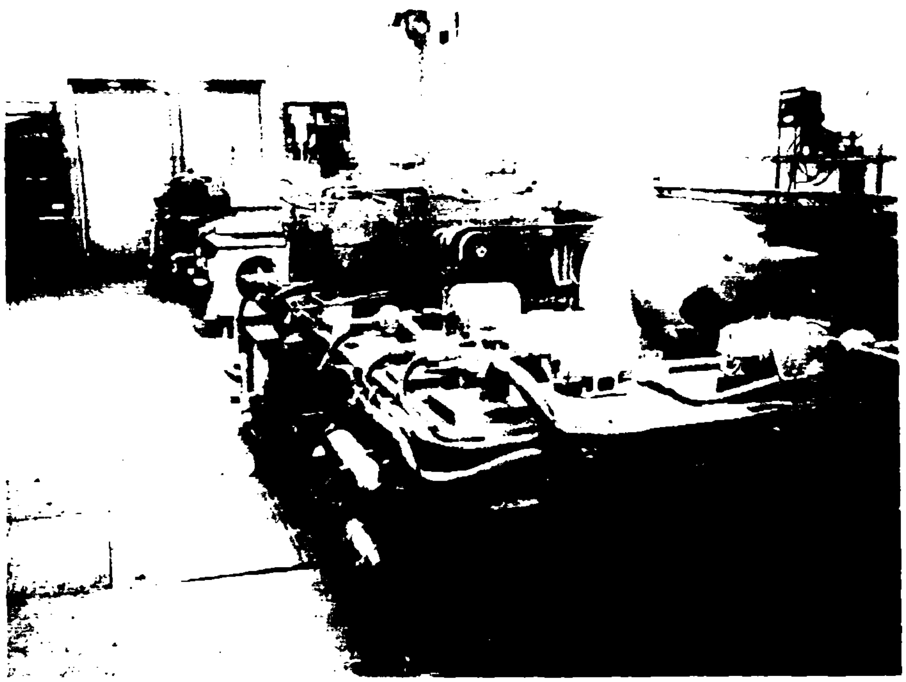


Figure 7. Gear research test facility.

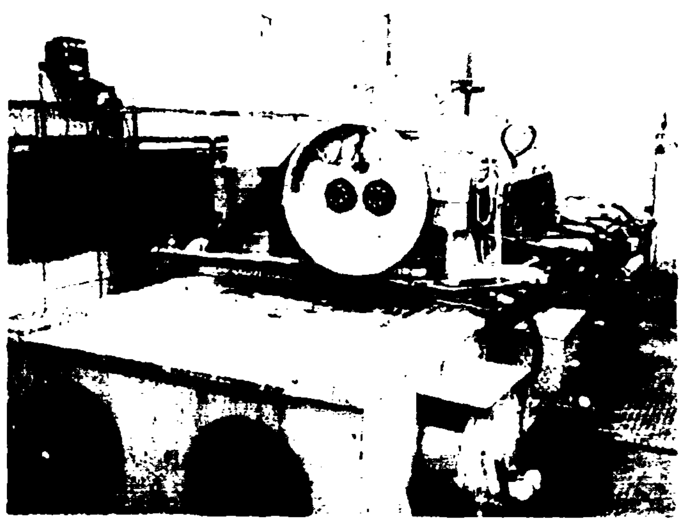


Figure 8. Scoring test setup.

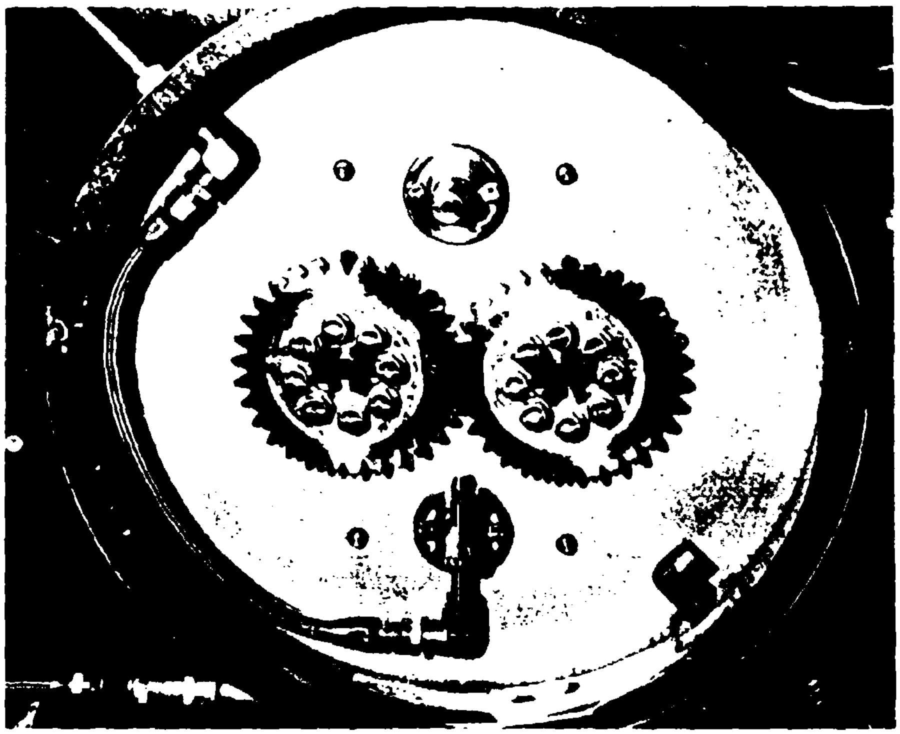


Figure 9. Research test stand overhung configuration.

Since scoring is sensitive to the oil temperature as well as oil type and gear material, a sophisticated temperature control system is incorporated in the test setup.

A single jet on the out-of-mesh side of the gear set is utilized in (Figure 9) to supply 0.32 GPM of oil at 40 psi to the test gears. The bearings supporting the test gears are sealed from this oil flow and are separately lubricated. By maintaining the test oil (MIL-L-23699) in a temperature controlled, heated tank (Figure 10), the temperature to the test gear jet is controlled to 200°F. Very fine control over temperature is maintained by an electronically controlled in-line heater located just before the test gear jet. The test oil and both of the slave box oils are cooled and filtered (Figure 11) after leaving the boxes. A 12 micron filter element was used.

4.3.3.3 Testing Technique

The primary scoring test variables were shaft torque and oil inlet temperature. Gear tooth load, a function of shaft torque, was applied through a lever system at the beginning of each test run. Torque levels were observed on a Strainsert SR2 instrument at the beginning and conclusion of each test run.

Deviation from the initial target torque was controlled within ±5 percent at test startup. The torquemeter was calibrated, through a load spectrum of 0 to 40,000 inch-pounds before and at the conclusion of the test program. Recalibration curves agreed with the initial curve within 2 percent. Test time (cycles) was determined by a log record of running time and an elapsed-time meter in the test stand console. Power was supplied by a 100 horsepower electrical motor driving the input shaft through a toothed belt arrangement, which maintained the input pinion speed at 3,660 revolutions per minute. Test runs were initiated only after stabilization had been achieved.

Although the theory that a gear set's load capacity may be improved by incremental loading techniques has been advanced from time to time, it should be noted that it only holds true for relatively soft gears and/or those with very rough initial surface finishes. Carburized and ground gears such as

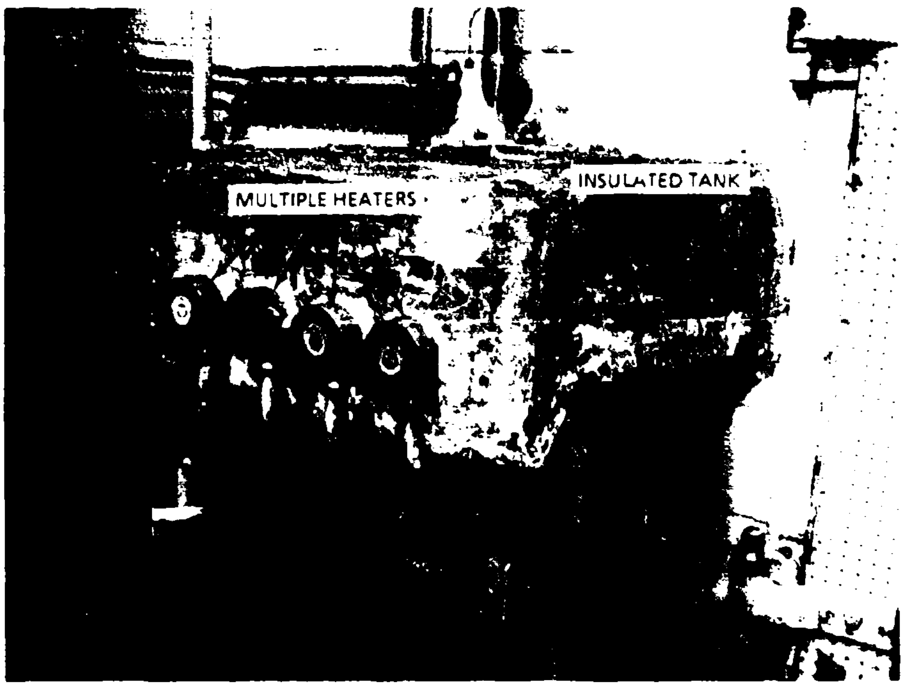


Figure 10. Insulated, temperature controlled test-oil supply tank.

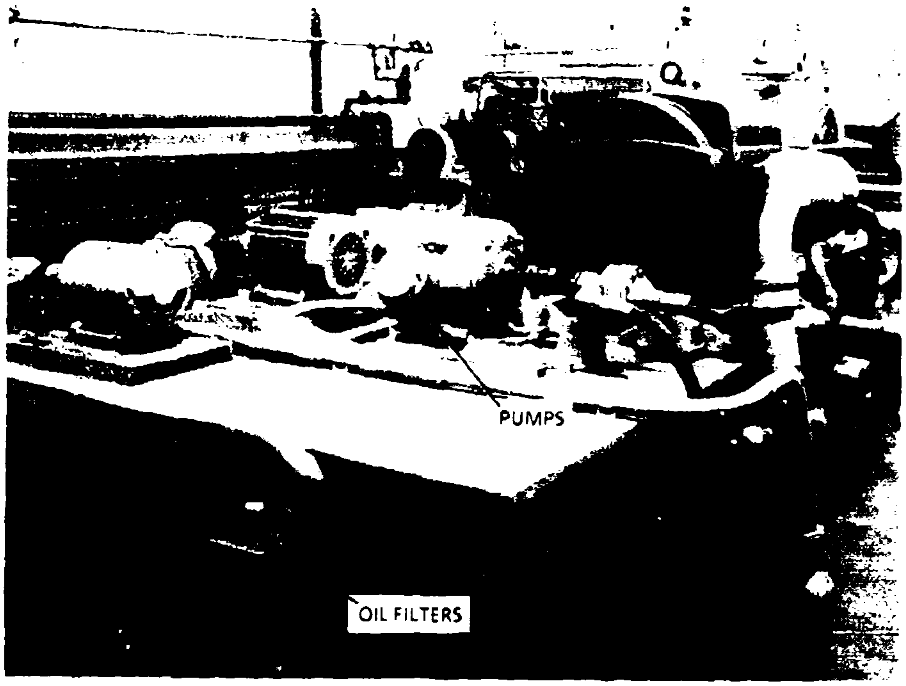


Figure 11. Cooling, lubrication, and filtering system.

these may also benefit from such incremental loading if a special high load capacity oil is utilized. None of these were the case for these gears, thus, run-in yields insignificant advantage. With this in mind, each test gear set was step loaded as shown in Figure 12 until a scoring failure was obtained. A scoring failure was obtained in every case. There were no runouts and no other types of failures occurred.

4.3.3.4 Gear Stress and Flash Temperature Calculations - The gear stresses and flash temperatures presented in this report were calculated by a computer program based on AGMA standards for rating the strength, durability, and scoring hazard of spur gear teeth. Equation 1 (Paragraph 4.3.2.5) is the basic bending stress equation. By utilizing the information shown on the engineering drawing (Appendix H), this basic equation can be reduced to a function of tangential tooth load or shaft torque for these score test gears, as follows:

$$S_t = 24.17 \ W_t = 8.06 \ T \qquad (3)$$

where: S_t = Calculated tensile stress at critical section, PSI

W_t = Transmitted tangential load, pounds

T = Shaft torque, in-lb

While AGMA methods include factors to account for dynamic loading, misalignment, etc., in our analysis, all of these factors have been taken as unity. The test system configuration and gear quality are such that these effects are negligible.

The basic contact stress equation is:

$$S_C = C_p \ (WT/FdI)^{0.5} \qquad (4)$$

where: S_C = Calculated contact stress, psi

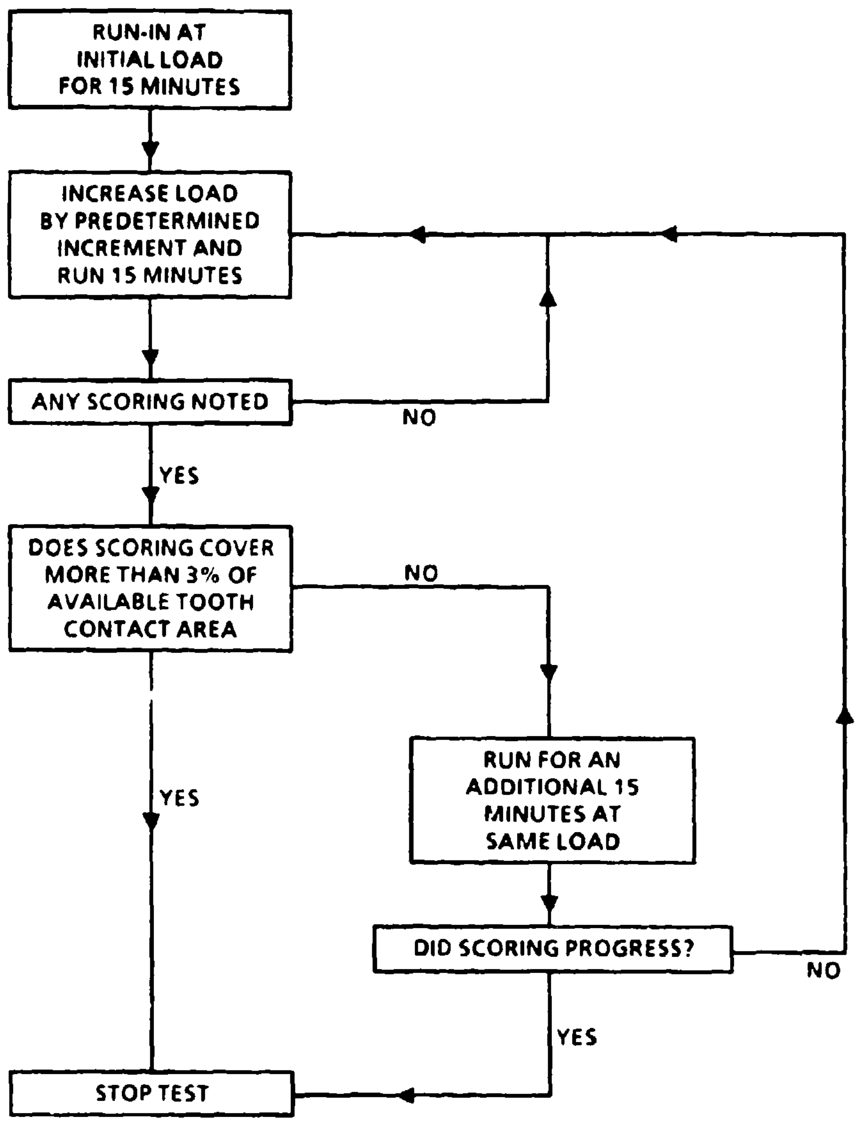


Figure 12 Scoring test procedure.

C_p = Material factor (2300 for steel spur gears)

W_T = Tangential load, lb

F = Net face width, inch

d = Pinion pitch diameter, inch

I = Geometry factor

As was the case for the bending stress equation, equation four can also be reduced to a function of tangential tooth load or shaft torque only, for these test gears.

$$S_c = 4628\, W_T^{\,0.5} = 2672\, T^{0.5} \qquad (5)$$

Finally, the parameter of greatest interest in this test, the flash temperature, is calculated by:

$$T_F = T_I + (W_T / F)^{0.75}(50/(50-S)(Z_t n_p^{\,0.5})/(P_d 0.25) \qquad (6)$$

where: T_f = Flash temperature scoring index (^oF)

T_i = Initial temperature (^oF), (oil jet temperature for these test gears is virtually the same as the gear blank initial temperature)

S = Surface finish (RMS)

Z_t = Scoring geometry factor

n_p = Pinion speed (RPM)

As with the single tooth bending fatigue calculations, by utilizing the specific geometry of these test gears, this equation can be reduced to a function of shaft torque or tangential tooth load.

$$T_F = 200 + 0.735 (W_T)^{0.75} = 200 + 0.322 (T) 0.75 \qquad (7)$$

The critical point for scoring occurs just below the lowest point of single tooth contact, thus the first signs of scoring should occur at the tips and/or flanks of the teeth.

4.3.3.5 Test Data - The data recorded for the score tests consisted of:

- Part Number
- Serial Number
- Applied Shaft Torque
- Loaded Side Designation
- Inlet Test Oil Temperature
- Gear Tooth Condition
- Run Time
- Oil Flow Rate
- Oil Pressure
- Slave Gearbox Data (Pressure, Temperature, etc).

A summary of the score test results is discussed in paragraph 5.1.5.

4.4 DESCRIPTION OF PHASE II TEST PROCEDURES

The design of the spur and spiral bevel test gears used in Phase II of this program was within the experience range of helicopter main transmission power gears in pitch diameter, diametrical pitch, pressure angle, and profile modification. Processing procedures, tolerance parameters, and recording requirements conformed to the appropriate Boeing Helicopters production specifications.

With these design criteria in mind, and to determine the surface load capacity of the heat treatment process under investigation, the test gears for this program were designed with the following specific parameters.

4.4.1 Spur Gears

The gear r ' io (Mg) of 1.67 to 1.00 was selected as the most practical for a 6.00-inch center distance while maintaining a reasonable volt circle for mounting purposes. The roll angle to the first point of contact on the pinion member was maintained below 7 degrees. The pinion member was designed with a short addendum (0.06-inch) and the gear member with a long addendum (0.22-inch). The resulting profile contact ratio was 1.13 minimum, which is below normal design practice. Pinion input speed was selected as 910 revolutions per minute.

Kinetic analysis of the design parameters, using an existing Boeing Helicopters computer program, indicated a very high specific sliding (slide/roll ratio) value at the first point of contact on the pinion member. The specific sliding value at this point was considerably higher than the value for any other point along the tooth profile, indicating a high probability of experiencing surface type failures in the pinion dedendum. The general design parameters are listed in Table 4. The actual dimensions of the spur gears are shown in Appendix K.

TABLE 4. TEST SPECIMEN GENERAL DESIGN PARAMETERS - SPUR GEARS

Member	Material (Steel)	Pitch Diameter (inches)	Diametrical Pitch	Gear Ratio	Pressure Angle (degrees)	Face Width (inches)
Gear	AISI 9310	7.500	5.333	1.67	20	0.500
Pinion	AISI 9310	4.500	5.333	1.67	20	0.500

The final design parameters selected for the gear test specimens were specifically chosen to increase the pitting probability; consequently, they are not representative of typical aircraft design practice.

4.4.2 Spiral Bevel Gears

The spiral bevel gear test rig, unlike the spur rig is designed to simulate the CH-47C engine transmission bevel gear set. The rig will accommodate two bevel gear configurations. The first is an actual production set of CH-47C gears. The second is a less expensive set of slightly smaller test gears which simulate but do not actually duplicate the CH-47 engine box gears.

Since these gears simulate an actual aircraft application, it was not possible to bias the design to produce only pitting failures.

The final design parameters for the spiral bevel gears are shown in Table 5. The actual dimensions are shown in Appendix L.

TABLE 5. TEST SPECIMEN GENERAL DESIGN PARAMETERS - SPIRAL BEVEL GEARS

Member	Material (Steel)	Diameter (inches)	Diametrical Pitch	Gear Ratio	Pressure Angle (degrees)	Spiral Angle (degrees)	Face width (inches)
Gear	AISI 9310	7.372	5.833	1.72	22.5	26	1.43
Pinion	AISI 9310	6.000	5.833	1.72	22.5	26	1.43

4.4.3 Spur and Sprial Bevel Gear Testing

4.4.3.1 Test Apparatus - The gear specimens were tested on a Boeing Helicopters regenerative (four square) load test stand. These test stands were specifically designed and constructed to conduct rotating load test programs for gear research and development. The spur test machine is capable of operation with three center distance options and provisions for control of torque, oil temperature, and quantity of oil. Lubrication of all gear meshes and bearings is provided by individual oil jets.

To facilitate short term operation and surface durability type testing, the design of this test stand includes the provision for testing outboard of the main gear housing, as shown in Figure 13. This feature provides for rapid assembly and disassembly of the test specimens, with improved accessibility for frequent visual inspection. This test stand configuration has a separate lubrication system with heating and cooling capabilities and direct oil flow measurement. Lubrication is directed to the test gears by individual externally cooled oil jets, which can be directed on the in-mesh side, out-of-mesh side, or both sides simultaneously. This configuration also permits control of oil flow rate, oil inlet temperature, and operating torque, while maintaining a constant speed.

The spiral bevel test rig is almost identical to the spur rig in design and operation. In fact, either stands may be used for testing spur helical or bevel gears, depending on which of the interchangeable test heads is mounted on the rig.

4.4.3.2 Testing Technique - The primary test variables were shaft torque and oil inlet temperature. Gear tooth load was a function of shaft torque, which was applied through a lever system at the beginning of each test run. Torque levels were observed on an SR2 Strainsert instrument at specified intervals, and recorded. A final torque reading was taken and recorded at the conclusion of each test run. Deviation from the initial target torque was controlled to plus or minus five percent at start-up and withi or minus two percent during the individual test runs.

The torquemeter was calibrated prior to and at the completion of the test program. Recalibration curves agreed within two percent with the initial calibration. Test time (cycles) was determined by a log record of running time and an elapsed time meter located in the test stand console. Power was supplied by an electric motor driving the input shaft through a toothed belt arrangement, maintaining the input pinion speed at 910 Revolutions Per Minute for the spur gears and at 3,660 revolutions per minute for the bevel gears.

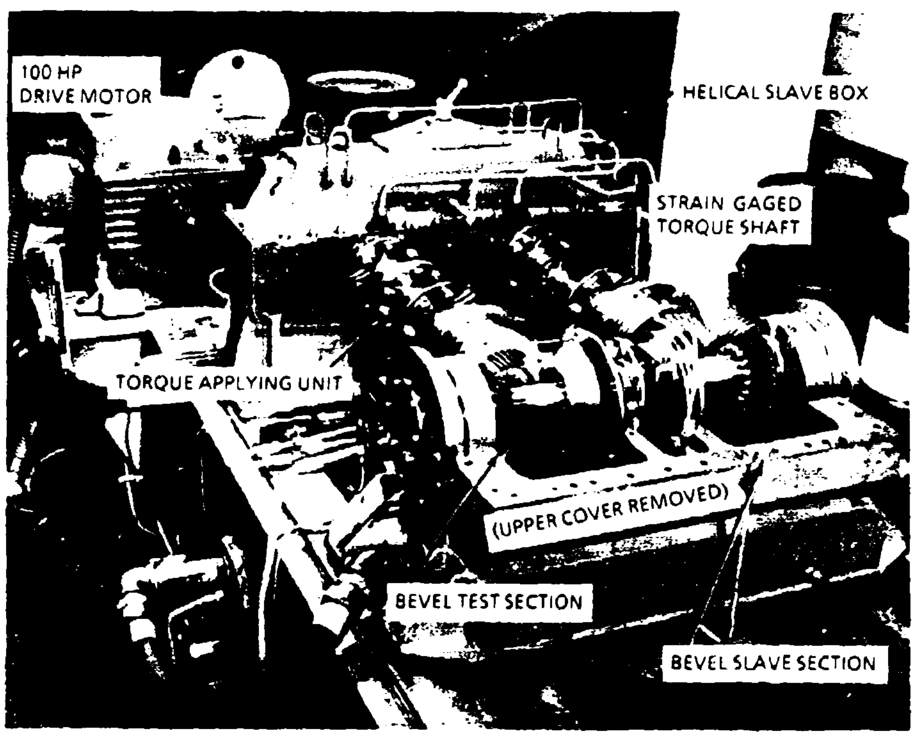


Figure 13. Test stand for surface durability testing.

Input oil temperature for the test gearbox was maintained at less than 135°F with input oil pressure of 55 ±5 per square inch. The oil used for lubricating the test gearbox was MIL-L-23699. Testing technique for this test program consisted of rotating load tests at each of the specified load levels for a maximum of three million cycles (or failure). Successful completion of a particular test run for three million cycles was considered as a test runout data point. This runout was then considered to be below the fatigue endurance limit. Prior to conducting the test runs, the lubricating oil was circulated until the oil-temperature stabilized. Jet lubrication was provided on the out-of-mesh side for the test gear mesh.

The test procedure for all test gears in this program was the same, and consisted of the following sequence:

1. Conduct static pattern checks at the 50 percent and 100 percent load levels for load distribution evaluation.

2. Complete the test load schedule by conducting rotating tests for a maximum of 3×10^6 cycles (or failure) at each of the specified load levels.

4.4.3.3 Gear Stress Calculations - The gear stress levels presented in this report were calculated by an existing Boeing Helicopters computer program which uses AGMA (American Gear Manufacturers Association) standards in the analysis.

AGMA rates the bending strength of spur gears as follows:

$$St = \frac{W_t \times K_o \times P_d \times K_s \times K_m}{K_v \times F \times J} \qquad (8)$$

Where

Wt = transmitted tangential load (pounds)
Ko = overload factor

Kv = dynamic factor

Pd = diametrical pitch

F = face width

Ks = size factor

Km = load distribution factor

J = geometry factor

For the spur test gears utilized in this program, the following was assumed:

$$Ko = Kv = Ks = Km = 1.0$$

For the bevel test gears, the following was assumed:

$$Ko = Kv = 1.0$$
$$Ks = 0.64$$
$$Km = 1.1$$

Then,

$$St = 32.5 \times Wt \text{ (spur pinion)} \tag{9}$$
$$St = 7.95 \times Wt \text{ (bevel pinion)} \tag{10}$$

AGMA rates the surface durability of spur gears as follows:

$$Sc = CP\left(\frac{W_t \times C_o \times C_s \times C_m \times C_f}{Cv \times d \times F \times I}\right)^{0.5} \tag{11}$$

where

Sc = calculated contact stress number at the lowest point of single tooth contact

Cp = elastic coefficient (2300 for spurs, 2800 for bevels)

Wt = transmitted tangential load at operating pitch diameter (pounds)

Co = overload factor

C_v = dynamic factor

d = pinion operating pitch diameter (inches)

F = face width (inches)

C_s = size factor

C_m = load distribution factor

I = geometry factor

C_f = surface condition factor

For the spur test gears used in this program, the following was assumed:

$$C_o = C_v = C_s = C_m = C_f = 1.0$$

For the bevel gears:

$$C_o = C_v = C_s = C_f = 1.0$$
$$C_m = 1.1$$

then,

$$S_c = 6520\ (W_t)^{0.5} \quad \text{(spur gears)} \tag{12}$$
$$S_c = 3644\ (W_t)^{0.5} \quad \text{(bevel gears)} \tag{13}$$

4.4.3.4 Test Data - The basic 100 percent spur gear test load level for this program was established as 3094 inch-pounds of pinion torque resulting in a pinion bending stress of 44,688 psi and a contact stress at the lowest point of single tooth contact of 241,768 psi.

The basic 100 percent bevel gear test load level for this program was established as 12,606 inch-pounds of pinion torque resulting in a pinion bending stress of 36,948 psi and a contact stress of 236,277 psi.

The criteria for definition of a failure for all of the test gears used in this experimental program were established as follows:

A. A minimum of one pit per tooth, on each of three nonadjacent teeth having a minimum dimension of 1/16 inch shall constitute a failure.

B. The appearance of a crack anywhere on the test parts. The results of this testing are discussed in paragraph 6.

4.5 DESCRIPTION OF PHASE III TEST PROCEDURES

The test gear design and fabrication and all test procedures are described under paragraph 5.3.

5. RESULTS AND DISCUSSION

5.1 PHASE I - VACUUM CARBURIZE DEVELOPMENT

5.1.1 Development of the Vacuum Carburize Cycle for the Vasco X2M Gear Material

To develop the vacuum carburize cycle for the Vasco X2M material, approximately 50 standard heat treat test slugs were obtained from Litton Precision Gear and sent to C.I. Hayes. Litton had prepared these slugs by machining a gear tooth profile in a cylindrical bar. The profile was representative of gear teeth presently machined by Litton for CH-47D helicopter transmission components. Use of this standard type of specimen allowed an accurate assessment of the amount of carburization throughout the tooth profile to be made.

Vasco X2M is conventionally carburized at 1,700°F. To make full use of the inherent high process temperature and enhanced diffusion advantages of the vacuum carburization process, the initial temperature evaluated was 1,750°F. This temperature is 100 degrees below the hardening temperature and below the grain coarsening temperature of the alloy. The remainder of the heat treat procedure, i.e., the hardening cycle, was the same as the conventional cycle for this material. The conventional hardening cycle was used so that the carburizing method and temperature would be the only variables to observe when comparing conventional data previously generated to the data obtained in this program.

In addition, use of the standard hardening cycle would allow a much easier implementation of the entire process into industry.

To develop the vacuum carburization procedure for X2M, C.I. Hayes personnel reviewed previous Boeing Helicopters IR&D data obtained from vacuum carburizing the Vasco X2M material. Then, various cycles were evaluated during the developmental stage of this program, as listed in Table 6. Evaluation of the data from these runs led to the formulation of the cycle listed below. At least three heat-treat test slugs were used per run (a run being one complete

TABLE 6. VACUUM CARBURIZE - X2M EXPERIMENTAL PROCEDURES

Parameter	1	2	3	4	5
Pump Down	--	10 min	10 min	--	--
Heat to 1,900°F	28 min	50 min	50 min	--	--
Soak @ 1,900°F	35 min	35 min	20 min	35 min	35 min
Cool to 1,800°F	1,750°F for 22 min	1,750°F for 10 min	6 min	--	--
Soak @ 1,800°F	1,750°F for 10 min	1,750°F for 10 min	10 min	10 min	10 min
Carb @ 1,000°F	1,750°F C_3H_8, 150 Torr at 40 ft^3/hr	1,750°F C_3H_8,125 Torr at 40ft^3/hr	60 min CH_4,255 at 75 ft^3 /hr	150 min CH_4,250 Torr at 75 SCF/hr	150 min CH_4,250 Torr at 75 SCF/hr
Diffuse @ 1,800°F	1,750°F for 4 min	1,750°F for 4 min	5 min	255 min	315 min
Gas Quench	64 min	60 min	60 min	Yes	Yes
Temper @ 1,250°F	No	90 min, N_2	90 min, N_2	90 min	90 min
Heat to 1,850°F	31 min	45 min	45 min	--	--
Soak @ 1,850°F	20 min	35 min	35 min	30 min	30 min
Oil Quench	35 min	35 min	35 min	Yes	Yes
Freeze @ -120°F	--	--	Yes	Yes	Yes
Temper @ 600°F 2+2	--	--	Yes	Yes	Yes
ECD'S	0.040 in Hayes 1.1% C-Hayes 0.045-.050" 1.1% C-BH	0.045 in. Hayes 0 per BH	0.047 in. Hayes	0.080 in. Hayes	0.085 in.
Microstructure	Carbide Network Broken	Heavy Carbides	Heavy Carbides-Hayes	Carbides @ 0.5 Hayes	Broken Network Hayes

vacuum carburize and harden cycle), and ten to twelve runs were made using this cycle.

a) Place test slugs in VSQ vacuum carburize furnace.
b) Heat to 1,900°F.
c) Soak @ 1,900°F for 35 minutes.
d) Cool to 1,750°F.
e) Carburize @ 1750°F for 90 minutes, CH_4 -250 Torr, 75 SCF/NA; Target effective case depth (ECD) was 0.040-0.060 inch.
f) Gas quench.
g) Reheat to 1,850°F for hardening.
h) Hold @ 1,850°F for 20 minutes.
i) Oil quench.

Each run was made to simulate an actual production cycle by placing several hundred pounds of scrap in the furnace with the test samples. After completion of a run, the samples were analyzed by both Hayes and Boeing Helicopters laboratory personnel.

The metallurgical characteristics shown on Table 7 of the material processed by the cycle above were assessed at the flank, root, and root fillet positions of the test slugs. All of these characteristics were considered acceptable.

TABLE 7. METALLURGICAL TEST RESULTS OF VASCO X2M VACUUM CARBURIZED AT 1,750°F

Property	Flank	Root	Root Fillet
Carburization Uniformity	Acceptable	Acceptable	Acceptable
Effective Case Depth	0.048-in.	0.044-in.	0.044-in.
Surface Hardness*	R/C 63	R/C 62	R/C 62
Core Hardness	R/C 42	R/C 42	R/C 42
Surface Carbon Content**	1.2%	1.1%	1.0%

* Direct Rockwell C Scale.

**Determined by Electron Beam Microprobe Analysis.

The hardness versus depth curve obtained from the same test slug is given in Figure 14.

A typical percent carbon versus depth curve, obtained by electron beam microprobe analysis on a cross section through the test slug with a deep ECD of 0.070-0.110 inch, is shown in Figure 15.

Even though the metallurgical data indicated that acceptable results were obtained from this vacuum carburization run, the following changes were made to the process to orient it to production processing:

a) An increase in the Vasco X2M steel carburizing temperature from 1,750°F to 1,800°F.
b) A longer diffusion time during carburizing was added.
c) A stress relief anneal cycle at 1,250°F was added.

The carburizing temperature was increased to improve furnace cycle times, while the diffusion time was increased to enhance the carburized case microstructure by reducing the amount of carbide at the surface of the part. (Note that the carbon content at the surface, Figure 15, is approximately 1.5 percent. This is higher than the desired 0.9 to 1.2 percent optimum carbon content). The purpose of the stress relief anneal was to facilitate standard CH-47 manufacturing techniques where it sometimes becomes necessary to machine gears between the carburizing and hardening cycles. This anneal essentially lowers the hardness of the carburized surface to Rockwell C (R/C) 28-35, which allows machining of the carburized areas, if required.

Incorporation of these changes resulted in the vacuum carburize cycle detailed below. Note that use of the vacuum carburizing procedure negates the use of the preoxidation process, which is required to overcome differences between surface and bulk diffusion rates when carburizing by conventional methods. This cycle contains the standard hardening sequence used for X2M.

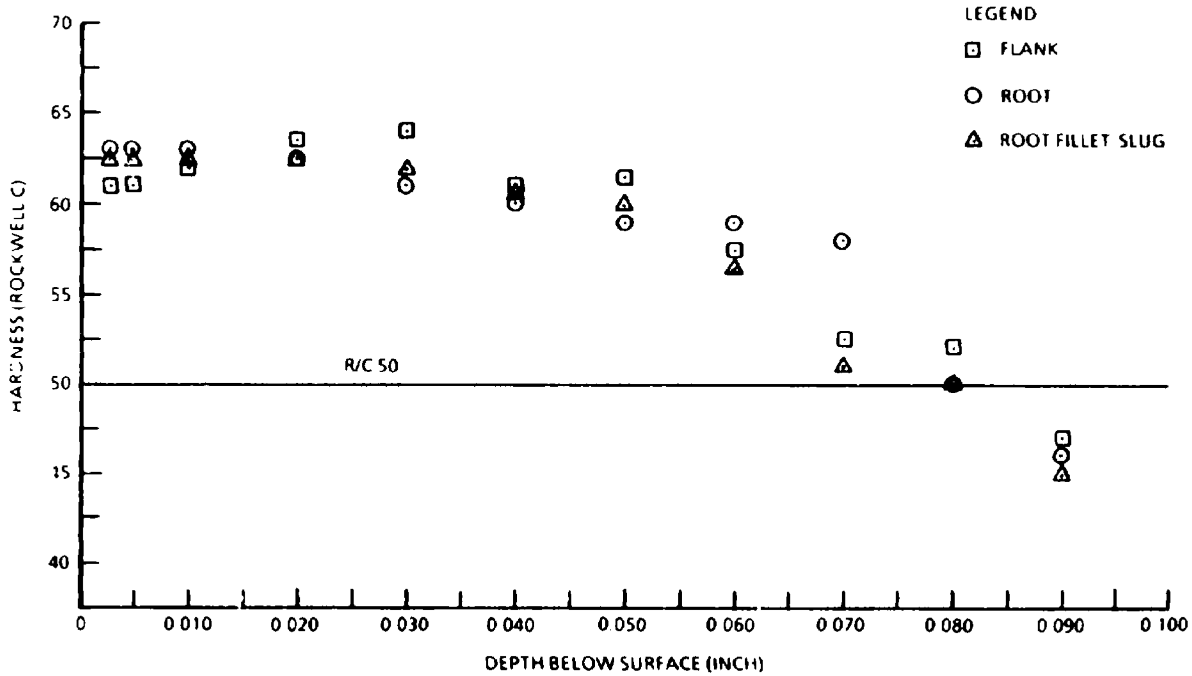


Figure 14. Effective case depth of X2M, vacuum carburized at 1,750°F.

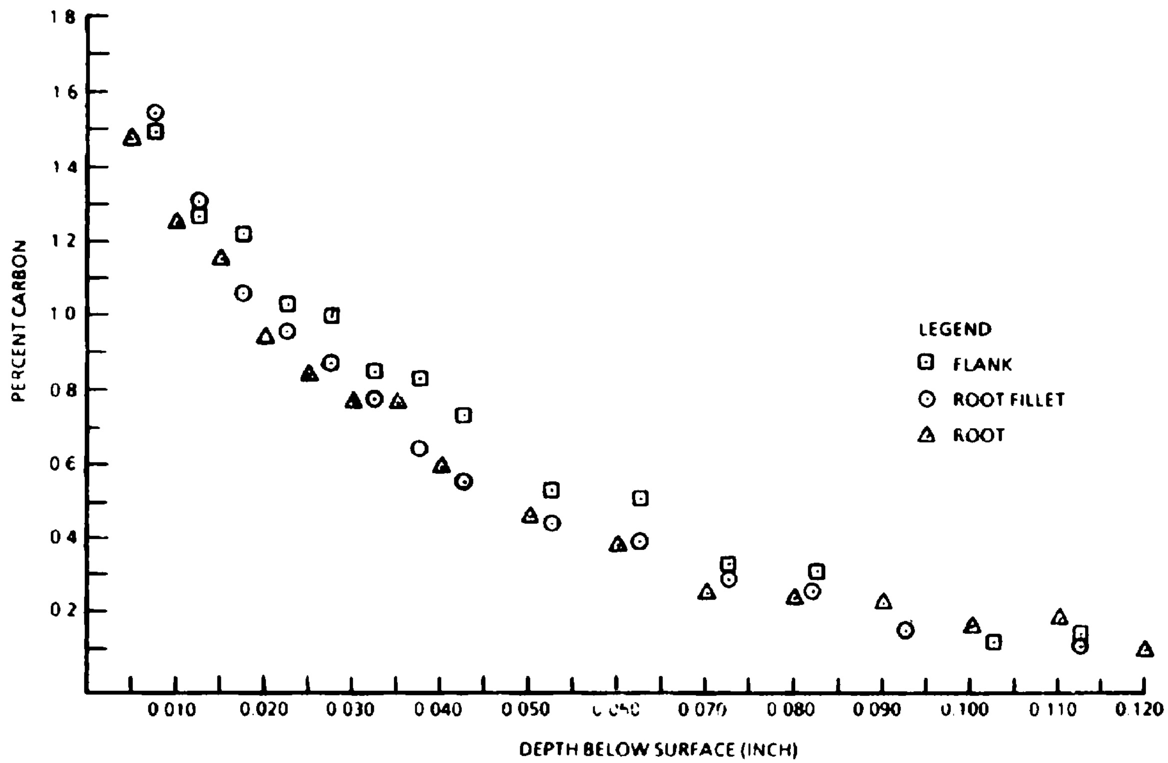


Figure 15. Carbon content near surface of Vasco X2M, vacuum carburized at 1,750°F.

a) Place test slugs, test part, etc., in VSQ vacuum carburize furnace.

b) Evacuate chamber to 500 Mu vacuum level. (The heaters in the VSQ furnace do not come on until a vacuum of 500 Mu is reached.)

c) Heat to 1,900°F.

d) Soak @ 1,900°F for 35 minutes.

e) Cool to 1,800°F.

f) Soak at 1,800°F for 10 minutes.

*g) Carburize 150 minutes at 1,800°F - CH_4 - 250 Torr - 75 SCF/HR; Target ECD of 0.070-0.110 inch.

**h) Diffuse for 315 minutes at 1,800°F.

i) Gas quench.

j) Stress relieve at 1,250°F for 90 minutes in vacuum.

k) Reheat to 1,850°F for hardening (500 Mu vacuum).

l) Hold @ 1,850°F for 30 minutes.

m) Oil quench.

n) Deep freeze at -120°F for 120 minutes at temperature.

o) Double temper at 600°F for 2 hours each.

*Carburizing time for STBF & scoring tests is 60 minutes.

**Diffusion time for STBF & scoring tests is 15 minutes.

The above cycle was utilized to vacuum carburize all of the X2M geared roller test specimens, Part Numbers SK20895-1 and -2. The single tooth bending fatigue and scoring test specimens were processed by the same cycle, with the exception of those items denoted by the asterisks.

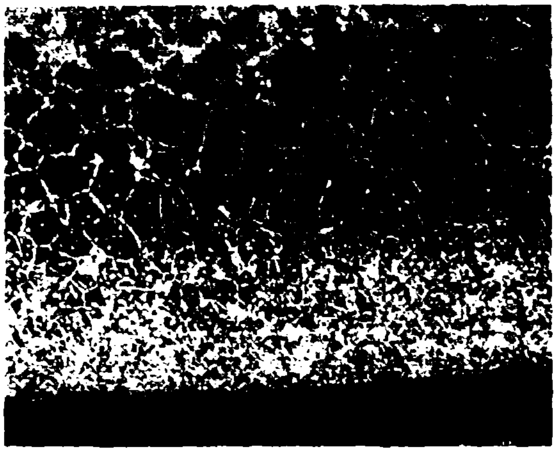
Both C.I. Hayes and Summit Gear Co. processed these gears according to this process. Evaluation of test slugs processed with the geared roller specimens revealed the metallurgical characteristics shown on table 8.

TABLE 8. METALLURGICAL TEST RESULTS OF VASCO X2M VACUUM CARBURIZED

Property	Result
Uniformity	Acceptable
Effective Case Depth	0.086-in
Surface Hardness	R/C 63.5
Surface Carbon Content	N/A

The case and core microstructures of the test slugs are shown in Figures 16 and 17. The case microstructure consisted of a relatively heavy, interconnected carbide network interspersed in a tempered martensite matrix while the core microstructure consisted primarily of tempered martensite with less than two percent free ferrite. The heavy carbide network observed at the surface of the test slugs was considered rejectable per Boeing's conventional carburizing specification D210-10342-1 (Reference 1). However, since the test slug had not been ground and the geared roller test samples were to be ground, it was considered that the heavy network at the surface would be removed during grinding. As a result, the test components were heat treated.

It is important to note here that this process was successful in producing the desired metallurgical case depth characteristics. In addition, the use of the proprietary preoxidation process (Reference 1) was not required nor was it utilized. Also, a time savings of approximately 60 percent was obtained by vacuum carburizing (approximately 10 hours) compared to conventional carburizing (approximately 24 to 30 hours). This time savings can also be viewed on the basis that the total time for vacuum carburization and hardening was approximately 21 hours compared to the 24 to 30 hours required solely for conventional carburization.



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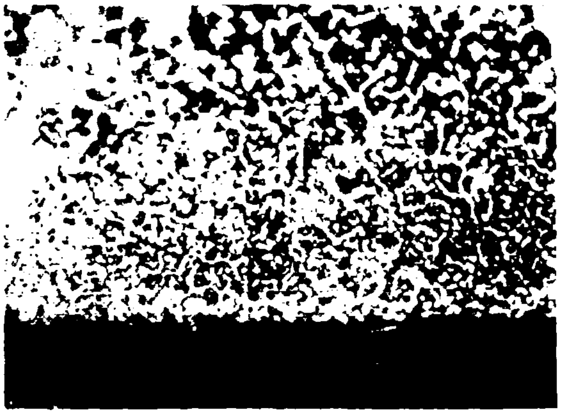

400X

Figure 16. Case microstructure of vacuum carburized X2M consisting of heavy, interconnected carbides in a tempered martensite matrix. The as-ground condition is shown.

Figure 17. Core microstructure of vacuum carburized X2M consisting of tempered martensite. Arrows indicated areas of the free ferrite

As a result of the development of the vacuum carburize procedure for X2M, C.I. Hayes completed the formulation of the empirical equations to control furnace time in relation to effective case depth. The equations take into account the possibility of carburizing, diffusion, and hardening at different temperatures and times. The report written by C.I. Hayes covering this work is shown in Appendix M.

Following the above evaluations, gear roller test specimens were fabricated and tested. Initial test results revealed that the microstructural constituents, i.e. primarily carbide networks, had not been ground off of the specimens as expected. As a result, the gear test data was considered invalid and not representative of aircraft quality processing. These test results are discussed in paragraph 5.1.3. Due to the scope and schedule of the program, further efforts to develop an optimized vacuum carburization procedure for X2M were continued in an originally unplanned Phase IV, which was developed, submitted to AMTL, and approved. The results of this Phase IV work are discussed in paragraph 5.4.

All of the 9310 vacuum carburization development work was completed in Phase I, as detailed in the next section.

5.1.2 Development of the Vacuum Carburize Cycle for the 9310 Gear Material

As stated previously in this report, the procedure for carburizing 9310 steel in a vacuum had been developed previously by the C.I. Hayes Company. Effective case depth (R/C 50 depth) versus time in the furnace for both carburizing and diffusion cycles had also been developed. Hayes' work encompassed vacuum carburizing temperatures of 1,650°F to 1,900°F, while varying surface carbon present from 0.6 to 1.10. This data is given in Appendix N.

In accordance with the program requirements, the vacuum carburizing temperature first evaluated was 1,900°F. (It was later found that 1,800°F was optimum, as discussed below.) The 1,900°F temperature was 200F above the conventional carburizing temperature of 1,700°F. As with the Vasco X2M alloy, the subsequent hardening heat treat procedure for 9310 was similar to the alloy's conventional heat treatment so that the only variable between the data developed under this program and previously developed data for conventionally carburized material would be the carburizing method and temperature. In addition, implementation of the process into industry could be more easily accomplished.

A typical vacuum carburize test cycle procedure utilizing the 1,900°F vacuum carburize temperature is given below:

a) Place test slugs in VSQ vacuum carburize furnace.
b) Heat to 1,900°F.
c) Soak @ 1,900°F for 30 minutes.
d) Carburize at 1,900°F for 60 minutes, 250 Torr - 75 SCF/HR; Target ECD of 0.070-0.110 inch.
e) Diffuse at 1,900°F for 210 minutes.
f) Gas quench.
g) Reheat to 1,550°F.
h) Soak at 1,550°F for 40 minutes.
i) Oil quench.
j) Freeze at -120°F for 120 minutes
k) Double temper at 300°F for 2 hours each.

Test slugs were exposed to this cycle and then metallurgically evaluated. Results of the evaluation are as follows:

Property	Result
Uniformity	Acceptable
Effective Case Depth	0.080 in.
Surface Hardness	R/C 65
Case Hardness	R/C 41.0
Surface Carbon Content	N/A

The above data is graphically illustrated in Figure 18. Case and core microstructures are shown in Figures 19 and 20. The case microstructure was not considered typical compared to that observed from conventionally

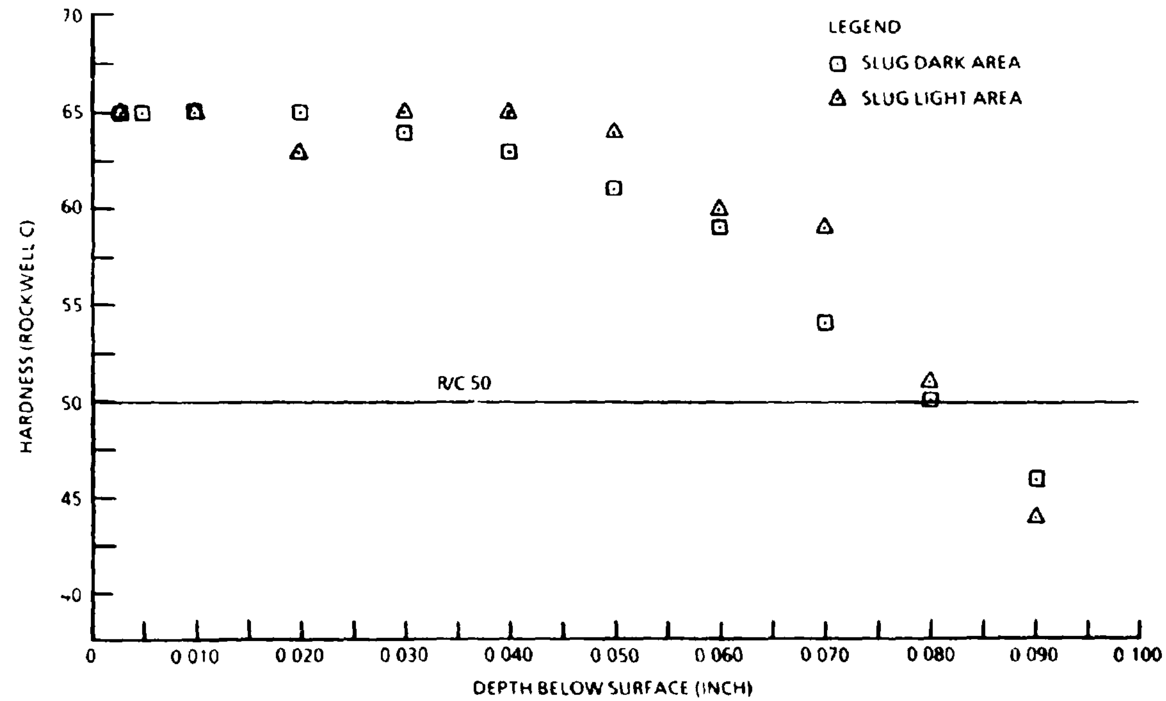

Figure 18. Effective case depth of AISI 9310 vacuum carburized at 1,900°F

Figure 19. Case microstructure of vacuum 9310 carburized at 1,900°F. Structure consists of large tempered martensite needles, retained austenite, and some carbides.

Figure 20. Core microstructure of 9310 vacuum carburized at 1,900°F. Structure consists primarily of tempered martensite.

carburized material. Very little carbide was observed, large martensite needles were apparent, and retained austenite was prevalent throughout the case structure. The core structure consisted primarily of tempered martensite, which is typical for this alloy. It was not until testing of the geared roller test specimens began that the detrimental effects of the case microstructure were characterized.

After evaluation of the test slugs, the following cycle was utilized for the geared roller test specimens. These specimens required an 0.065-0.085 inch effective case depth after grinding.

a) Place test slugs, test parts, etc., in VSQ vacuum carburize furnace.
b) Evacuate chamber to 500 Mu level.
c) Carburize at 1,900°F for 60 minutes, 250 Torr - 75 SCF; Target ECD 0.070-0.110 inch.
d) Diffuse at 1,900°F for 210 minutes.
e) Gas quench.
f) Reheat to 1,550°F - hold 40 minutes.
g) Oil quench.
h) Cool to -120°F - hold 2 hours.
i) Double temper at 300°F for 2 hours each.

Evaluation of the test slugs ran with these specimens revealed the following:

Property	Carburized @ Summit	Carburized @ Hayes
Uniformity	Acceptable	Acceptable
Effective Case Depth	0.088-in.	0.093-in.
Surface Hardness	R/C 63.0	R/C 63.0
Surface Carbon Content	0.9-1.2	1.0-1.2

*Results from three test slugs evaluated at Boeing Helicopters.

Metallurgical evaluation of the carburized case microstructure again indicated an unusually large martensite needle formation. A lack of precipitated carbide and approximately 20 percent retained austenite (determined by X-ray analysis) was also noted. The structure was considered to be the result of (1) carburizing at 1,900°F, (2) an ineffective quench procedure during hardening of the material, and (3) a lack of stress relief annealing in the carbide precipitation range.

As a result, changes to the carburizing procedure were incorporated for items two and three above. The carburizing temperature of 1,900°F was not changed. It was noted that the core microstructure was considered acceptable on all test samples evaluated.

Processing of the single tooth bending fatigue test and rotating fatigue test gears followed closely, from a scheduling standpoint, to the geared roller test specimens. While vacuum carburizing these components at 1,900°F at C.I. Hayes, an inadvertent vacuum furnace temperature overrun occurred whereby the temperature of the furnace exceeded the melting point of copper (approximately 1,980°F). All of the gears had been previously copper plated for carburizing stop-off purposes in the web section, and as a consequence of the over temperature, the copper plate melted on all of the components in the furnace. C.I. Hayes indicated the furnace had most likely reached 2000F before the over temperature was observed. Since the gears were suspended on a bar in the furnace, the molten copper dripped down onto the teeth. In some cases the copper diffused into the case microstructure, as shown in Figures 21 through 24. As a result of the copper melting onto the parts, the effective case depths on the gears varied significantly depending on whether the gear teeth were up or down while on the bar in the furnace. This is illustrated in Figures 25 and 26.

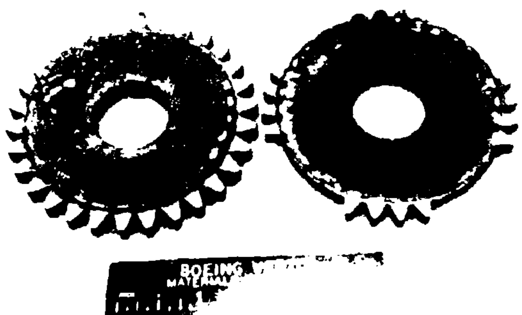

Figure 21. Rotating fatigue test gear (left) and single-tooth fatigue test gear (right) vacuum carburized in a lot which was inadvertently exposed to 2,000°F. Center web sections were copper plated, the teeth were not.

Figure 22. Magnified view of test gear shown in Figure 21. Copper is seen on tooth tip (arrow).

Figure 23. Flank area of gear tooth shown in Figure 5.9. Arrow indicates copper on tooth surface.

Figure 24. Root area of gear tooth shown in Figure 22. Arrow shows copper penetrating into the 9310 substrate

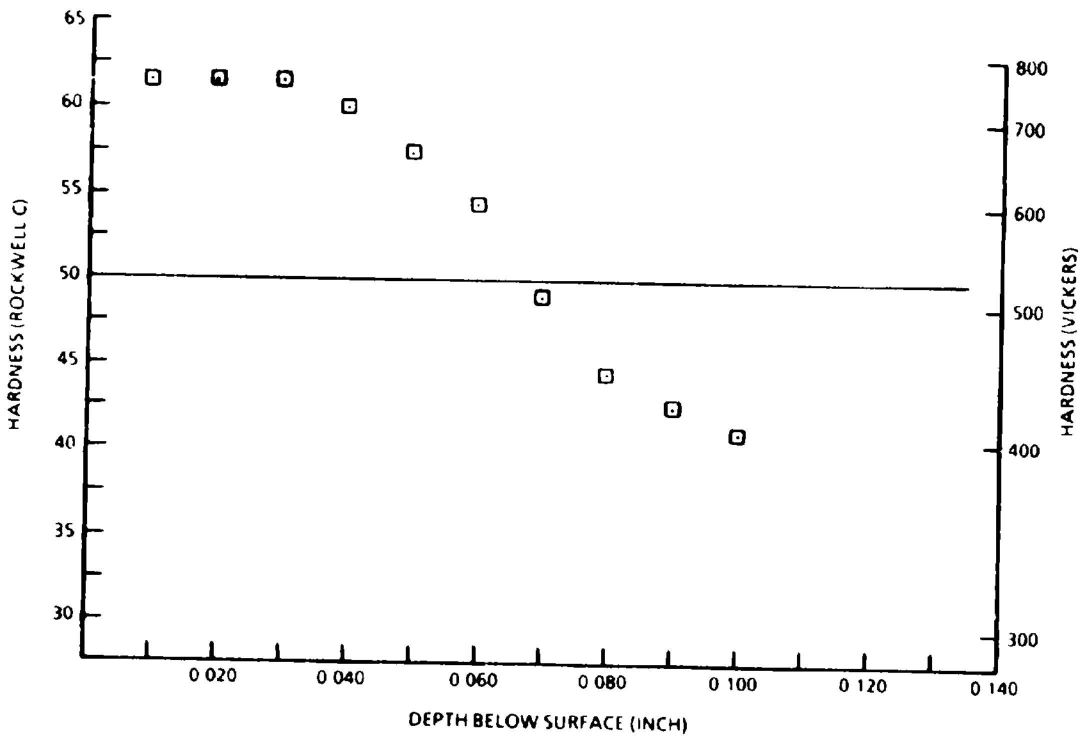

Figure 25. Acceptable hardness profile from root of gear inadvertently exposed to 2,000° F. Compare to Figure 26 showing unacceptable hardness profile in another root due to copper penetration.

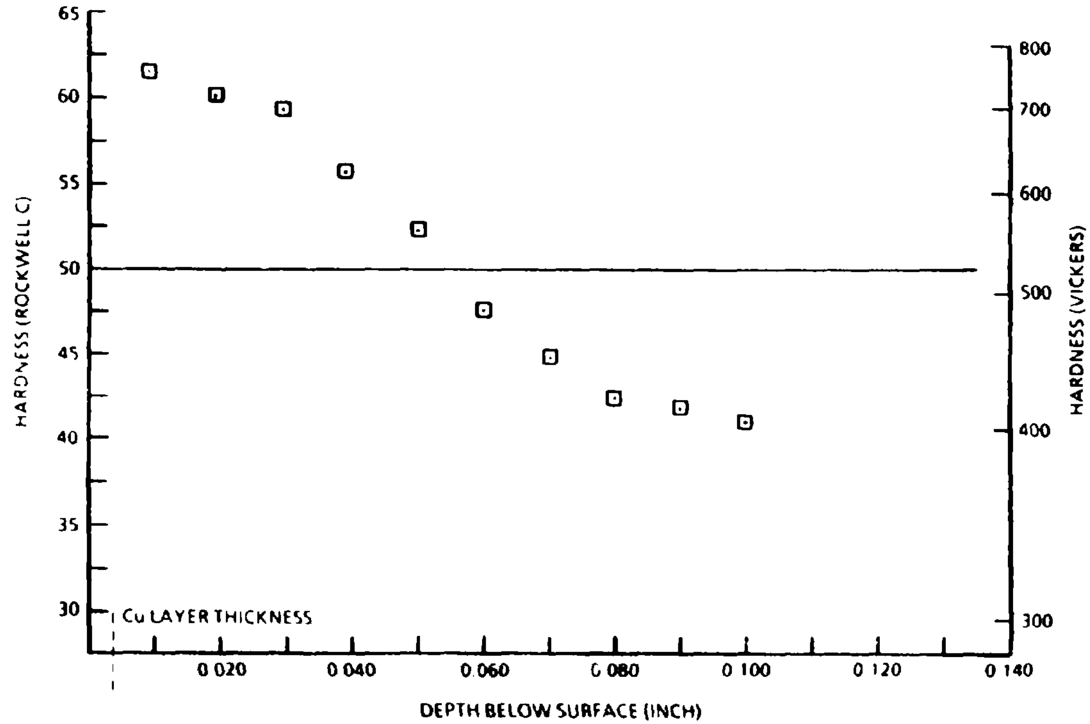

Figure 26. Unacceptable hardness profile from root of gear inadvertently exposed to 2,000° F. Profile is unacceptable due to copper penetration into surface. Compare to Figure 25 showing acceptable hardness profile.

Although these gears had to be scrapped, several important carburizing considerations were brought to light:

1) Carburizing at 1,900°F of parts which are copper plated requires precise temperature control to insure the 1,980°F copper melting point is not achieved. This could pose material and processing restrictions to industrial use of the process.

2) Vacuum carburizing furnaces must have temperature overrun controlling thermocouples which are placed relatively close to the production load of components.

While all of the above was occurring, testing of the geared roller test specimens, which were vacuum carburized at 1,900°F, had begun. Approximately 25 of the 60 specimens were tested. Evaluation by Weibull plot analysis of the data revealed rolling contact fatigue lives much less than expected. A brief summary of this data compared with previously obtained Weibull plots from conventionally carburized material is shown in Table 9.

TABLE 9. ROLLING CONTACT FATIGUE LIVES (x 10^5 CYCLES) OF 9310 VACUUM CARBURIZED AT 1,900°F

Carburized Method	Life (Cycles)		
	B10	B50	B90
1,900°F Vacuum Carburize	41.9	72.1	112.3
Conventional Carburize	101.0	182.0	250.0

The above data indicated that the 1,900°F vacuum carburized samples exhibited less than one-half the life of conventionally carburized material. Metallurgical evaluation of the vacuum carburized samples revealed unacceptable microstructural characteristics similar to those indicated previously in this report for test slugs. It was noted that even with the changes that were incorporated, a refinement of the microstructure and an increase in the amount of carbide did not occur.

As a result of these gear roller evaluations, processing of the single tooth bending fatigue and rotating fatigue test gears was stopped. Although the gears had been heat treated, finish grinding was stopped. Due to the problems experienced, it was decided to lower the vacuum carburizing temperature from 1,900°F to 1,800°F, remanufacture, and retest new specimens, i.e., geared roller, single tooth bending fatigue, and rotating fatigue test gears.

It should be noted that all of these remanufactured samples were produced within the budget of the original program. Summit Gear, Stulen Machine Co., and Litton Precision Gear are to be commended for their assistance in this regard.

The revised vacuum carburization procedure used for these new specimens was as follows:

a) Evacuate chamber to 500 Mu.
b) Soak @ 1,800°F for 35 minutes.
c) Carburize at 1,800°F for 45 minutes; Target ECD 0.040-0.060 inch.
d) Diffuse at 1,800°F, 80 minutes.
e) Gas quench.
f) Anneal at 1,275°F in nitrogen for 120 minutes.
g) Soak at 1,525°F for 40 minutes.
h) Oil quench.
i) Freeze at -120°F, 3 hours minimum at temperature.
j) Double temper at 300°F for 2 hours each.

Metallurgical evaluation of test slugs from this cycle showed a refined grain structure in the case with some precipitated carbide at the surface. This structure was a significant improvement over that of the 1,900°F vacuum carburized material and indicated that the lower carburizing temperature should produce the desired surface contact fatigue properties.

As a result, the following heat treat cycle was used to vacuum carburize the replacement 9310 geared roller test specimens, Part Number SK70895-4.

a) Place test slugs, test part, etc., in VSQ vacuum carburize furnace.

b) Evacuate chamber to 500 Mu vacuum level. (The heaters in the VSQ furnace do not come on until a vacuum of 500 Mu is reached).

c) Heat to 1,800°F.

d) Soak @ 1,800°F for 35 minutes.

e) Carburize 150 minutes at 1,800°F - CH_4 - 250 Torr - 75 SCF/HR; Target ECD 0.070-0.110 inch.

f) Diffuse for 275 minutes at 1,800°F.

g) Gas quench.

h) Stress relieve at 1,250°F for 2 hours in vacuum.

i) Gas quench.

j) Reheat to 1,525°F for 40 minutes in vacuum.

k) Oil quench.

l) Deep freeze at -120°F for 3 hours at temperature.

m) Double temper at 300°F for 2 hours each.

Evaluation of test slugs from these runs revealed the following:

Property	Result
Uniformity	Acceptable
Effective Case Depth	0.082-in.
Surface Hardness	R/C 64.5
Surface Carbon Content	N/A

The case and core microstructures produced in 9310 by this cycle are seen in Figures 27 and 28. The case microstructure consisted primarily of tempered martensite with precipitated carbide at the surface. Some large martensite needles can be seen. The core microstructure appeared to be typical of that of conventionally processed 9310 steel.

Similar to that mentioned previously for X2M, a significant time savings of approximately 60 percent was obtained by vacuum carburizing (approximately 9 hours) compared to conventional carburizing (approximately 24-30 hours). This time savings can also be viewed on the basis that the total time for vacuum

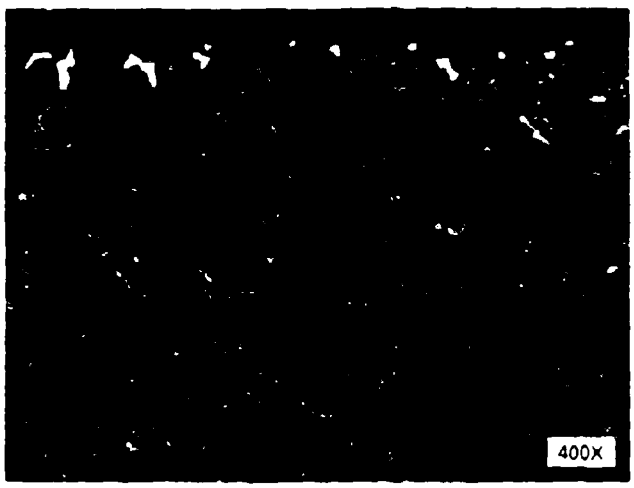

Figure 27. Case microstructure of 9310 steel vacuum carburized at 1,900°F. The structure is primarily martensite with some precipitated carbide at the surface.

Figure 28. Core microstructure of 9310 vacuum carburized at 1,800°F. Structure consists of tempered martensite.

carburization and heat treatment was 21 hours compared to the 24-30 hours required solely for conventional carburization.

Excepting the changes to the carburizing and diffusion times as shown below, all of the remanufactured components were heat treated in a similar manner as detailed above. Summit Gear Company heat treated all of these components since time did not permit manufacturing and shipping of two groups of specimens. Also detailed below is the number of specimens in each group that were processed. The results of the testing of these gears are discussed in the next paragraph 5.1.3.

TABLE 10. TEST GEARS MANUFACTURED FROM AISI 9310 VACUUM CARBURIZED AT 1,800°F

Specimen Type	P/N	Number of Specimens	Carburizing Time (min)	Diffusion Time (min)
Geared Roller	SK20895-4	15	150	275
Single Tooth Bending Fatigue	SK29572-10	8	45	80
Rotating Fatigue	SK29571-10	20	45	80

5.1.3 Geared Roller Test Results for X2M and 9310 - A typical Caterpillar geared roller test machine, shown in Figure 29, was used for these tests. Two machines were used. A typical one inch diameter test roll made from the Vasco X2M steel and the mating five inch diameter slave roll can be seen in Figure 30.

5.1.3.1 Gear Roller Test Machine Problems - During the testing, several problems developed with the test machine apparatus which invalidated certain test data. These problems are briefly listed below:

(a) Lubricating jets in the test machine were clogged with debris, thus not allowing proper lubrication of the test specimen. To remedy this, the machine was completely drained of oil, cleaned and

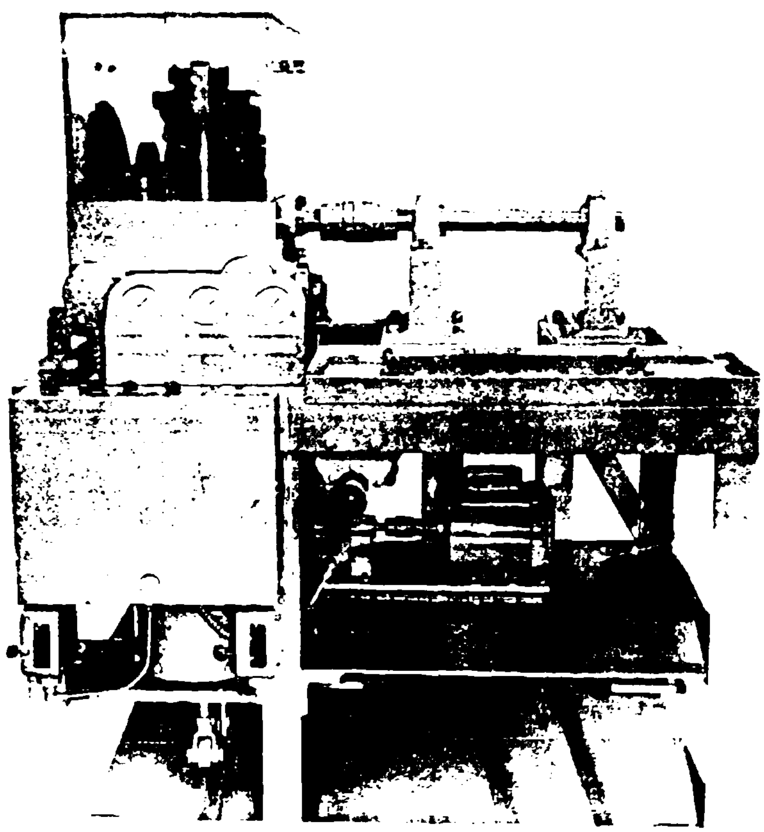

Figure 29 Gear roller test machine

Figure 30. Test and slave roll for geared roller testing.

refilled. All oil lines were freed by forced air cleaning, after which testing again commenced.

(b) Several of the test rolls slipped during testing. This slipping resulted in a greater number of recorded test cycles than the specimen actually experienced. This slipping was caused by dimensional discrepancies on the test roll or in the test fixture. In an effort to eliminate this problem, the following were tried:

(1) Increasing the dimensions on the stub end of the test specimens during machining (this was done prior to manufacture of certain test rolls).

(2) Plating the stub end of the specimens with copper, nickel, etc.

(3) Applying 3M Loctite material to joint.

Items (2) and (3) were relatively unsuccessful.

(c) Failure, by spalling fatigue, of tne five-inch diameter slave roll. Since this component mates with the test roll, spalling of the slave roll results in distress on the test roll.

(d) Specimen holder test machine shafts spalled. To solve this problem, the shafts were ground down to sub-size and oversize bearings were purcnased and installed on the sub-size shaft diameter. Appendix D details the remachining requirements of the test machine shafts.

(e) Prior to any testing, one 5 inch diameter slave roll had to be reground for each of the original 120 roll test specimens. These were reground since they had previously been utilized on the program detailed in Reference 4. A drawing of the specimen is given in Appendix H. Each slave roll, after regrind, was magnetic particle inspected. Of the 120 slave rolls, approximately one third were found to contain cracks. None of the rolls with cracks were used in this program.

Testing of all geared roller test samples was not accomplished primarily due to problems (b) and (c) discussed above. However, sufficient data was obtained to provide the significant trends discussed below for 9310 and X2M.

5.1.3.2 Testing and Evaluation - Initial geared roller testing was performed at several hertz compressive stress loadings. The stress varied from 288,000 psi H_z to 637,000 psi H_z. Due to the scatter in the test results and the presence of scuffing-type failures rather than pitting or spalling, it was decided that all testing would be accomplished at only one load level of 450,000 psi Hertz stress. (A scuffing mode of failure is one in which heat exchange occurs after an oil film breakdown. Pitting or spalling is a fatigue failure with no evidence of heat or oil film breakdown at the critically stressed contact point.)

Each test roll was labeled with mill heat number, heat treat vendor and vacuum carburized temperature. This labeling, along with the number of rolls manufactured and tested, is shown in Table 11. The complete test data obtained for the 9310 specimens is also shown.

The method of evaluating surface contact fatigue data is by Weibull analysis, i.e., Weibull Distribution. This method utilizes straight line graphs to represent cumulative percentages of failures by means of appropriate coordinate scales. This method is especially convenient for engineering purposes because a clear graphic picture of fatigue life distribution enhances conveyance of statistical decisions based on the data. Reference 3 lists the method of evaluating data by this technique.

TABLE 11. GEARED ROLLER TEST SPECIMEN IDENTIFICATION

TEST ROLL LABEL	MATERIAL	MILL HEAT NUMBER	VAC CARB TEMP°(F)	VAC CARB VENDOR	NUMBER OF ROLLS MANUFACTURED	NUMBER OF ROLLS TESTED
-1A	Vasco X2M	5842	1,800	Summit	15	10
-1B	Vasco X2M	5842	1,800	Hayes	15	10
-2A	Vasco X2M	86510	1,800	Summit	15	10
-2B	Vasco X2M	86510	1,800	Hayes	15	10
-3A	9310	86510	1,900	Summit	15	5
-3B	9310	86670	1,900	Hayes	15	5
-4A	9310	86043	1,900	Summit	15	7
-4B	9310	86043	1,900	Hayes	15	6
-4	9310	86043	1,800	Summit	15	10

Each test group was plotted individually on Weibull Distribution paper. In addition, the data was plotted together in one sample size. This was done since the combining of similar groups result in more significant data because, as the sample size increases, the reliability of the data also increases. The data obtained is shown in Figures 31 to 33. The raw data is shown in Appendix P.

One of the values of the Weibull distribution plot is that comparisons can be made by determining the variation of B10, B50, and B90 life of the different

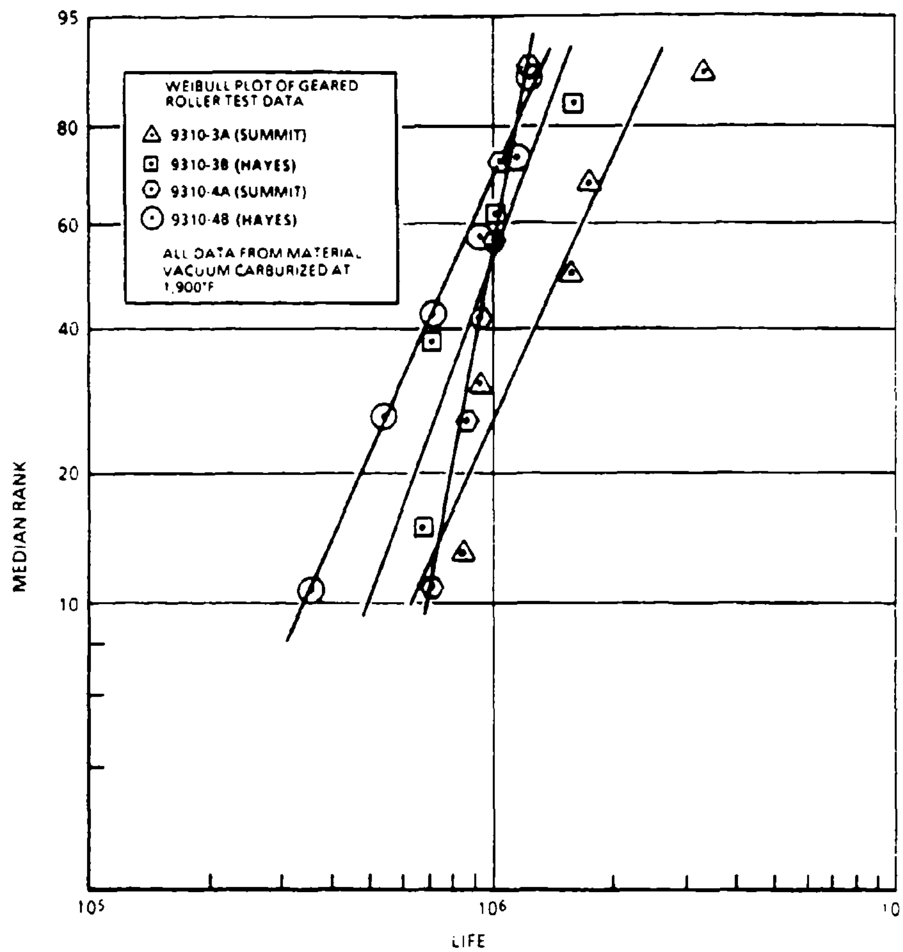

Figure 31. Weibull plot of gear roller test data for AISI 9310 vacuum carburized at 1,900°F.

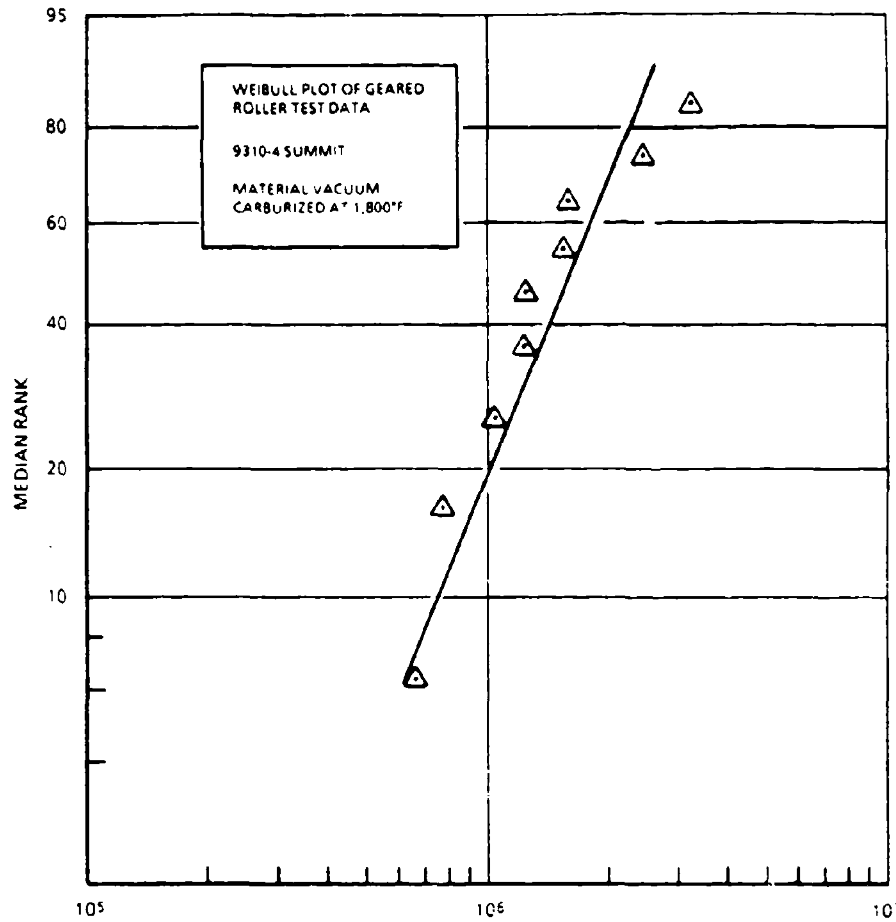

Figure 32. Weibull plot of gear roller test data for AISI 9310 vacuum carburized at 1,800°F.

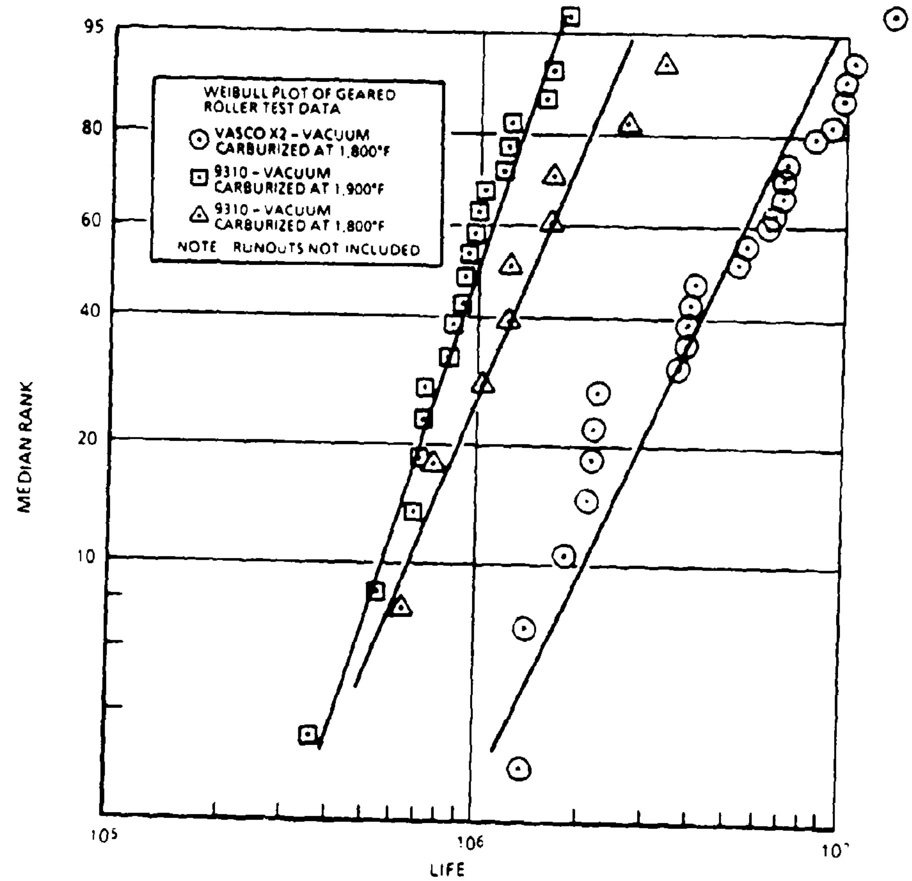

Figure 33. Weibull plot of gear roller test data for AISI 9310 and Vasco X2M.

groups tested. B10 life is defined as the life, in cycles, at which 10 percent of all tested samples have failed. B50 and B90 lives are similarly defined.

After determining the B10, B50, and B90 lives of 9310 and X2M, bar charts comparing the vacuum carburized versus conventionally carburized rolling contact fatigue lives were developed, as shown in Figure 34. The conventionally carburized data was obtained from References 4 and 5.

Evaluation of the data revealed the following:

9310 Steel

Comparison of the vacuum carburized 9310 steel, carburized at 1,800°F, with the conventional carburized data revealed the B10 and B50 lives of the former were slightly lower than the latter, as seen in Table 12. B90 lives were the same. This data is also shown in Figure 34.

TABLE 12. 9310 ROLLING CONTACT FATIGUE LIFE COMPARISON MATERIAL VACUUM CARBURIZED AT 1800F.

Carburized Method	Life (Cycles)		
	B10	B50	B90
Vacuum	6.9×10^{5}	1.55×10^{6}	2.55×10^{6}
Conventional	1.17×10^{6}	1.85×10^{6}	2.55×10^{6}

Also illustrated in Figure 34 are the lives of the 9310 vacuum carburized at 1,900°F. The lives of material produced at the 1,900°F vacuum carburizing temperature were much reduced compared to the lives of conventionally carburized steel.

Observing Figure 31, little effect of the two different mill heats or vacuum carburizing vendors is apparent. This is one of the reasons that, when redeveloping the heat treatment of this material at 1,800°F, it was decided to

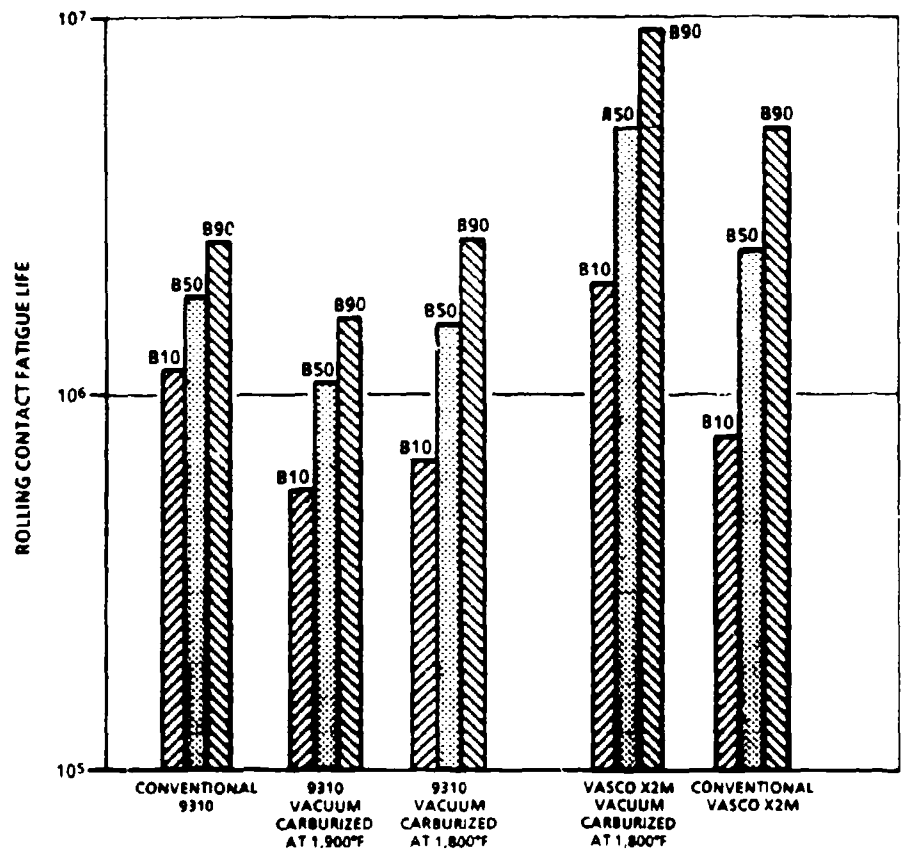

Figure 34. Comparison of rolling contact fatigue lives of conventional vs vacuum carburized steel.

use only one mill heat and one vacuum carburizing vendor (other salient reasons were cost and schedule).

Vasco X2M

The results of the X2M geared roller tests are compared in Figure 34 with those obtained previously for conventionally carburized X2M. The results show an improvement in rolling and sliding performance of the alloy based on B10, B50, and B90 lives compared to those of conventionally carburized X2M.

During these geared roller tests, the single tooth bending fatigue and scoring tests were initiated. As will be discussed in paragraphs 5.1.4 and 5.1.5 covering the results of these tests, an improvement in properties similar to those shown in Figure 34 was not obtained. The reason for the variability in property improvements was attributed to the interconnected carbide network in the case of X2M. The effects of this microstructure are discussed further in the following section.

5.1.3.3 Metallurgical Evaluation of Test Samples

Several test rollers of each alloy were metallurgically evaluated. The following metallurgical tests and characteristics were evaluated and documented:

(a) Spall circumferential and axial length dimensions
(b) Temper etch for grinding burrs
(c) Surface hardness
(d) Core hardness
(e) Effective case depth - determined at R/C 50 depth
(f) Case and core microstructure.

Metallurgical evaluation of a representative sampling of the geared roller test specimens is given in Table 13 with corresponding microstructures from test specimens shown in Figures 35 through 37.

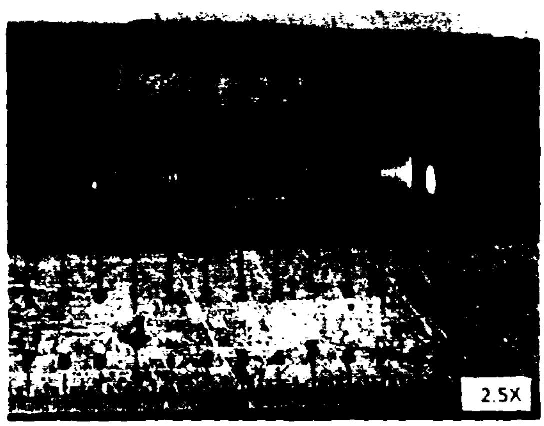

Figure 35. Vasco X2M geared roller test specimen.

Figure 36. Case microstructure of X2M geared roller test specimen

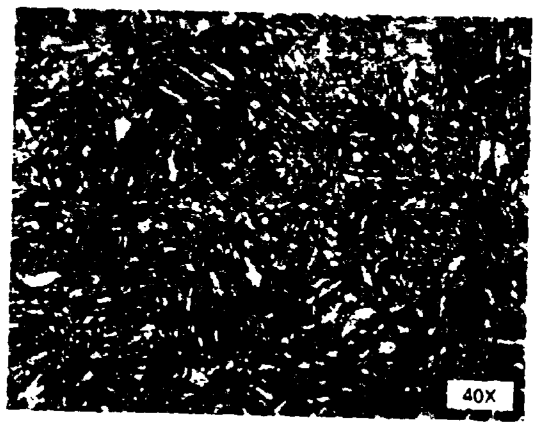

Figure 37. Case microstructure of X2M geared roller test specimen

TABLE 13. METALLURGICAL DATA OF GEARED ROLLER TEST SPECIMENS

Material	Specimen Number	Spall Dimensions Circumferential Length-in.	Spall Dimensions Axial Length-in.	Surface Hardness R/C	ECD (IN)	Core Hardness R/C
Vasco X2M	-1A,1	0.17	0.12	63.5	0.080	43.5
Vasco X2M	-1B,5	0.24	0.20	62.0	0.092	45.0
Vasco X2M	-2A,6	0.15	0.12	61.0	0.081	44.0
Vasco X2M	-2B,1	0.18	0.06	63.5	0.078	43.0
9310	-4,10	0.20	0.29	63.5	0.065	38.5

As mentioned in paragraph 5.1.1, microstructural evaluation of the Vasco X2M material disclosed that the case consisted of tempered martensite with a continuous carbide network. This carbide network was found to extend to a maximum depth of 0.020-in. Data detailed in Reference 6 indicates that the carbide network has been shown to produce better contact fatigue life than that produced by a pure martensite structure. Apparently, the network acts as a stiffener to the structure. This is consistent with the results shown in this work since the vacuum carburized AISI 9310 material case microstructure did not contain a carbide network and did not exhibit an equivalent rolling contact fatigue life. As the data bears out, the vacuum carburized Vasco X2m contact fatigue life was superior to that of the 9310 steel. It is noted here that the X2M case microstructure was not typical of that observed in conventionally carburized transmission components due to carbide networks that are not permitted by specification. As mentioned previously, refinements to the vacuum carburizing technique for X2M were undertaken in Phase IV of this program to eliminate this type of unwanted structure.

The core microstructure of both materials, Vasco X2M and 9310, was considered typical to that observed during conventional heat treatment. The only difference noted was that there was less than one percent visual estimate free ferrite in the core microstructure of the Vasco X2M materials. This, however, is not considered significant.

Evaluation of several of the test rollers also confirmed that the carburization was uniform in both alloys with no evidence of spottiness. Surface hardness, case hardness and effective case depths were, for the most part, within drawing requirements. Dimensional evaluation of the spall present on each failed specimen revealed all to be similar. Representative examples of spall dimensions were given in Table 7.

5.1.4 Single Tooth Bending Fatigue Life Test Results

The results of each alloy are discussed separately below.

5.1.4.1 AISI 9310 Data Evaluation - All 9310 test gears in this program were manufactured from a single heat of double vacuum melted material. The results of this testing are presented in the S/N curve shown in Figure 38. All of the raw data are shown in Appendix Q. Baseline data for air melt quality and double vacuum melted quality 9310 were used for comparison to this data. Figure 39 shows the results of the previous double vacuum melt 9310 testing. Except for the fact that the 99% confidence band on the mean for the vacuum carburized material is slightly smaller than that for the conventionally carburized material, the two curves exhibit no significant differences. Based on this data, it must be concluded that the vacuum carburizing process did not affect the bending fatigue strength of the AISI 9310 material in any way, either beneficially or detrimentally.

An interesting sidelight to the vacuum vs. conventional carburization process evaluation is to compare both Figures 38 and 39 to Figure 40 which shows similar bending fatigue data for air melt 9310 steel. The improvement obtained from the double vacuum melt over air melt material is quite obvious and very significant.

5.1.4.2 Vasco X2M Data Evaluation - Two different heats of Vasco X2M material were used in manufacturing these test gears. All of the gears were machined by a single vendor. However, each heat was separated into two groups, and each group was heat treated by a different heat treat vendor. The different heats are identified by the dash number associated with each part number while the heat treaters are identified as "Heat Treater A" and "Heat Treater B,"

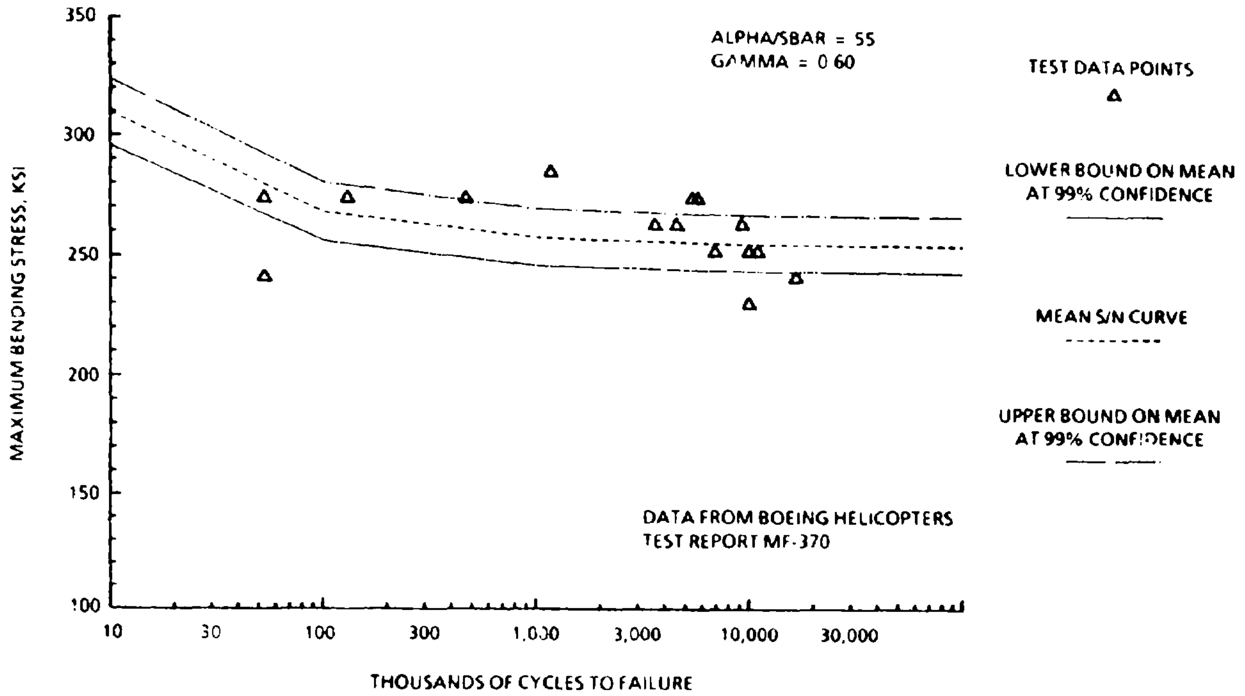

Figure 38 Single tooth bending fatigue life data of conventionally carburized DVM 9310.

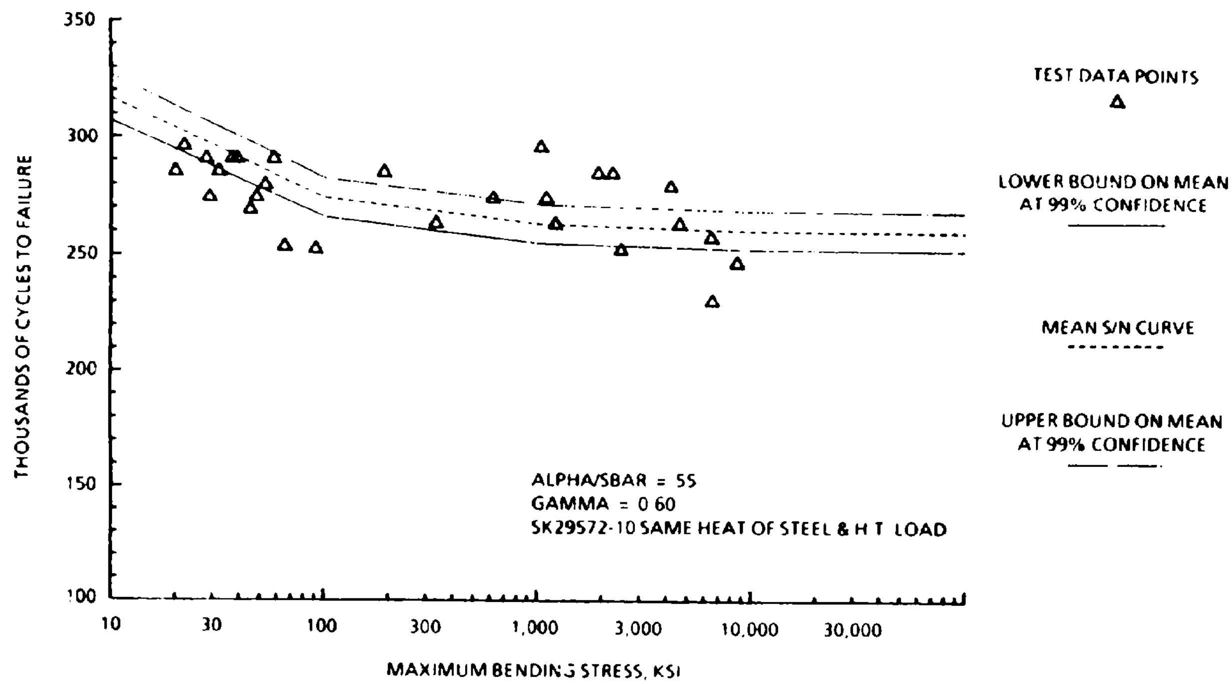

Figure 39. Single tooth bending fatigue life data of conventionally carburized DVM 9310. Data from Boeing Helicopters Test Report MF-370

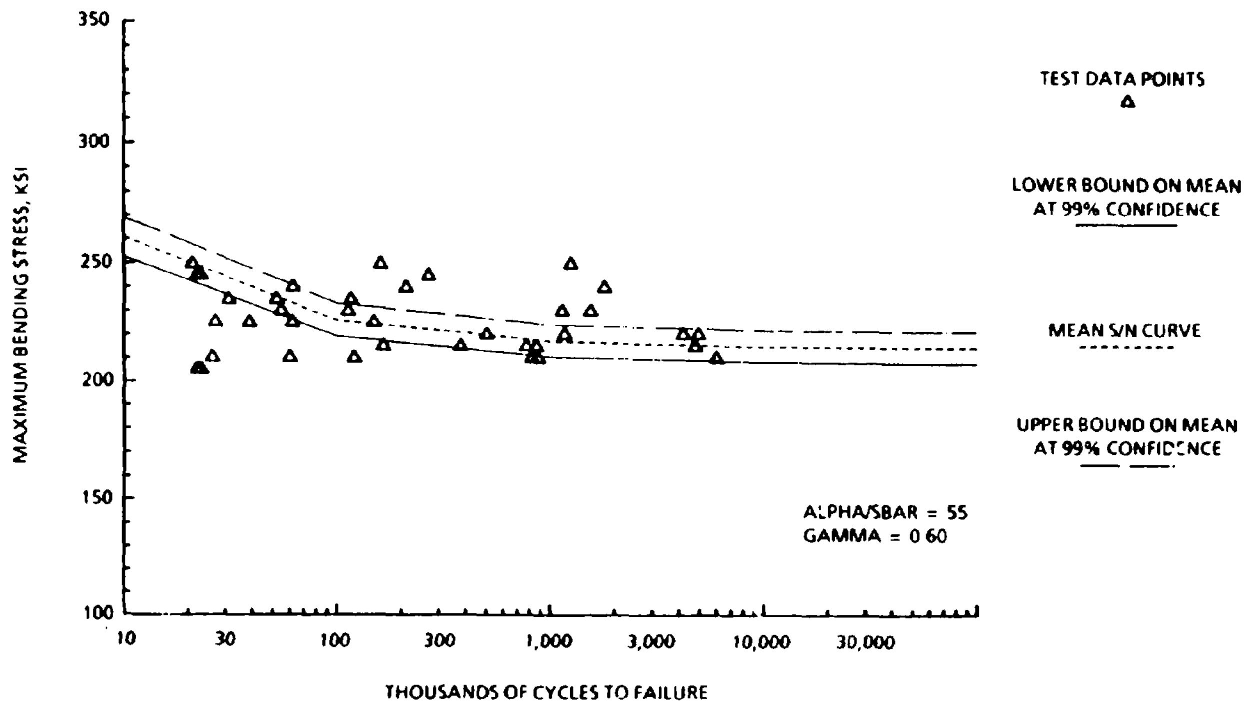

Figure 40. Single Tooth Bending Fatigue Life Data for Conventionally Carburized Air Melt 9310. Data from Boeing Helicopters Document D210-10025-1.

respectively. By manufacturing the gears in this manner, it was possible to determine if there was a significant difference in the results between either different heats of the same material or between different heat treaters working to the same heat treatment specifications.

Figure 41 shows all of the Vasco X2M data plotted together, i.e both heats and both treaters. From Figures 42 and 43 which show the results for the two heats of material separately, it can be concluded that there does not appear to be a difference between the two heats of material used. However, Figures 44 and 45 indicate that there is a difference between the two heat treat vendors, with Vendor B producing gears with a significantly higher bending fatigue load capacity.

The major consideration in this program, however, was whether or not the vacuum carburizing procedure significantly affected the bending fatigue capacity of the gears when compared with that of conventionally carburized material. As can be seen by comparing the data in Figure 46, which is the existing Vasco X2M baseline data, with any of the foregoing charts, the vacuum carburized Vasco X2M gears have significantly lower bending fatigue capacity, regardless of heat or heat treat vendor.

As mentioned previously in paragraph 5.1.1, metallurgical evaluation of the vacuum carburized X2M material indicated the presence of a heavy carbide network in the surface and near surface microstructures. Since this is an undesirable condition for good bending fatigue resistance, the heat treatment procedure was revised in an effort to improve this property. The revision of the X2M vacuum carburization procedure was conduced in Phase IV, the results of which are discussed in paragraph 5.4.

5.1.5 Scoring Test Results

The data obtained from the scoring tests was evaluated in light of previous data obtained from similar test programs, References 5, 6, and 7. All three of the referenced programs used the same test rig and test method as the current program. The basic geometry of the test gears used in the Reference 6 and 7 testing was identical to the current specimen geometry. However,

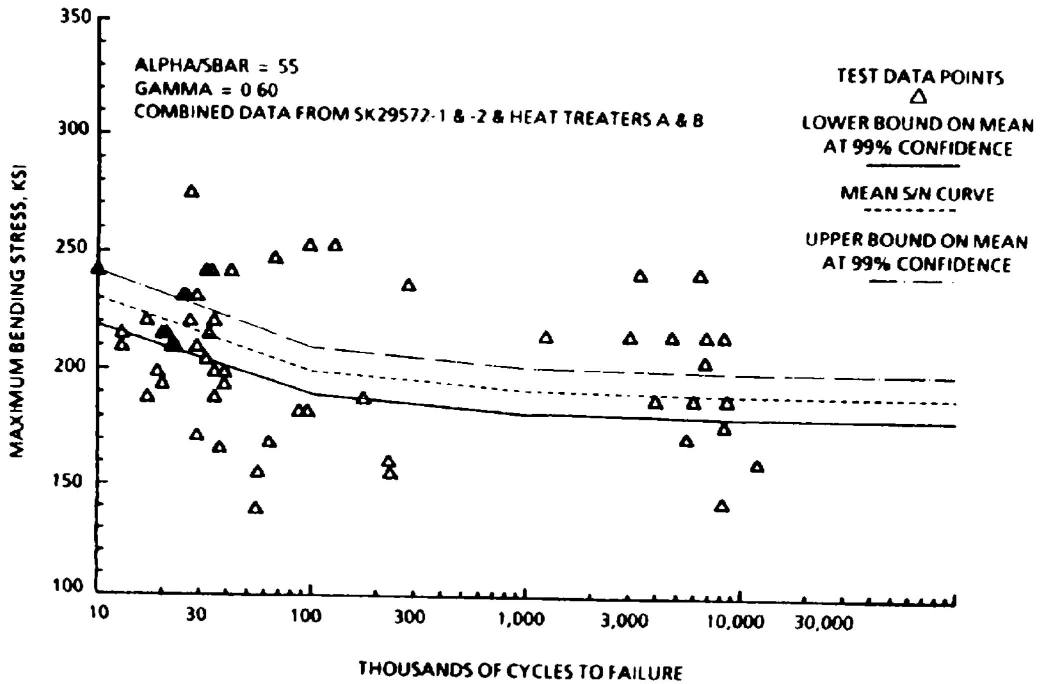

Figure 41. Single tooth bending fatigue life data of nonoptimized vacuum carburized Vasco X2M form two heats and two heat treaters.

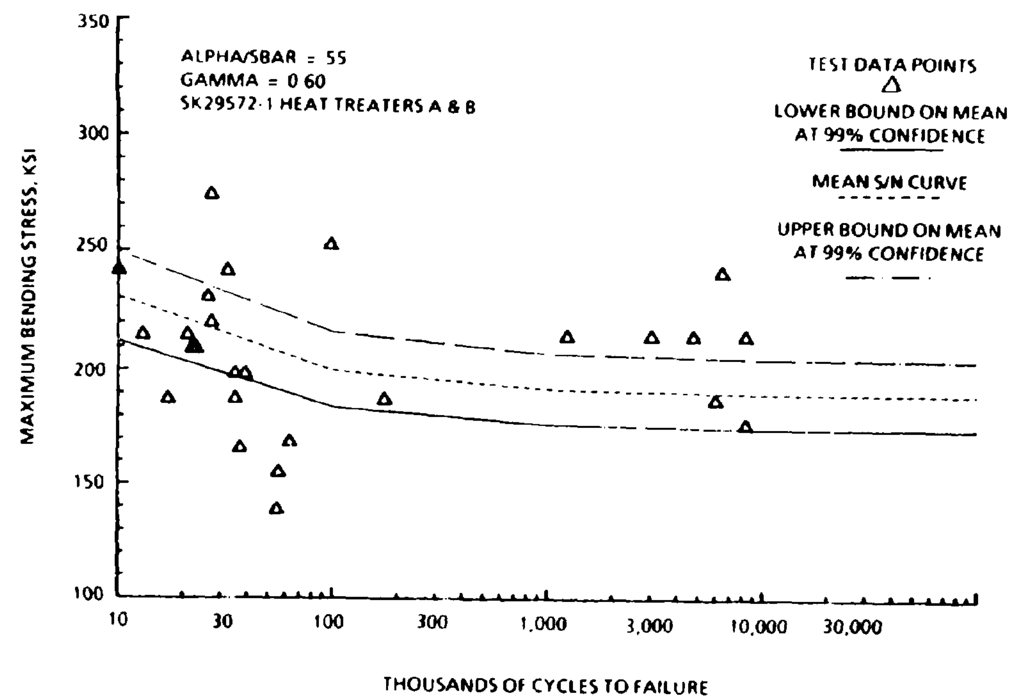

Figure 42 Single tooth bending fatigue life data of nonoptimized vacuum carburized Vasco X2M from mill heat 1.

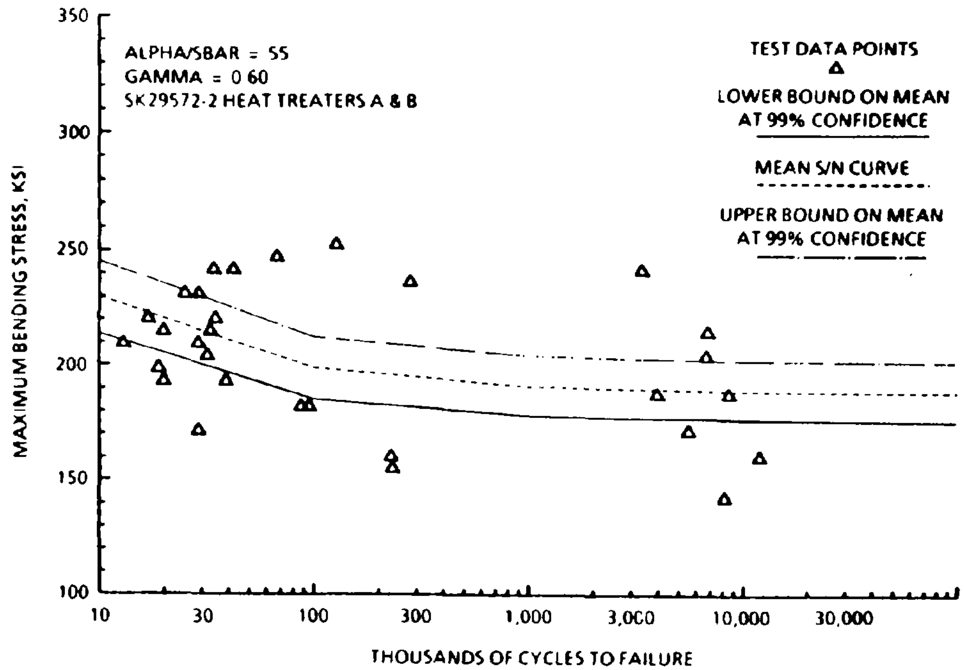

Figure 43. Single tooth bending fatigue life data of nonoptimized vacuum carburized Vasco X2M from mill heat 2

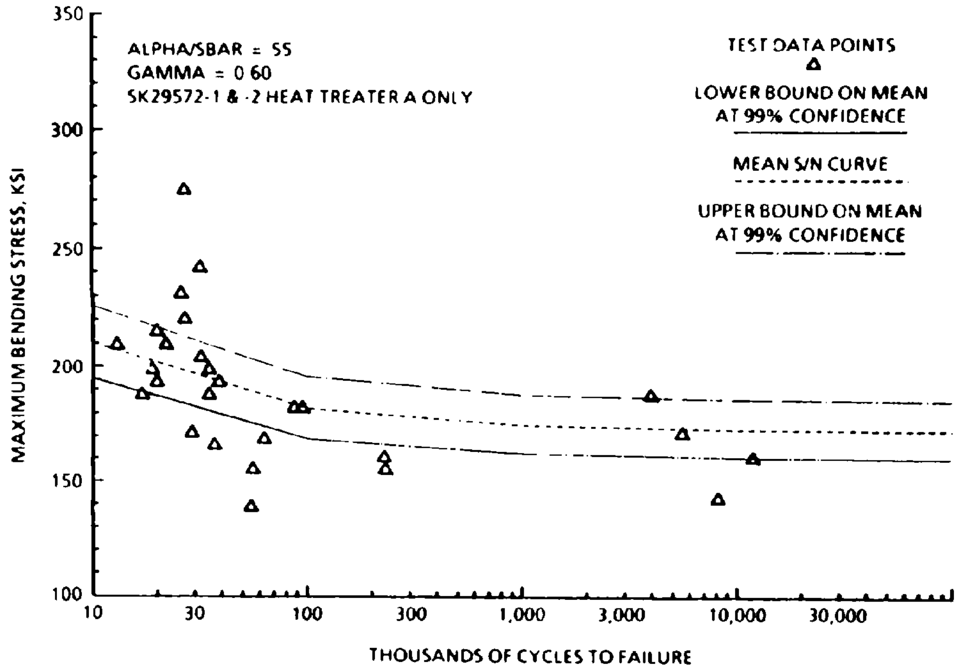

Figure 44. Single tooth bending fatigue life data of nonoptimized vacuum carburized X2M from heat treat vendor A.

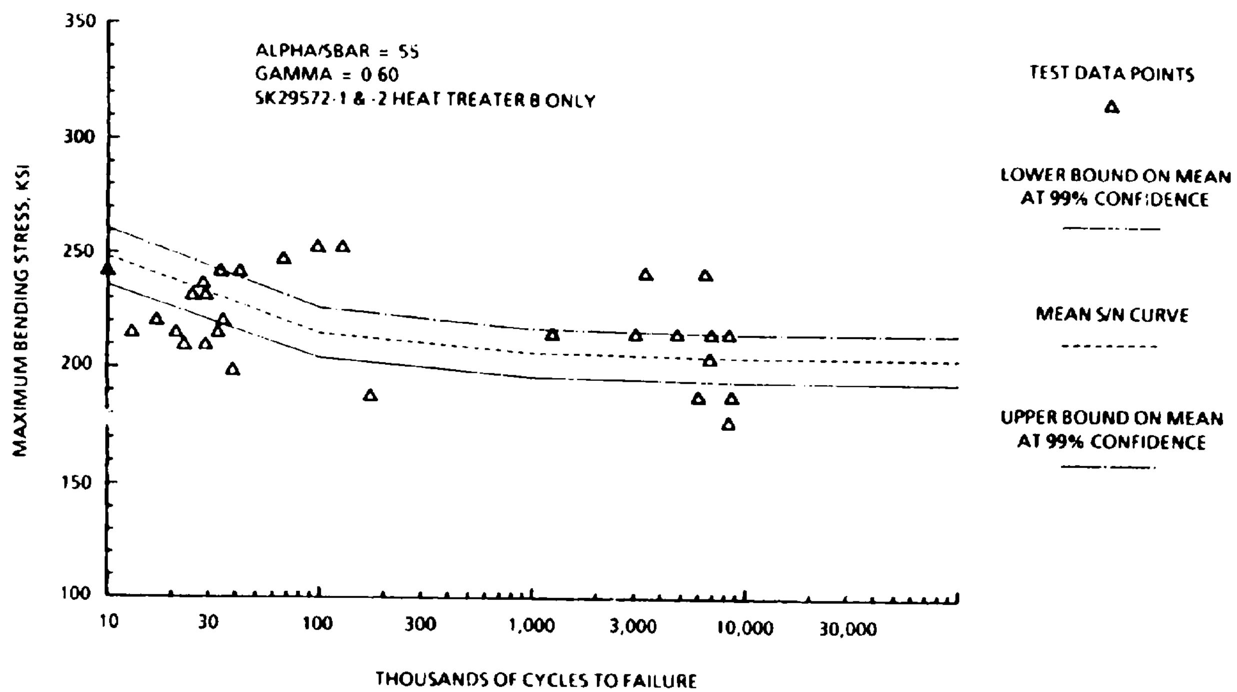

Figure 45. Single tooth bending fatigue life data of nonoptimized vacuum carburized X2M from heat treat vendor B.

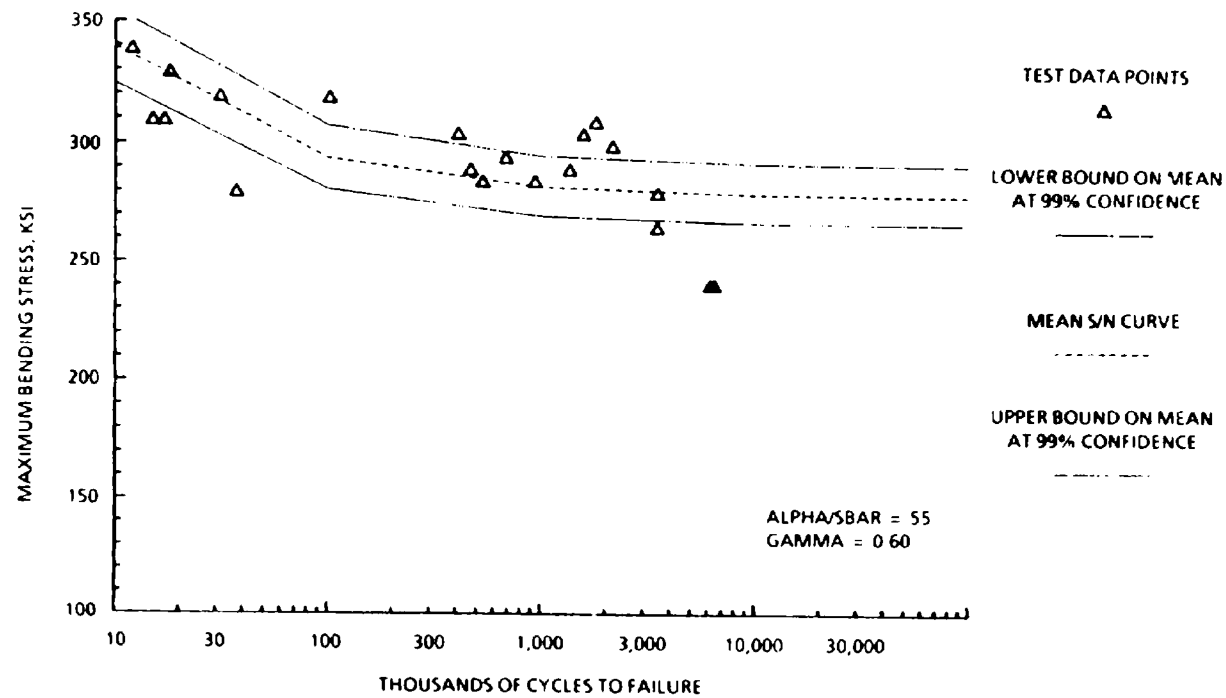

Figure 46. Single tooth bending fatigue life data of conventionally carburized Vasco X2M. Data from Boeing Helicopters document D210-10345-1.

MIL-L-7808 oil was used as the test oil. The testing defined in Reference 7 was conducted using gears of similar design and manufacture as those used in the current program but of somewhat large size (i.e., > 0.25-inch face width and 12.75 pitch diameter gear set operating on 10 inch center distance) than the current gears. The 9310 material used in Reference 2 was for air melt material and that used in Reference 4 was for single vacuum melt material, 0.24 carbon.

The raw data obtained from the scoring tests is shown in Appendix R. Table 14 presents a statistical summary of the data obtained in the current program and, for reference purposes, the same data from the baseline testing (References 5, 6, and 7). Figure 47 shows the same data graphically. Several very significant facts are immediately apparent from examination of this data. The most significant is that the mean flash temperature at failure is higher for the vacuum carburized 9310 and X2M materials than it is for the baseline data. Also important is that for X2M, the vacuum carburizing process (i.e., heat treater A vs. B) did result in a performance variation, but no difference based on mill heat (-1 vs -2) within each heat treater. The coefficient of variation (which is the standard deviation divided by the mean) is quite low for all samples.

In general, the data from the current program is slightly more consistent (within parameters) with less scatter, as evidenced by the smaller standard deviations, than the baseline data.

In addition, it is interesting to note that the scoring load capacity of gears heat treated by Vendor A is higher than that of gears heat treated by Vendor B, while the relationship for bending fatigue load capacity is exactly the opposite (i.e., for bending, Vendor B heat treat resulted in higher load capacity than Vendor A). Both conditions are likely due to the heavy continuous carbide networks which were present in gears heat treated by Vendor A. Since the carbide network condition reduces bending capacity but improves both durability and scoring, these results are certainly consistent.

TABLE 14. SCORING TEST RESULTS

PART NUMBER: MILL HEAT:	SK29571-1 5842A TELEDYNE		SK29571-2 86510 CARTECH		SK29571-10 87885-2 CARTECH
MATERIAL:	VASCO X2M		VASCO X2M		AISI 9310
HEAT TREATER:	A SUMMIT	B HAYES	A SUMMIT	B HAYES	A SUMMIT
FLASH TEMPERATURE AT FAILURE, °F					
MEAN	532.9	480.8	525.9	469.0	420.5
STANDARD DEVIATION	16.35	15.02	12.89	17.51	16.27
COEFFICIENT OF VARIATION	0.031	0.031	0.025	0.037	0.039
BASELINE DATA					
(REF. 3, 4, 5 DATA BASE)					
F. \SH TEMPERATURE AT FAILURE, °F					
MEAN	456.8				354.6
STANDARD DEVIATION	28.58				18.39
COEFFICIENT OF VARIATION	0.063				0.052

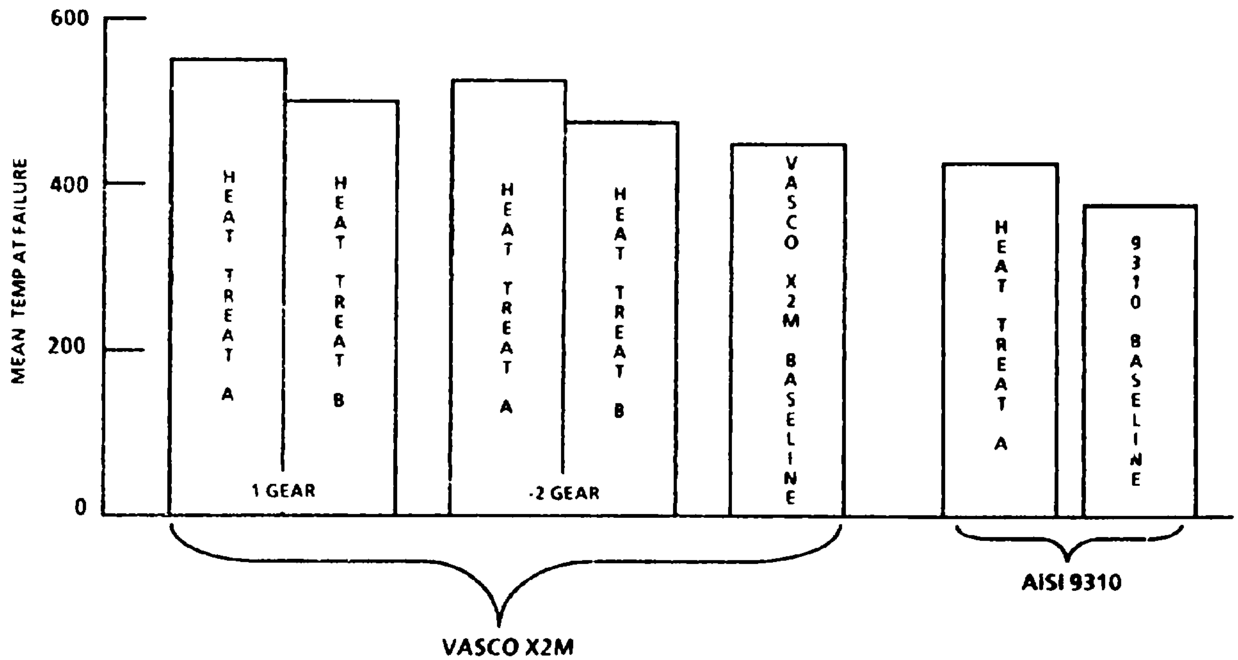

Figure 47 Scoring test results for Vasco X2M and AISI 9310.

5.2 PHASE II - SURFACE DURABILITY EVALUATIONS

In Phase II, the surface durability of the vacuum carburized 9310 material was investigated through testing and evaluation of spur and spiral bevel gears. The surface durability of X2M was not evaluated because the vacuum carburization procedure was not optimized, as discussed in Section 3 and paragraph 5.4.

5.2.1 Introduction

The primary concern of the transmission gear design engineer is to provide adequate tooth strength. For this reason, gear materials are selected mainly for beam strength. To improve the sliding behavior of the material, the usual procedure is to then harden the surfaces. Due to the emphasis on the development of gear materials for strength rather than for good sliding characteristics, most aircraft gears will pit or spall under conditions which are far less severe than those which would cause tooth breakage, particularly at low speeds. In many aircraft gear applications, pitting is a limiting factor in reducing the size and weight of transmissions.

As was the case with the previously described bending and scoring tests, the surface durability or pitting resistance of gears heat treated by the vacuum process must be evaluated to ensure that these gears exhibit load capacity levels at least equivalent to those of conventionally carburized gears.

Because the vacuum carburizing process was not optimized for the X2M material at the time the durability test gears were manufactured, no X2M gears were tested.

5.2.2 Results and Analysis of 9310 Gear Tests

Initial light scoring was observed at the 100 percent load level on most of the spur gear test specimens. However, after the gears were lightly polished, the light scoring appeared to stabilize and "heal over" at the conclusion of the 100-percent load run.

Initial light scoring is a state of lubrication phenomena which develops as a result of surface asperity contacts. The local high spots concentrate the load in these areas permitting metal-to-metal contact, along with concentrated pressures. Continued operation at moderate loads will eventually wear down the localized high spots (asperities) and thereby permit improved load distribution which in turn will result in a healed over (polished) condition.

A frosting condition on the pinion dedendum (the area between the pitch circle and the start of the root radius) was usually observed at the 160 percent load level; however, the severity of this condition was not apparent during normal visual observation.

The pitting condition sustained by the gear test specimens appears to be typical of destructive pitting usually found in the dedendum of the driving member in a reduction gear drive. This condition is characterized by the appearance of pits, of at least 1/32-inch in diameter, in the dedendum region. This type of pitting failure will usually progress in size and number of pits, with repeated stress cycles.

The data obtained from the durability testing was statistically analyzed in the same manner as the single tooth bending fatigue data. The results of this analysis are shown in Figures 48 and 49 for the spur and bevel gears, respectively.

When this data is compared to the spur gear durability baseline data shown in Figure 50, it is obvious that the vacuum carburizing process has not adversely affected the surface load capacity of the gears. It should be noted that the baseline data was obtained with air melt material and thus some improvement may be expected simply through the use of double vacuum melt material in the vacuum carburizing program. Even considering this effect, however, the comparison indicates that the vacuum process produces gears with surface load capacity characteristics at least as good as those of conventionally carburized gears. In all likelihood, the characteristics of the vacuum carburized gears is better in this respect.

In reviewing the spiral bevel gear data, it should be noted that no actual pitting failures occurred. Due to the very high loads which were required in this program, fretting occurred at the interface between the pinion bore and

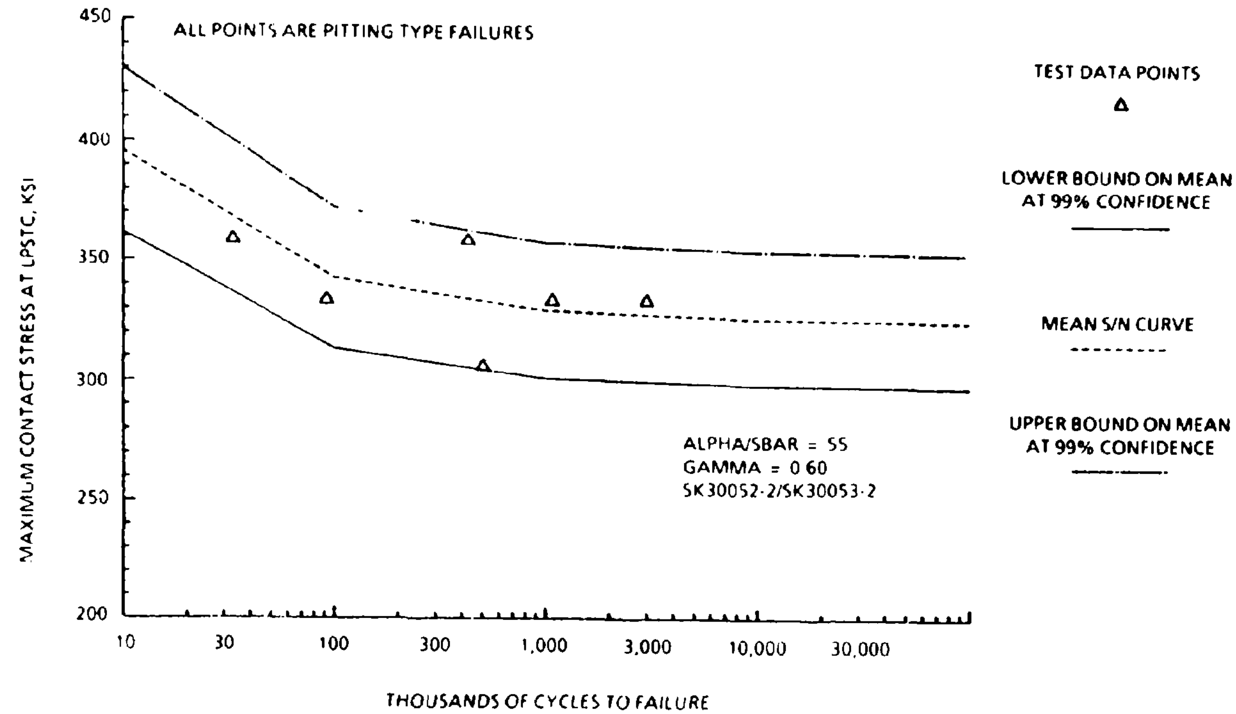

Figure 48. Spur gear durability test data for vacuum carburized 9310.

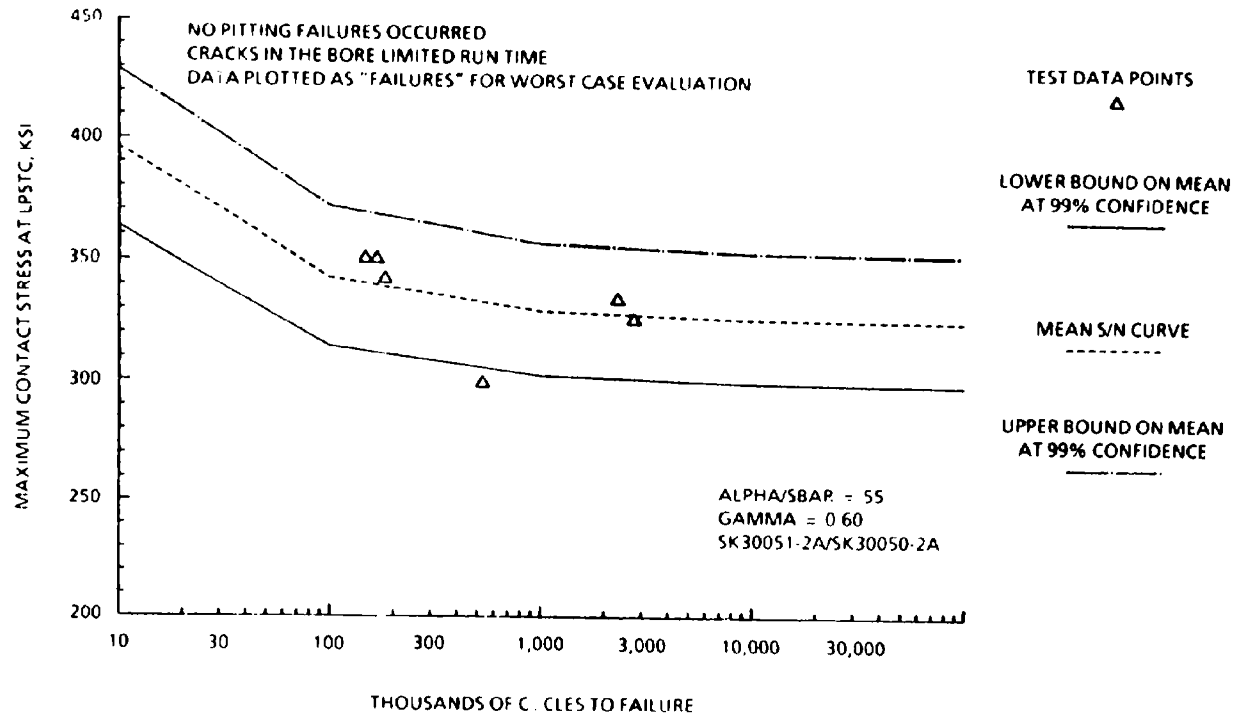

Figure 49. Spiral bevel durability test data for vacuum carburized 9310.

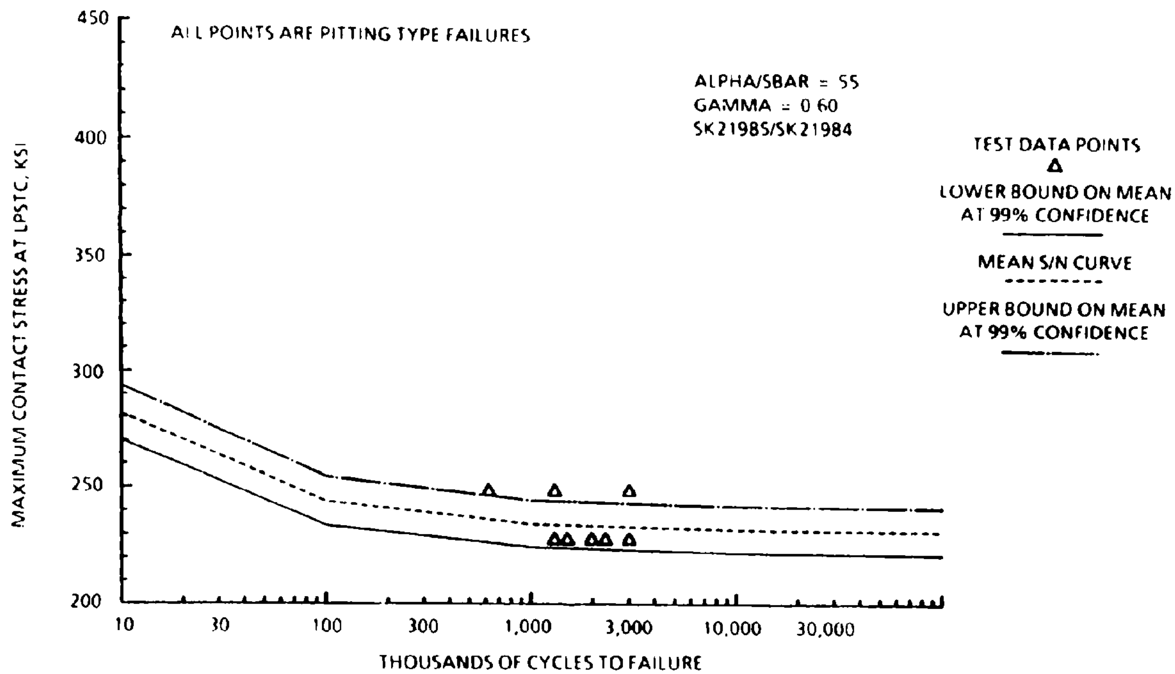

Figure 50. Spur gear durability test data for conventionally carburized air melt 9310. Data from Boeing Helicopters document D210-10193-1.

its supporting shaft. This fretting eventually generated a crack at the bore-shaft interface and the tests were halted each time a crack became apparent. Several attempts were made to improve this joint. The attempts included higher bolt torques and improved finish at the joint. These changes were only successful in forestalling the occurrence of the cracks, they did not eliminate them. Despite this problem, however, enough cycles were run without a pitting failure to provide a worst case indication of the behavior of the material. In performing the analysis of the bevel gears, therefore, each test data point was treated as a durability failure even though no pitting occurred. In this way, the data provided an indication of the behavior of the vacuum carburized gears.

5.3 Phase III - VACUUM CARBURIZED GEAR TESTING AND IMPLEMENTATION PLAN

The objective of this phase was two fold: first, to vacuum carburize and heat treat a gear of complex geometry and test it in a Boeing Helicopters CH-47C transmission, and second, to develop a plan to implement the vacuum carburization procedure developed in this program into production. The following sections detail the results of these efforts.

5.3.1 Vacuum Carburized Gear Testing

The gear selected for vacuum carburizing evaluation and helicopter transmission testing was a spiral bevel input pinion gear, Part Number 114D5245-10, Serial Number M5373, and is shown in Figure 51. The drawing for this part is found in Appendix S. This gear is used in Boeing Helicopters CH-47C combining transmissions, and is located in the position shown in Figure 52. This gear was selected due to its complex geometry and the extensive amount of time required for conventional carburization and hardening, which could be substantially reduced by use of the vacuum carburization and heat treat procedure developed in this program.

This gear was vacuum carburized by Summit Gear and heat treated and machined by Litton Precision Gear. The carburization and heat treat processing cycle as well as other processing details are discussed in paragraph 4.2.3.

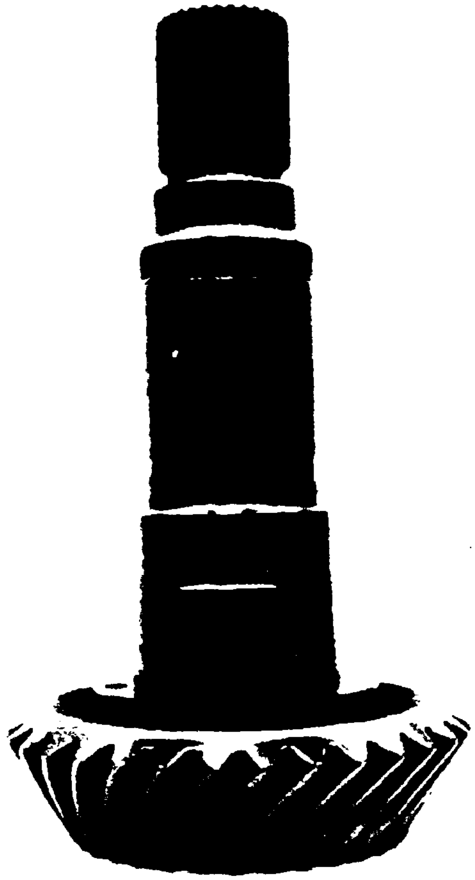

Figure 51. CH-47C Spiral bevel pinion gear, P/N 114D5245-10, S/N M5373.

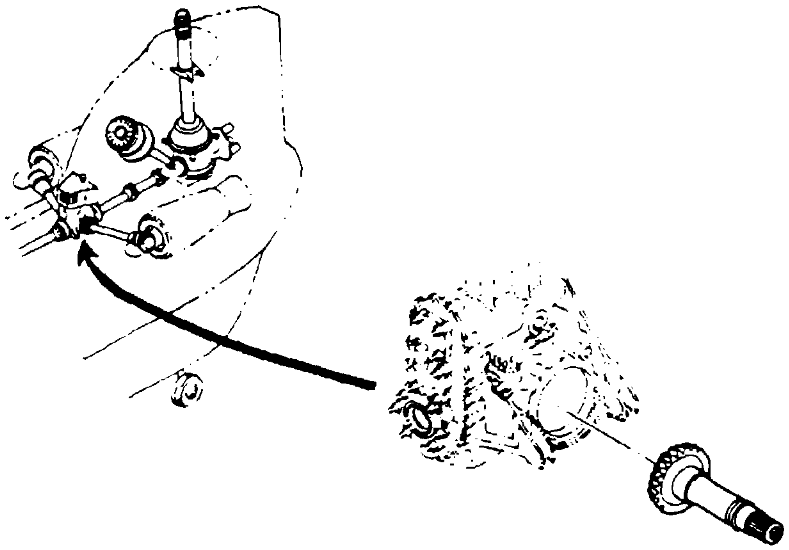

Figure 52. Location of spiral bevel input pinion gear in CH-47C transmission.

Following processing, the gear was assembled in a CH-47C combining transmission and bench patterned in accordance with normal Boeing Helicopters procedures. The bevel gear contact patterns obtained were typical of normal production. All components used in the gear box were standard production parts except that the right hand engine drive pinion was the vacuum carburized test part.

After the gear box was assembled, it was installed in the production test stand and subjected to a standard production run-in procedure. This procedure consists of running the box, in sequence, at 10 percent load and full speed for one-half hour, at 50 percent load and full speed for one-half hour, and at 100 percent load and full speed for one hour. The load run-in is followed by a visual inspection of the gear tooth contact patterns by removing only the pinion cartridge from the housing.

Subsequent to the production run-in, the gear box was reinstalled in the test stand and run for 20 hours at 100 percent of the single engine power and speed rating. During this running, all standard instrumentation (measuring oil temperature and pressure, ambient air temperature, shaft torque, etc.) was operational.

The gear box was then removed from the test cell, completely disassembled, and visually inspected. The condition of the vacuum carburized gear and all other components was typical of that observed on other gear boxes after similar loading conditions. No distress of any kind was observed, and all parts were in acceptable condition.

Metallurgical evaluations (both destructive and nondestructive) were conducted on the gear after the test. These evaluations included the following: magnetic particle inspection; temper etch inspection (to detect grinding burns); chemical composition; case and core microstructures; effective case depths and surface and core hardnesses; dimensional checks of the gear teeth root fillets; carbon content of the carburized case as a function of depth from the gear tooth surface; and a residual stress profile of a gear tooth. All of these items conformed to the requirements of the engineering drawing and related specifications. No cracks or temper burns were found during the magnetic particle or temper etch inspections, respectively. The chemical composition conformed to the requirements of Boeing Helicopters Specification BMS 7-249C, and the carbon content as a function of distance from a tooth flank surface was similar to that for a conventionally carburized gear. The residual stress profile was also similar to that for a conventionally carburized and shot peened gear. The case and core microstructures, shown in Figures 53 and 54 were also similar to those of a conventionally carburized gear. A closer view of the vacuum carburized gear teeth is shown in Figure 55. The appearance of the teeth surfaces is the same as that of a conventionally carburized gear. The evaluations are listed in the Boeing Helicopters Materials Engineering Laboratory Report number 88-164 found in Appendix T.

5.3.2 Implementation Plan

Implementation of vacuum carburization into the Aerospace gear industry could be relatively easily accomplished. As discussed previously in this report, the two spiral bevel gears produced in Phase III were manufactured alongside other gears of the same type, with the only exception being the use of a vacuum carburization procedure in place of a conventional carburization procedure. It should be noted that vacuum carburization was not conducted in a laboratory, but in an actual production environment at Summit Gear Corp. Use of this vacuum carburization procedure significantly reduced the amount of time needed to produce these two gears compared to that required to produce those in the same group that were conventionally carburized. All other production processes, such as grinding, heat treatment, and inspection, were the same for all gears.

Six items have been identified as requiring modification to allow the use of vacuum carburization in production. Each is discussed separately below.

1. Develop a vacuum carburization specification for AISI 9310. Boeing Helicopters carburizing and hardening specification for 9310, D210-12023-1, would be ammended to include the vacuum process as a second carburization method. To distinguish between the two carburization methods, the vacuum process would be identified as Type II, and the conventional process would be identified as Type I.

Figure 53. Case microstructure of vacuum carburized 9310 spiral bevel gear. Structure is primarily tempered martensite.

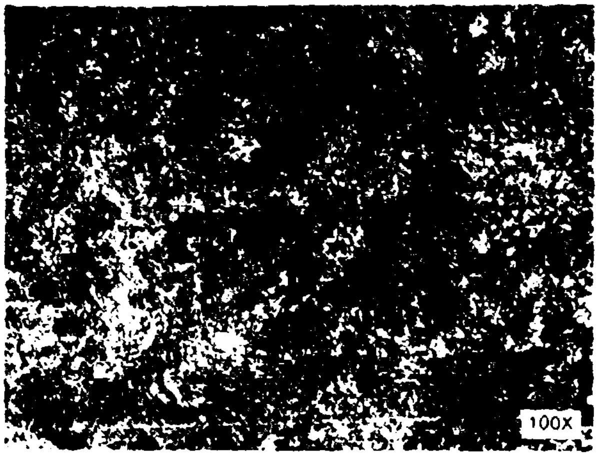

Figure 54. Core microstructure of vacuum carburized 9310 spiral bevel gear. Structure is primarily tempered martensite.

Figure 55. Vacuum carburized 9310 gear tooth surface.

All of the the details of the process including times and temperatures; gas type, pressure, and flow rates; etc., would be clearly specified.

2. Alter part drawings to indicate that the part is to be manufactured by vacuum carburization. The drawing note concerning carburization method would be changed to reflect the vacuum carburization method, as mentioned in number 1 above.

3. Alter manufacturing plans to change the carburization procedure from the conventional method to the vacuum method. The manufacturing plan for each part/vendor would be changed to detail how each would specifically produce the gear. Included would be all times and temperatures; gas type, pressure, and flow rates; and all other details of the method.

   In addition, manufacturing plans may be altered to allow less stock removal during final grinding, thus further decreasing gear production time. Any change in grinding stock would only be allowed, however, after careful evaluation of the amount of part warpage that occurs during vacuum carburization compared to that which occurs during conventional carburization. If it is found that the shorter vacuum carburization time does not allow for as much part warpage as the longer conventional caburization method, then a reduction in the grinding stock may be allowed.

4. Vendors and related equipment must be qualified. This is a standard procedure at Boeing Helicopters when any new vendor or equipment is used to produce parts. The vendor would be surveyed and all production processes would be audited to ensure that each conformed to the applicable Boeing Helicopters specifications.

5. Initially process small gears with simple geometries to ensure process stability. Once the process has been found to be stable at a particular vendor, more complex, critical gears would be produced.

6. Conduct a metallurgical evaluation/qualification of one part of each part type that is vacuum carburized. This is a standard procedure at Boeing Helicopters and is done when any significant process change has occurred or a new vendor is producing parts.

An ongoing evaluation of the performance of vacuum carburized gears would also be conducted through an examination of parts brought in for routine overhaul. Selected parts would be traced and the performance compared to that obtained from conventionally carburized parts of the same type with a similar service history and time.

All other items associated with the production of these gears, such as heat treatment, machining, grinding, surface treatments, etc., would remain unchanged.

Boeing Helicopters has a great interest in furthering the development/use of vacuum carburization, and suggests that the implementation plan discussed above be funded. This topic is discussed in the Recommendations Section 7.

5.4 PHASE IV - FURTHER DEVELOPMENT OF THE VACUUM CARBURIZATION PROCEDURE FOR VASCO X2M

As previously mentioned in Sections II and 5.4.1 of this report, this fourth phase was added to the program during the Phase I effort so that optimization of the vacuum carburization procedure for the Vasco X2M material could be continued in parallel with the gear testing of the 9310 material. During the originally planned Phase I effort, the vacuum carburization procedure was optimized for 9310, but not for X2M. During this Phase, the vacuum carburization procedure for X2M was further developed, but due to cost and scheduling restrictions, was not optimized. Because of this, the majority of the gear and gear element testing that was conducted on 9310 (see paragraphs 5.2 and 5.3) was not conducted on X2M. The following paragraphs describe the results of the additional X2M vacuum carburization evaluations.

Six trial vacuum carburization cycles were conducted in which the times and temperatures were varied to try and develop a vacuum carburization procedure that would yield an optimum case microstructure. The results of these runs, which were identified as numbers IV-1 through IV-6, are discussed below.

In the first cycle, IV-1, test slugs similar in configuration to those utilized in Phase I were exposed to the following cycle and then metallurgically evaluated:

CYCLE IV-1

1. Heat to 1,900°F in a vacuum and hold for 35 minutes to stabilize temperature.
2. Cool to 1,800°F and hold for 10 minutes.
3. Carburize at 1,800°F for 15 minutes.
4. Diffuse at 1,800°F for 60 minutes.
5. Gas quench, and hold for 10 minutes, 250 Torr at 36 CFM of methane gas.

The case microstructure resulting from this cycle consisted of tempered martensite with a heavy carbide network located in the grain boundaries, which was not acceptable.

In an attempt to reduce the amount of carbides in the grain boundaries, the following cycle (IV-2) was run.

CYCLE IV-2

1. Heat to 1,900°F and hold for 35 minutes.
2. Cool to 1,650°F and hold for 10 minutes.
3. Carburize at 1,650°F for 240 minutes, 650 CFM methane/propane, 175 Torr.
4. Diffuse at 1,800°F for 60 minutes.
5. Nitrogen quench.

The case microstructure of the material from this cycle also contained the carbide network at the grain boundaries similar to that resulting from Cycle IV-1.

In the third cycle, IV-3, the test slugs were carburized at a higher temperature and a shorter time than that used in run IV-2, followed by several subcritical anneals, as shown.

CYCLE V-3

1. Heat to 1,900°F and hold for 35 minutes.
2. Cool to 1,800°F and hold for 10 minutes.
3. Carburize at 1,800°F for 15 minutes, 360 CFM methane/propane, 250 Torr.
4. Diffuse at 1,800°F for 60 minutes.
5. Gas quench.
6. Anneal at 1,380°F for 120 minutes.
7. Cool to 1,150°F and hold for 120 minutes.
8. Heat to 1,380°F and hold for 120 minutes.
9. Cool to 1,150°F and hold for 120 minutes.
10. Air cool.

This cycle did not remove the heavy carbide network at the grain boundaries, as seen in Figure 56 and 57. To again try and reduce the carbide network, the carburization temperature was reduced to 1,700°F, and the carburization time was increased to 60 minutes, resulting in cycle IV-4 shown.

CYCLE IV-4

1. Heat to 1,900°F and hold for 35 minutes.
2. Cool to 1,700°F and hold for 10 minutes.
3. Carburize at 1,700°F for 60 minutes.
4. Diffuse at 1,800°F for 15 minutes.
5. Gas quench.

Evaluation of the case microstructure resulting from cycle IV-4 revealed a region of martensite needles at the surface of the test slugs with a carbide network in the grain boundaries immediately below this region, as seen in Figure 58.

Figure 56. Case microstructure of X2M resulting from vacuum carburization run IV-3

Figure 57. Higher magnification of the microstructure shown in Figure 56.

Figure 58. Case microstructure of X2M resulting from vacuum carburization run IV-4.

To eliminate the martensite needles and reduce or eliminate the carbide network, the diffusion time was altered and a stress relief and temper was added to create the desired case microstructure. The resultant cycle (IV-5) was as follows:

1. Heat to 1,900°F and hold for 35 minutes.
2. Cool to 1,700°F and hold for 10 minutes.
3. Carburize at 1,700°F for 180 minutes, 75 CFH, 175 Torr, 10 propane +65 methane.
4. Diffuse at 1,700°F for 180 minutes.
5. Gas quench.
6. Stress relieve at 1,150°F for 90 minutes.
7. Heat to 1,850°F and hold for 30 minutes.
8. Oil quench.
9. Freeze to -120 and hold for 120 minutes.
10. Double temper at 600 for 120 minutes each.

Evaluation of the microstructure resulting from Cycle IV-5 showed that the martensite needles were eliminated and that the heavy carbide network had been reduced slightly, as seen in Figure 59.

The reduction in the amount of carbide network resulting from cycle IV-5 suggested that increasing the time and/or number of tempers could further reduce or eliminate the carbide network. Incorporation of this idea in the carburization procedure resulted in Cycle IV-6 shown below.

1. Heat to 1,900°F and hold for 30 minutes.
2. Cool to 1,800°F and hold for 10 minutes.
3. Carburize at 1,800°F for 60 minutes.
4. Diffuse at 1,800°F for 15 minutes.
5. Gas quench.
6. Stress relieve at 1,250°F for 90 minutes.
7. Heat to 1,850°F and hold for 95 minutes.
8. Oil quench.
9. Freeze to -120°F and hold for 180 minutes.
10. Double temper at 600°F for 120 minutes each.

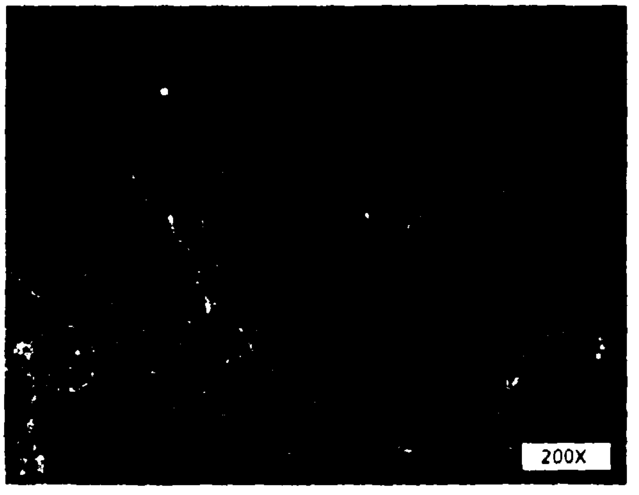

Figure 59. Case microstructure of X2M resulting from vacuum carburization run IV-5.

11. Reheat to 1,850°F and hold for 45 minutes.
12. Oil quench.
13. Freeze to -120°F and hold for 180 minutes.
14. Double temper at 600°F for 120 minutes each.
15. Reheat to 1,850°F and hold for 45 minutes.
16. Oil quench.
17. Freeze to -120°F and hold for 180 minutes.
18. Double temper at 600°F for 120 minutes each.

The case microstructure resulting from Cycle IV-6 is seen in Figure 60. The amount of carbide network in the grain boundaries was reduced compared to that found previously in the case of the Cycle IV-5 material. A hardness profile taken on the test slug at the flank, root, and root fillet showed that an acceptable hardness was obtained at the surface of the part and that the hardness was uniform in these three areas at various depths.

Using Cycle IV-6, single tooth bending fatigue test gears were produced and evaluated. The results of this testing are shown in Figure 61. Comparison of this data with that of X2M with heavy carbide from Phase I shown in Figure 41 indicates that the improved procedure increased the bending fatigue capacity of the material slightly. However, the increase was not great enough so that it was equal to that of baseline material. This data indicated that further development of the vacuum carburization procedure for X2M was necessary to optimize properties. However, cost and scheduling restrictions caused this effort to be discontinued at this point.

Figure 60. Case microstructur of X2M resulting from vacuum carburization run IV-6.

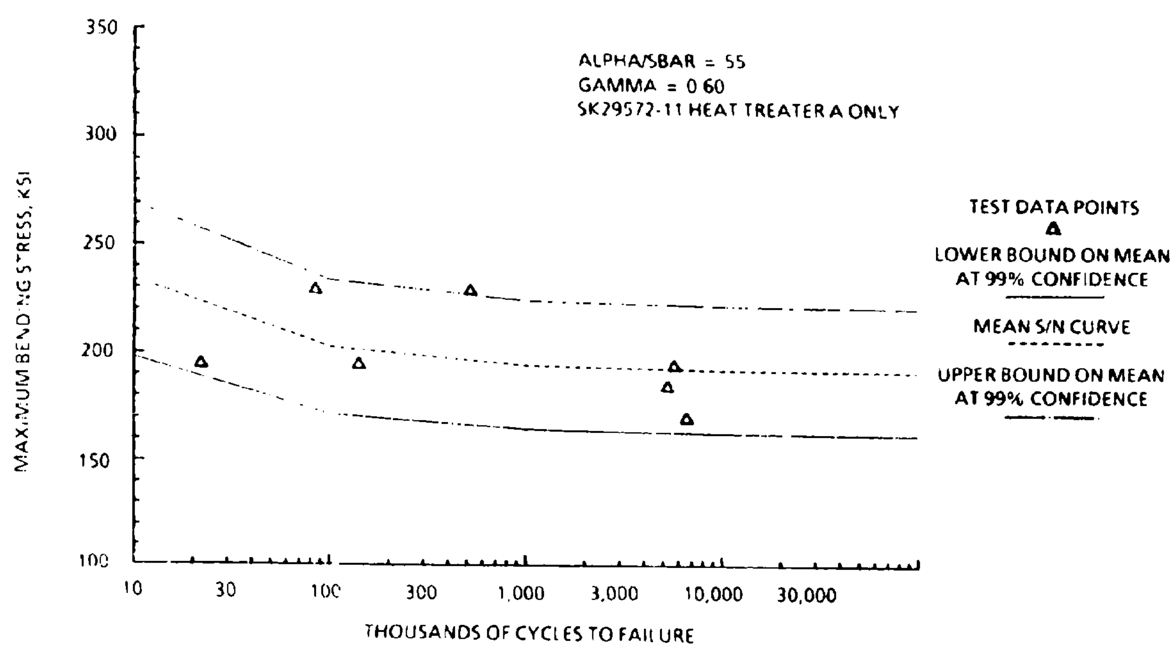

Figure 61. Single tooth bending fatigue life data of X2M vacuum carburization by run IV 6

6. SUMMARY AND CONCLUSION

6.1 AISI 9310 MATERIAL

1. A vacuum carburization procedure was successfully developed and optimized for the AISI 9310 alloy. This was accomplished on test coupons right on through to a production component. The time required to carburize this material was decreased approximately 60 percent. The resultant case microstructure was comparable to that of conventionally carburized material.

2. The single tooth bending fatigue life and scoring resistance of the vacuum carburized 9310 material was equivalent to that of conventionally carburized 9310 material. The B90 rolling contact fatigue life of the vacuum carburized 9310 material obtained from gear roller tests was also equivalent to that of conventionally carburized 9310. The B50 and B10 rolling contact fatigue lives of the vacuum carburized 9310 material was slightly less than that of conventionally carburized 9310.

3. The surface durability of the vacuum carburized 9310 material was evaluated through spiral bevel and spur gear testing, and was found to be equivalent to that of conventionally carburized material.

4. A production spiral bevel input pinion gear for a Boeing Helicopters CH-47C Combining Transmission was vacuum carburized and heat treated according to the processing conditions developed in this program, and then tested in an actual transmission. Post test evaluations of the test data and the gear showed that it performed as well as a conventionally carburized gear. These results indicate that use of the vacuum carburization process developed in this program for 9310 can produce gears in a shorter period of time compared to conventional carburization and that acceptable properties can be obtained from such a gear.

5. A plan was developed which will allow the vacuum carburization process to be implemented into the helicopter transmission gear production process.

6.2 VASCO X2M MATERIAL

1. A nonoptimized vacuum carburization procedure was developed for the Vasco X2M alloy. The case microstructure resulting from this nonoptimized procedure contained a uniform, continuous carbide network which had deleterious effects on the alloys properties. However, this uniform case microstructure was obtained without the preoxidation procedure which is required to obtain a uniform case microstructure in conventional carburization. Further efforts are required to optimize this process so that acceptable mechanical properties may be obtained.

2. The single tooth bending life of the vacuum carburized X2M material was less than that of conventionally carburized X2M. This lower fatigue life was attributed to the unacceptable carbide network in the carburized case.

3. Further work is required to continue the development of an optimized vacuum carburization procedure for X2M.

General Comment

The results of the Phase I Vasco X2M gear element testing illustrate the need to fully evaluate all of the mechanical properties of a new alloy and/or process being considered for use in a gearing application. In this program, a thorough examination of all properties, i.e., single tooth bending fatigue life, scoring resistance, as well as geared roller testing, was conducted and revealed that the vacuum carburization process as developed for X2M yielded poor single tooth bending fatigue properties while at the same time yielding good geared roller properties. If only geared roller tests had been conducted and the decision to use the currently developed vacuum carburization process for X2M in production had been based solely on these results, serious problems with transmissions would have occurred.

To avoid the possibility of a material or process being used in critical components without first undergoing thorough testing, it is suggested that a specification be developed in which a minimum amount of testing be required.

These specified tests would ensure that all pertinent properties of the new alloy and/or process are fully understood and that all loading conditions normally encountered by the component be evaluated.

7. RECOMMENDATIONS

It is recommended that a follow on program to optimize the vacuum carburization procedure for the Vasco X2M alloy be funded. This alloy is currently used in large quantities by Boeing Helicopters as well as other companies. The reduction in carburization and heat treatment time would significantly reduce acquisition costs of any products incorporating this alloy. The knowledge gained from this program on vacuum carburization indicates that the procedure can be optimized and implemented into production.

8 REFERENCES

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2. Seeley & Smith, "Advanced Mechanics of Materials," John Wiley & Sons, Publisher, 1952.

3. Blok, H., "Lubrication of a Gear Design Factor," Proceedings of the International Conference of Gearing, Institute of Mechanical Engineering, 1958.

4. Cunningham, R.J., Boeing Document D301-10036-1, Vasco X2, 0.157 Carbon (BMS-7-223) Steel HLH/ATC Transmission Gear Material Evaluation. Test Results and Final Report.

5. Boeing Helicopters Interoffice Memo 8-7525-1-5472, "Metallurgical Property Comparison of Gear Steel Materials," March 31, 1978.

6. Parrish, G., "The Influence of Microstructure on the Properties of Case Carburized Component," American Society for Metals, Metals Park, OH, 1980.

7. Johnson, L.G., "The Statistical Treatment of Fatigue Experiment," Research Laboratories, General Motors Corp., April, 1959.

9. GLOSSARY

R/C	Rockwell Hardness, C Scale
ECD	Effective Case Depth
AGMA	Aerospace Gear Manufacturers Association
CFH	Cubic Feet per Hour (gas flow)
Torr	A unit of pressure equal to 1.316×10^3 atmospheres
HPSTC	Highest Point of Single Tooth Contact

10. APPENDICES

APPENDIX A CARPENTER TECHNOLOGY TEST CERTIFICATE FOR 9310 MATERIAL

CARPENTER TECHNOLOGY CORPORATION

CARTECH

P.O. BOX 662 • READING, PA. 19603

CERTIFICATE OF TESTS

DATE 9 / 18 / 81

[redacted]
TUBE TURNS DIV
CHEMETRON CORP
P O BOX 32160
LOUISVILLE KY 40232
ATTN: PURCH DEPT

CUSTOMER ORDER NO.	CARP ORDER NO.	DATE SHIPPED	WEIGHT
96693	NV3901		42750

PRODUCT DESCRIPTION	SPECIFICATION
VACUMET CONSUMET 9310 HPA & HT	BMS-7-249E TYPE 3 (7/14/78) TYPE 3 VAP 6039

SIZE 6.5000 IN. RD

HEAT NO.- 86043 INGOTS #1+2

C	MN	SI	P	S	CR	NI	MO	CU
0.11	0.60	0.25	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

CHECK CHEMISTRY

	INGOT #1	INGOT #2
C	.106	.105
MN	.59	.58
SI	.23	.22
P	.007	.007
S	.001	.001
CR	1.32	1.33
NI	3.25	3.28
MO	.15	.16
CU	.10	.12

	INGOT #1	INGOT #2
MAG PARTICLE: FREQUENCY:	0	0
SEVERITY:	0	0

JOMINY TEST

NORMALIZE TEMP [illegible], QUENCH 1500°F

INGOT #1	INGOT #2
J39 [illegible]	J40 = 1
J36 = 8	J36 = 8

EHNS GRAIN SIZE

INGOT #1	INGOT #2
5/6	6

MACROETCH: TESTED TO ASTM-A-604; MAXIMUM VALUES ARE 1A, 2A, 3A & 4A

ULTRASONIC INSPECTION: SATISFACTORY PER CARPENTER PROCEDURE S-UT-1-325 R2 (4/14/80)

JERNKONTORET INCLUSION RATINGS
METHOD D - ATTACHED

CHEKED 4
MS 3

I CERTIFY THIS INFORMATION TO BE TRUE AND CORRECT AS CONTAINED IN THE RECORDS OF
CARPENTER TECHNOLOGY CORPORATION

AUTHORIZED REPRESENTATIVE

NOTE: THE VALUES AND OTHER TECHNICAL DATA SHOWN REPRESENT THE RESULTS OF ANALYSES AND TESTS MADE ON SAMPLES COLLECTED FROM THE TOTAL LOT. ORIGINAL DATA RECORDS CAN BE [illegible] BY REFERENCE TO THE CARP ORDER NO.

CARPENTER TECHNOLOGY CORPORATION

FORM NO. 2-53-C

(6715

JERNKONTORET INCLUSION RATING

CUSTOMER Tube Turns HEAT NO. K86043 ORDER NO. M93981

GRADE 8059 SIZE 8 1/2 ○

SAMPLE IDENTITY	INCLUSION TYPE		A THIN	A THICK	B THIN	B THICK	C THIN	C THICK	D THIN	D THICK
1A			.5						.5	
	WORST FIELD	J.K. FREQUENCY	0	0	0	0	0	0	1	0
		TOTAL LENGTH	0	0	0	0	0	0	—	0
	NUMBER OF FIELDS	J.K. 1/2	0	0	0	0	0	0	—	0
		J.K. 1	0	0	0	0	0	0	—	0
		J.K. 1-1/2	0	0	0	0	0	0	0	0
		J.K. 2	0	0	0	0	0	0	0	0
	LARGEST INCLUSIONS	THICKNESS	—	—	—	—	—	—	—	—
		LENGTH	—	—	—	—	—	—	—	—
	NO. FIELDS OVER .0075" LONG		—	—	—	—	—	—	—	—

SAMPLE IDENTITY	INCLUSION TYPE		A THIN	A THICK	B THIN	B THICK	C THIN	C THICK	D THIN	D THICK
1X	WORST FIELD	J.K. FREQUENCY	0	0	0	0	0	0	1	0
		TOTAL LENGTH	0	0	0	0	0	0	—	0
	NUMBER OF FIELDS	J.K. 1/2	0	0	0	0	0	0	—	0
		J.K. 1	0	0	0	0	0	0	—	0
		J.K. 1-1/2	0	0	0	0	0	0	—	0
		J.K. 2	0	0	0	0	0	0	0	0
	LARGEST INCLUSIONS	THICKNESS	—	—	—	—	—	—	—	—
		LENGTH	—	—	—	—	—	—	—	—
	NO. FIELDS OVER .0075" LONG		—	—	—	—	—	—	—	—

SAMPLE IDENTITY	INCLUSION TYPE		A THIN	A THICK	B THIN	B THICK	C THIN	C THICK	D THIN	D THICK
2A	WORST FIELDS	J.K. FREQUENCY	0	0	0	0	0	0	1	0
		TOTAL LENGTH	0	0	0	0	0	0	—	0
	NUMBER OF FIELDS	J.K. 1/2	0	0	0	0	0	0	—	0
		J.K. 1	0	0	0	0	0	0	—	0
		J.K. 1-1/2	0	0	0	0	0	0	0	0
		J.K. 2	0	0	0	0	0	0	0	0
	LARGEST INCLUSIONS	THICKNESS	—	—	—	—	—	—	—	—
		LENGTH	—	—	—	—	—	—	—	—
	NO. FIELDS OVER .0075" LONG		—	—	—	—	—	—	—	—

SAMPLE IDENTITY	INCLUSION TYPE		A THIN	A THICK	B THIN	B THICK	C THIN	C THICK	D THIN	D THICK
2X	WORST FIELD	J.K. FREQUENCY	0	0	0	0	0	0	1	0
		TOTAL LENGTH	0	0	0	0	0	0	—	0
	NUMBER OF FIELDS	J.K. 1/2	0	0	0	0	0	0	—	0
		J.K. 1	0	0	0	0	0	0	—	0
		J.K. 1-1/2	0	0	0	0	0	0	0	0
		J.K. 2	0	0	0	0	0	0	0	0
	LARGEST INCLUSIONS	THICKNESS	—	—	—	—	—	—	—	—
		LENGTH	—	—	—	—	—	—	—	—
	NO. FIELDS OVER .0075" LONG		—	—	—	—	—	—	—	—

RATED TO: (ASTM E-45 METHOD) D

MEETS REQUIREMENTS OF: BMS 7-249

MAGNIFICATION: 100X

RATED BY: M [illegible]

DATE: 8/19/81

APPROVED BY: [illegible]

APPENDIX B CARPTENTER TECHNOLOGY TEST CERTIFICATE FOR 9310 MATERIAL

CERTIFICATE OF TESTS

CARPENTER TECHNOLOGY CORPORATION

CarTech

P.O. BOX 662 • READING, PA. 19603

NOTE
THE VALUES AND OTHER TECHNICAL DATA SHOWN REPRESENT THE RESULTS OF ANALYSES AND TESTS MADE ON SAMPLES COLLECTED FROM THE TOTAL LOT. ORIGINAL DATA RECORDS CAN BE TRACED BY REFERENCE TO THE CARP ORDER NO.

DATE 4 / 19 / 83

[redacted]

THE STEEL IMPROVEMENT & FORGE
970 E 64TH ST
CLEVELAND OH 44103

CUSTOMER ORDER NUMBER	CARPENTER ORDER NUMBER	DATE SHIPPED	CAD
569697	M98239	4/18/83	4904

PRODUCT DESCRIPTION	SPECIFICATION
VAC CONS 9310 HF ANL RT FORGE BAR	BOEING BMS 7-249-8 (7/14/80) TYPE 3

1 BAR

SIZE 5.0000 IN. RD
INGOT #2
HEAT NO.- 86470

C	MN	SI	P	S	CR
0.11	0.60	0.24	0.005	0.002	1.32
NI	MO	CU			
3.23	0.14	0.03			

MAG PARTICLE: FREQUENCY 0/SEVERITY 0

EHNS GRAIN SIZE - 8

JOMINY TEST
NORMALIZE TEMP 1700°F, QUENCH 1500°F
INGOT #2
J40 = 1
J38 = 8

ULTRASONIC INSPECTION - SATISFACTORY PER CARPENTER PROCEDURE 5-UT-1-325, R2 (4/14/80)

CHECK CHEMISTRY

C	.110
MN	.57
SI	.26
P	.008
S	.002
CR	1.34
NI	3.27
MO	.14
CU	.04

CMP/IN 4

Caroline M. Sacco
AUTHORIZED REPRESENTATIVE
CARPENTER TECHNOLOGY CORPORATION

CARPENTER TECHNOLOGY CORPORATION FORM NO. 2-53-C

JERNKONTORET INCLUSION RATING

COMP. Car Tech HEAT NO. K86670-2 ORDER NO. W43379

GRADE 8059 SIZE 4140

SAMPLE IDENTITY	INCLUSION TYPE		A THIN (1.5)	A THICK (.0)	B THIN (1.5)	B THICK (0)	C THIN (1.5)	C THICK (0)	D THIN (1.5)	D THICK (1)
2A	WORST FIELD	J.K. FREQUENCY	0	0		0			1	0
		TOTAL LENGTH	0	0	0	0		0	—	0
	NUMBER OF FIELDS	J.K. 1/2	0	0	0	0		0		0
		J.K. 1	0	0	0	0	0	0	—	0
		J.K. 1-1/2	0	0	0	0	0	0		0
		J.K. 2	0	0	0	0	0	0	0	0
	LARGEST INCLUSIONS	THICKNESS	—	—	—	—		—	0	—
		LENGTH	—	—	—	—	—	—	—	—
	NO. FIELDS OVER .0075" LONG		—	—	—	—	—	—	—	—

SAMPLE IDENTITY	INCLUSION TYPE		A THIN	A THICK	B THIN	B THICK	C THIN	C THICK	D THIN	D THICK
2X	WORST FIELD	J.K. FREQUENCY	0	0	0	0		0	1	
		TOTAL LENGTH	0	0	0	0	0		—	0
	NUMBER OF FIELDS	J.K. 1/2	0	0	0	0	0	0	—	0
		J.K. 1	0	0	0	0	0	0	—	0
		J.K. 1-1/2	0	0	0	0	0	0	0	0
		J.K. 2	0	0	0	0	0	0	0	0
	LARGEST INCLUSIONS	THICKNESS	—	—	—	—	—	—	—	—
		LENGTH	—	—	—	—	—	—	—	—
	NO. FIELDS OVER .0075" LONG		—	—	—	—	—	—	—	—

SAMPLE IDENTITY	INCLUSION TYPE		A THIN	A THICK	B THIN	B THICK	C THIN	C THICK	D THIN	D THICK
	WORST FIELDS	J.K. FREQUENCY								
		TOTAL LENGTH								
	NUMBER OF FIELDS	J.K. 1/2								
		J.K. 1								
		J.K. 1-1/2								
		J.K. 2								
	LARGEST INCLUSIONS	THICKNESS								
		LENGTH								
	NO. FIELDS OVER .0075" LONG									

SAMPLE IDENTITY	INCLUSION TYPE		A THIN	A THICK	B THIN	B THICK	C THIN	C THICK	D THIN	D THICK
	WORST FIELD	J.K. FREQUENCY								
		TOTAL LENGTH								
	NUMBER OF FIELDS	J.K. 1/2								
		J.K. 1								
		J.K. 1-1/2								
		J.K. 2								
	LARGEST INCLUSIONS	THICKNESS								
		LENGTH								
	NO. FIELDS OVER .0075" LONG									

RATED TO: (ASTM E-45 METHOD)

MEETS REQUIREMENTS OF: BMS 7-249

SPECIFICATION: 100X

DATE: 3/11/82

RATED BY: [illegible signature]

APPROVED BY: [illegible signature]

APPENDIX C CARPENTER TECHNOLOGY TEST CERTIFICATE FOR X2M MATERIAL

CARPENTER TECHNOLOGY CORPORATION

P.O. BOX 662 • READING, PA. 19603

CERTIFICATE OF TESTS

DATE 3 / 11 /82

[redacted]

THE STEEL IMPROVEMENT & FORGE
970 E 64TH ST
CLEVELAND OH 44103

CUSTOMER ORDER NO	CARP ORDER NO	DATE SHIPPED	WEIGHT
S-48069	M98816 RPT		

PRODUCT DESCRIPTION	SPECIFICATION
VIM VAR 7-225 HAR FORG BAR	BOEING BMS-7-223C (1/15/79) TYPE 3 REFER O.V.P.

SIZE 4.5000 IN. RD

HEAT NO.- 86510

C	MN	SI	P	S	CR
0.14	0.31	0.08	0.007	0.001	5.30

MO	W	V
1.38	1.34	0.45

MACRO ETCH TESTED AND APPROVED per ASTM A 604, Class 1A, 2A, 3A & 4A.
Magnetic Particle: Frequency/Severity = 0/0 Grain Size: 6/7
Ultrasonic Inspection - Satisfactory per Carpenter Procedure S-UT-1-325 Rev. 2

Chemistry Check:

	C	
2A	.15	(Top, Middle & Bottom)
2B	.15	
2BO	.15	

JERNKONTORET INCLUSION RATINGS
METHOD D

	A THIN	A THICK	B THIN	B THICK	C THIN	C THICK	D THIN	D THICK
Avg.	0	0	0	0	0	0	1	0

Ingot #2
CMP/IN 3
WS 3

I CERTIFY THIS INFORMATION TO BE TRUE AND CORRECT AS CONTAINED IN THE RECORDS OF
CARPENTER TECHNOLOGY CORPORATION

AUTHORIZED REPRESENTATIVE

NOTE: THE VALUES AND OTHER TECHNICAL DATA SHOWN REPRESENT THE RESULTS OF ANALYSES AND TESTS MADE ON SAMPLES COLLECTED FROM THE TOTAL LOT ... REFERENCE TO THE CARP. ORDER NO.

CARPENTER TECHNOLOGY CORPORATION

FORM NO. 2-53-2

7962

JERNKONTORET INCLUSION RATING

CUSTOMER [illegible] HEAT NO K86510-2 ORDER NO M28816 Zst

GRADE 8091 SIZE 5" O

SAMPLE IDENTITY	INCLUSION TYPE		A 1.5 THIN	A 0 THICK	B 1.5 THIN	B 0 THICK	C 1.5 THIN	C 0 THICK	D 1.5 THIN	D 1 THICK
2A	WORST FIELD	J.K. FREQUENCY	0	0	0	0	0	0	1	0
		TOTAL LENGTH	0	0	0	0	0	0	–	0
	NUMBER OF FIELDS	J.K. 1/2	0	0	0	0	0	0	–	0
		J.K. 1	0	0	0	0	0	0	–	0
		J.K. 1-1/2	0	0	0	0	0	0	0	0
		J.K. 2	0	0	0	0	0	0	0	0
	LARGEST INCLUSIONS	THICKNESS	0	0	0	0	0	0	–	0
		LENGTH	0	0	0	0	0	0	–	0
	NO. FIELDS OVER .0075" LONG		0	0	0	0	0	0	–	0

SAMPLE IDENTITY	INCLUSION TYPE		A THIN	A THICK	B THIN	B THICK	C THIN	C THICK	D THIN	D THICK
2X	WORST FIELD	J.K. FREQUENCY	0	0	0	0	0	0	1	0
		TOTAL LENGTH	0	0	0	0	0	0	–	0
	NUMBER OF FIELDS	J.K. 1/2	0	0	0	0	0	0	–	0
		J.K. 1	0	0	0	0	0	0	–	0
		J.K. 1-1/2	0	0	0	0	0	0	0	0
		J.K. 2	0	0	0	0	[illegible]	0	0	0
	LARGEST INCLUSIONS	THICKNESS	0	0	0	0	[illegible]	0	–	0
		LENGTH	8	8	0	0	[illegible]	0	–	0
	NO. FIELDS OVER .0075" LONG		8	8	0	0	0	0	–	0

SAMPLE IDENTITY	INCLUSION TYPE		A THIN	A THICK	B THIN	B THICK	C THIN	C THICK	D THIN	D THICK
	WORST FIELDS	J.K. FREQUENCY								
		TOTAL LENGTH								
	NUMBER OF FIELDS	J.K. 1/2								
		J.K. 1								
		J.K. 1-1/2								
		J.K. 2								
	LARGEST INCLUSIONS	THICKNESS								
		LENGTH								
	NO. FIELDS OVER .0075" LONG									

SAMPLE IDENTITY	INCLUSION TYPE		A THIN	A THICK	B THIN	B THICK	C THIN	C THICK	D THIN	D THICK
	WORST FIELD	J.K. FREQUENCY								
		TOTAL LENGTH								
	NUMBER OF FIELDS	J.K. 1/2								
		J.K. 1								
		J.K. 1-1/2								
		J.K. 2								
	LARGEST INCLUSIONS	THICKNESS								
		LENGTH								
	NO. FIELDS OVER .0075" LONG									

RATED TO: (ASTM E-45 METHOD) D

MEETS REQUIREMENTS OF: BMS 7-223

MAGNIFICATION: 100X

DATE: 12/18/87

RATED BY: C Frankin

APPROVED BY: [illegible]

Best Available Copy

APPENDIX D CARPENTER TECHNOLOGY TEST CERTIFICATE FOR 9310 MATERIAL

CERTIFICATE OF TESTS

CARPENTER TECHNOLOGY CORPORATION

CarTech

P.O. BOX 662 • READING, PA. 19603

NOTE: THE VALUES AND OTHER TECHNICAL DATA SHOWN REPRESENT THE RESULTS OF ANALYSES AND TESTS MADE ON SAMPLES COLLECTED FROM THE TOTAL LOT. ORIGINAL DATA RECORDS CAN BE TRACED BY REFERENCE TO THE CARP. ORDER NO.

DATE 6 / 13 / 83

BOEING VERTOL COMPANY
DIV BOEING COMPANY
P O BOX 16858
PHILADELPHIA PA 19142

PHL

CUSTOMER ORDER NUMBER	CARPENTER ORDER NUMBER	DATE SHIPPED	WEIGHT
KT 814225	M63364	6/7/83	545#

PRODUCT DESCRIPTION	SPECIFICATION
VACUMET CONS 9310 HF ANL & RT	BMS 7-249B (7/14/78) TYPE 3 & VAP 8059

SIZE 8.5000 IN. RD INGOT #2

HEAT NO.- 87885

C	MN	SI	P	S	CR
0.10	0.56	0.24	0.005	0.001	1.32

NI	MO	CU
3.27	0.14	0.04

CHECK CHEMISTRY

C	.104
MN	.49
SI	.25
P	.004
S	.001
CR	1.33
NI	3.30
MO	.15
CU	.04

MAG PARTICLE: FREQUENCY - 0 / SEVERITY - 0

JOMINY TEST
NORMALIZE TEMP 1700°F, QUENCH 1500°F
J38 = 1
J35 = 8

EHNS GRAIN SIZE - 5/6

MACROETCH: TESTED TO ASTM-A-604;
MAXIMUM VALUES ARE 1A,2A,3A & 4A

ULTRASONIC INSPECTION - SATISFACTORY PER CARPENTER PROCEDURE S-UT-I-325, R2 (4/14/80)

JERNKONTORET INCLUSION RATINGS
METHOD D - ATTACHED

CMP/IN 3

Caroline M. Sacco

I CERTIFY THE ABOVE INFORMATION TO BE TRUE AND CORRECT AS CONTAINED IN THE RECORDS OF CARPENTER TECHNOLOGY CORPORATION

AUTHORIZED REPRESENTATIVE

RDG. TEST REPORT # 019257

CERT TEST CODE "250"

TEST PIECE SIZE 8 1/2"

TEST PIECE SHAPE RL

87X85

M47554

GRADE # 8059

INGOT #

ITEM # 1

HT SPEC # 20

TEST SUBMISSION DATE 10/29/82

SAMPLE IDENTITY (T # / BAR #)	INCLUSION TYPE		A THIN (1.5)	A THICK (0)	B THIN (1.5)	B THICK (0)	C THIN (1.5)	C THICK (0)	D THIN (1.5)	D THICK (/)
7	WORST FIELD	J. K. FREQUENCY	0	0	0	0	0	0	1	0
		TOTAL LENGTH	0	0	0	0	0	0	—	0
	NUMBER OF FIELDS	J. K. 1/2	0	0	0	0	0	0	—	0
		J. K. 1	0	0	0	0	0	0	—	0
		J. K. 1-1/2	0	0	0	0	0	0	0	0
		J. K. 2	0	0	0	0	0	0	0	0
	LARGEST INCLUSIONS	THICKNESS	—	—	—	—	—	—	—	—
		LENGTH	—	—	—	—	—	—	—	—
	NO. FIELDS OVER .0075" LONG		—	—	—	—	—	—	—	—

T # / BAR #	INCLUSION TYPE		A THIN	A THICK	B THIN	B THICK	C THIN	C THICK	D THIN	D THICK
X	WORST FIELD	J. K. FREQUENCY	0	0	0	0	0	0	1	0
		TOTAL LENGTH	0	0	0	0	0	0	—	0
	NUMBER OF FIELDS	J. K. 1/2	0	0	0	0	0	0	—	0
		J. K. 1	0	0	0	0	0	0	—	0
		J. K. 1-1/2	0	0	0	0	0	0	0	0
		J. K. 2	0	0	0	0	0	0	0	0
	LARGEST INCLUSIONS	THICKNESS	—	—	—	—	—	—	—	—
		LENGTH	—	—	—	—	—	—	—	—
	NO. FIELDS OVER .0075" LONG		—	—	—	—	—	—	—	—

T # / BAR #	INCLUSION TYPE		A THIN	A THICK	B THIN	B THICK	C THIN	C THICK	D THIN	D THICK
	WORST FIELD	J. K. FREQUENCY								
		TOTAL LENGTH								
	NUMBER OF FIELDS	J. K. 1/2								
		J. K. 1								
		J. K. 1-1/2								
		J. K. 2								
	LARGEST INCLUSIONS	THICKNESS								
		LENGTH								
	NO. FIELDS OVER .0075" LONG									

T # / BAR #	INCLUSION TYPE		A THIN	A THICK	B THIN	B THICK	C THIN	C THICK	D THIN	D THICK
	WORST FIELD	J. K. FREQUENCY								
		TOTAL LENGTH								
	NUMBER OF FIELDS	J. K. 1/2								
		J. K. 1								
		J. K. 1-1/2								
		J. K. 2								
	LARGEST INCLUSIONS	THICKNESS								
		LENGTH								
	NO. FIELDS OVER .0075" LONG									

TEMP	TIME	Q	TEMP	TIME	Q	TEMP	TIME	Q	TEMP	TIME	Q

QTY 100%

BMS 7-249

ST COMPLETION DATE [redacted] D-2

SPT. TEST #

TEST PIECES

R. Franken

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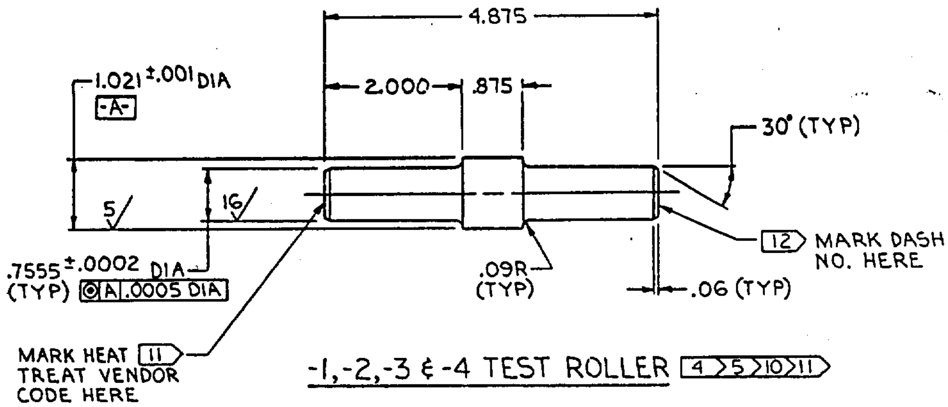
APPENDIX E TEST ROLLER SPECIMEN FOR GEARED ROLLER TEST, DRAWING NUMBER SK20895



-1,-2,-3 & -4 TEST ROLLER 4 5 10 11

NOTES

2. MAXIMUM SURFACE ROU
3. BREAK ALL SHARP EDG OR CHAMFER OF .010 T THIS DIMENSION IS SAT
4 NITAL ETCH INSPECTION
5 FLUORESCENT MAGNETIC BAC 5424 CLASS A.
6 MATERIAL: 9310 STEEL
7 MATERIAL: 5CR-1.4 MO TYPE III.
8 HEAT TREATMENT
A. VACUUM CARBURIZE
B. CARBURIZED CASE
C. EFFECTIVE CASE DE GRINDING .065-.08
D. CORE HARDNESS R
E. DRAW AT 550°F ±2 FINAL GRIND.
9 HEAT TREATMENT
A. VACUUM CARBURIZ
B. CARBURIZED CASE
C. EFFECTIVE CASE D GRINDING .065-.08
D. CORE HARDNESS R
E. DRAW AT 300°F ±2 FINAL GRIND.
10 FIFTEEN (15) TEST ROLL ARE TO BE VACUUM CAR EACH VENDOR.
VENDOR "A"-SUMMIT
VENDOR "B"-C.I. HAYE
11 HEAT TREAT VENDORS IDENTIFYING LETTER "A"
12 MACHINING VENDOR TO ONLY (-1,-2,-3 OR -4).

QTY REQD	QTY REQD	FSCM NO	PART OR IDENTIFYING NUMBER	NOM
			SK20895-4	TES
			SK20895-3	TES
			SK20895-2	TES
			SK20895-1	TES

DIMENSIONING & TOLERANCING PER ANSI Y14.5
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES ANGLES ±2°
DECIMALS .XX ±.02
DECIMALS .XXX ±.005

FASTENER CODES

PART NUMBER | NEXT ASSY | USED ON | EFFECTIVITY | REV LTR
APPLICATION

1

DWG NO SK20895 -

REVISIONS

REV	DESCRIPTION	DATE	APPROVED

NOTES

1. [illegible]

2. MAXIMUM SURFACE ROUGHNESS 125/ EXCEPT AS NOTED.
3. BREAK ALL SHARP EDGES NOT SPECIFIED TO A RADIUS OR CHAMFER OF .010 TO .020. VISUAL INSPECTION OF THIS DIMENSION IS SATISFACTORY.
4. NITAL ETCH INSPECTION PER BAC 5436.
5. FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BAC 5424 CLASS A.
6. MATERIAL: 9310 STEEL PER BMS 7-249 TYPE III.
7. MATERIAL: 5CR-1.4 MO 1.35W STEEL PER BMS 7-223 TYPE III.
8. HEAT TREATMENT
   - A. VACUUM CARBURIZE ALL OVER.
   - B. CARBURIZED CASE HARDNESS ROCKWELL C 60-64.
   - C. EFFECTIVE CASE DEPTH AT ROCKWELL C 50 AFTER GRINDING .065-.085.
   - D. CORE HARDNESS ROCKWELL C 36-44.
   - E. DRAW AT 550°F ±25°F FOR FOUR HOURS AFTER FINAL GRIND.
9. HEAT TREATMENT
   - A. VACUUM CARBURIZE ALL OVER.
   - B. CARBURIZED CASE HARDNESS ROCKWELL C 60-64.
   - C. EFFECTIVE CASE DEPTH AT ROCKWELL C 50 AFTER GRINDING .065-.085.
   - D. CORE HARDNESS ROCKWELL C 32-42.
   - E. DRAW AT 300°F ±25°F FOR FOUR HOURS AFTER FINAL GRIND.
10. FIFTEEN (15) TEST ROLLERS OF EACH DASH NUMBER ARE TO BE VACUUM CARBURIZED AND HARDENED BY EACH VENDOR.

    VENDOR "A"-SUMMIT GEAR CO., PLYMOUTH, MINN.

    VENDOR "B"-C.I. HAYES CO., CRANSTON, R.I.
11. HEAT TREAT VENDORS ARE TO ADD APPROPRIATE IDENTIFYING LETTER "A" OR "B" TO PART.
12. MACHINING VENDOR TO MARK PART DASH NUMBER ONLY (-1, -2, -3 OR -4).

ASH
RE

QTY REQD	QTY REQD	FSCM NO	PART OR IDENTIFYING NUMBER	NOMENCLATURE OR DESCRIPTION	MATERIAL AND SPECIFICATION	HT TR	FINISH	PT MK	CALC UNIT WT	ACT UNIT WT	REV LTR
			SK20895-4	TEST ROLLER	6 FROM MILL HEAT D	9		VE			
			SK20895-3	TEST ROLLER	6 FROM MILL HEAT C	9		VE			
			SK20895-2	TEST ROLLER	7 FROM MILL HEAT B	8		VE			
			SK20895-1	TEST ROLLER	7 FROM MILL HEAT A	8		VE			

PARTS LIST

DIMENSIONING & TOLERANCING PER ANSI Y14.5

UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN INCHES
TOLERANCES: ANGLES ±2°
DECIMALS .XX ±.02
DECIMALS .XXX ±.005
RIVET & BOLT EDGE MARGIN ±.05
BEND RADII ±.01 ON .03 & .06
±.03 ON .09 & GREATER
SHEET METAL CORNER RADII
INT .10 +.03 -.00 EXT .22 +.03 -.22
DIMENSIONS AND SURFACE TEXTURE DESIGNATIONS APPLY BEFORE PLATING OR FINISH COATINGS

FASTENER CODES

REVIEW & APPROVAL		
DWG QUAL		
STRUCT		
MATL & PRCS	R. CUNNINGHAM	9-2-82
WTS		
CHANGE/ITEM NUMBER		
DRAWING DATE		

CONTRACT NUMBER DAAG-32-C-0034

DWN	F.J. LOKAJ	7-21-82
CHK	[signature]	9-2-82
ENGR	[signature]	9-2-82
GRP	[signature]	9-2-82
PROJECT APPROVAL	[signature]	9-2-82

BOEING VERTOL COMPANY
A DIVISION OF THE BOEING COMPANY
PHILADELPHIA, PENNSYLVANIA 19142

TEST ROLLER, VACUUM CARBURIZATION PROGRAM

SIZE D FSCM NO. 77272 SK20895

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DRAWING RECORDS CLERK

DWG ORIG OF RCRD 7484

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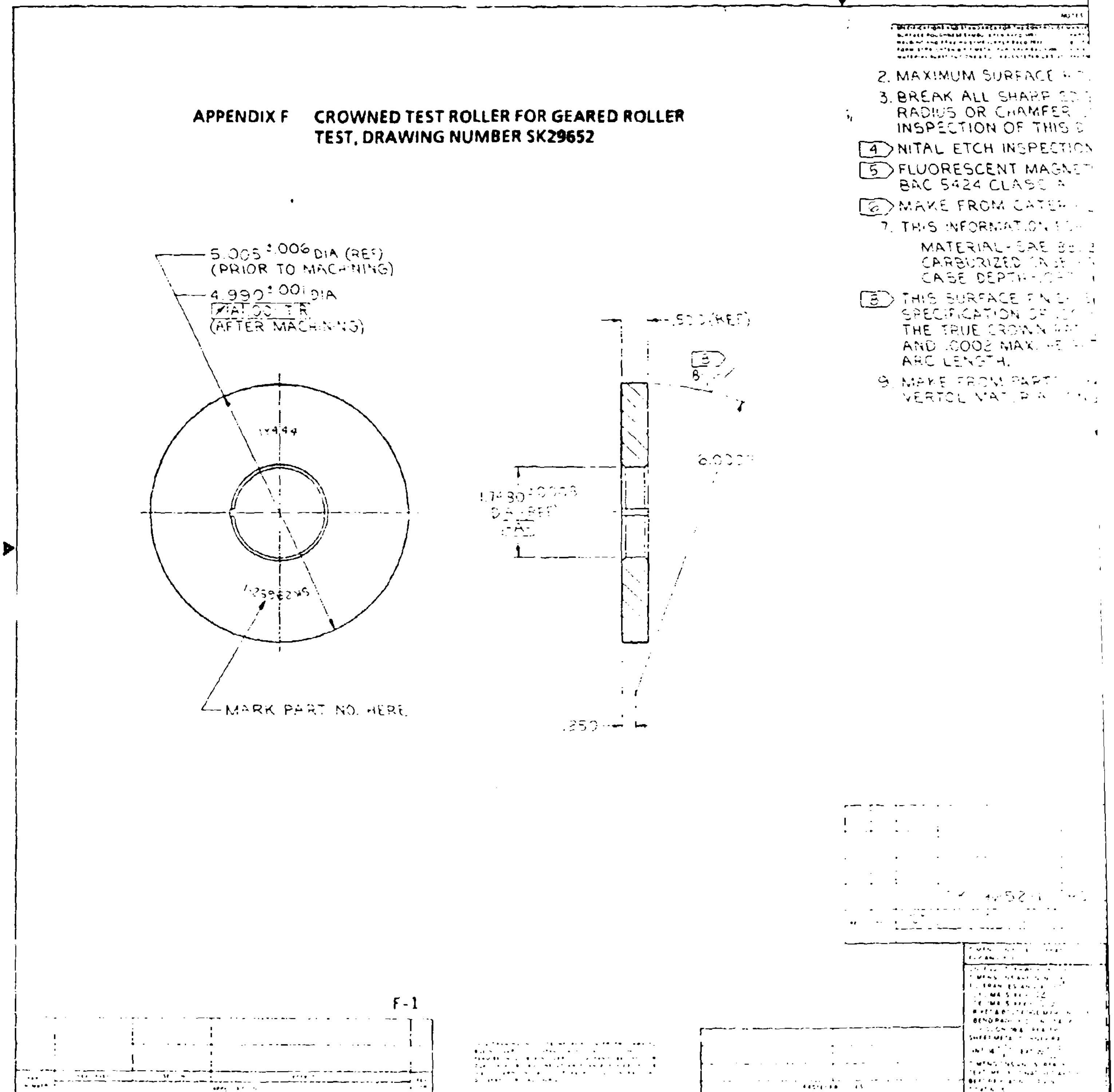
2

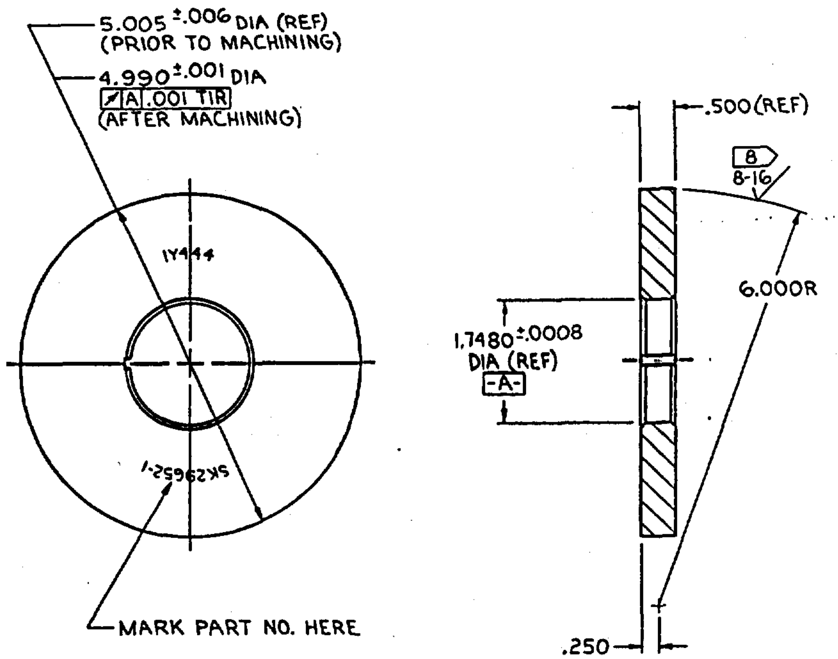
APPENDIX F CROWNED TEST ROLLER FOR GEARED ROLLER TEST, DRAWING NUMBER SK29652



APPENDIX F CROWNED TEST ROLLER FOR GEARED ROLLER TEST, DRAWING NUMBER SK29652

NOTES

2. MAXIMUM SURFACE RO
3. BREAK ALL SHARP EDG RADIUS OR CHAMFER O INSPECTION OF THIS DI
4. NITAL ETCH INSPECTION
5. FLUORESCENT MAGNET BAC 5424 CLASS A.
6. MAKE FROM CATERPIL
7. THIS INFORMATION FOR
   MATERIAL-SAE 882
   CARBURIZED CASE HA
   CASE DEPTH-.087-.
8. THIS SURFACE FINISH S SPECIFICATION OF .000 THE TRUE CROWN RADIU AND .0002 MAX. HEIGHT ARC LENGTH.
9. MAKE FROM PARTS (IY VERTOL MATERIAL ENG



SK29652-1 ROLL

DIMENSIONING & TOLERANCING PER ANSI Y14.5

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES: ANGLES ±1° DECIMALS .XX ±.02 DECIMALS .XXX ±.010

APPLICATION

FASTENER CODES

DWG NO SK29652 REV –

REVISIONS			
REV	DESCRIPTION	DATE	APPROVED

NOTES

1. SPECIFICATIONS AND STANDARDS FOR THE CONTROL OF MANUFACTURING OPERATIONS (AS APPLICABLE): SURFACE ROUGHNESS SYMBOLS PER BACD [illegible]; WELDING AND BRAZING SYMBOLS PER BACD [illegible]; [illegible] METAL PARTS PER BAC [illegible]; MATERIAL SUBSTITUTIONS & EQUIVALENTS PER [illegible]; PART MARKING PER BAC [illegible]; BOLT & NUT INSTALLATION PER BAC [illegible]; FINISH CODES PER [illegible]; [illegible]

2. MAXIMUM SURFACE ROUGHNESS 125√ EXCEPT AS NOTED.
3. BREAK ALL SHARP EDGES NOT SPECIFIED TO A RADIUS OR CHAMFER OF .010 TO .020. VISUAL INSPECTION OF THIS DIMENSION IS SATISFACTORY.
4. NITAL ETCH INSPECTION PER BAC 5436.
5. FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BAC 5424 CLASS A.
6. MAKE FROM CATERPILLAR TRACTOR CO. PART NO. 1Y444.
7. THIS INFORMATION FOR REFERENCE ONLY:
   MATERIAL-SAE 8822H VACUUM MELT STEEL.
   CARBURIZED CASE HARDNESS-ROCKWELL C 60-64.
   CASE DEPTH-.087-.102.
8. THIS SURFACE FINISH SHALL ALSO INCLUDE A WAVINESS SPECIFICATION OF .0001 MAX. HEIGHT DEVIATION FROM THE TRUE CROWN RADIUS IN A MIN. .125 INCH ARC LENGTH AND .0002 MAX. HEIGHT DEVIATION IN A MIN. .500 INCH ARC LENGTH.
9. MAKE FROM PARTS (1Y444) TO BE SUPPLIED BY BOEING VERTOL MATERIAL ENGINEERING (155 PIECES).

(REF)

6

OOOR

PARTS LIST

QTY REQD	QTY REQD	FSCM NO	PART OR IDENTIFYING NUMBER	NOMENCLATURE OR DESCRIPTION	MATERIAL AND SPECIFICATION	HT TR	FINISH	PT MK	CALC UNIT WT	ACT UNIT WT	REV LTR
			SK29652-1	ROLLER-CROWNED	6 4 5			VE			

DIMENSIONING & TOLERANCING PER ANSI Y14.5

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES. TOLERANCES: ANGLES ±1°; DECIMALS .XX ±.02; DECIMALS .XXX ±.010; RIVET & BOLT EDGE MARGIN ±.05; BEND RADII ±.01 ON .03 & .06, ±.03 ON .09 & GREATER; SHEET METAL CORNER RADII INT. .16 +.03 -.00, EXT .22 +.03 -.22. DIMENSIONS AND SURFACE TEXTURE DESIGNATIONS APPLY BEFORE PLATING OR FINISH COATINGS

FASTENER CODES

REVIEW & APPROVAL	
DWG QUAL	
STRUCT	
MATL & PRCS R. CUNNINGHAM	9-2-82
WTS	
CHANGE/ITEM NUMBER	
DRAWING DATE	

CONTRACT NUMBER DAAG-82-C-0034

DWN	F. J. LOKAJ	7-22-82
CHK	[signature]	9-2-82
ENGR	[signature]	9-2-82
GRG	[signature]	9-2-82
PROJECT APPROVAL	[signature]	9-2-82

BOEING VERTOL COMPANY
A DIVISION OF THE BOEING COMPANY
PHILADELPHIA, PENNSYLVANIA 19142

TEST ROLLER-CROWNED, VACUUM CARBURIZATION PROGRAM

SIZE D | FSCM NO. 77272 | SK29652

SCALE FULL | SH 1 OF 1

DRAWING RECORDS CLERK

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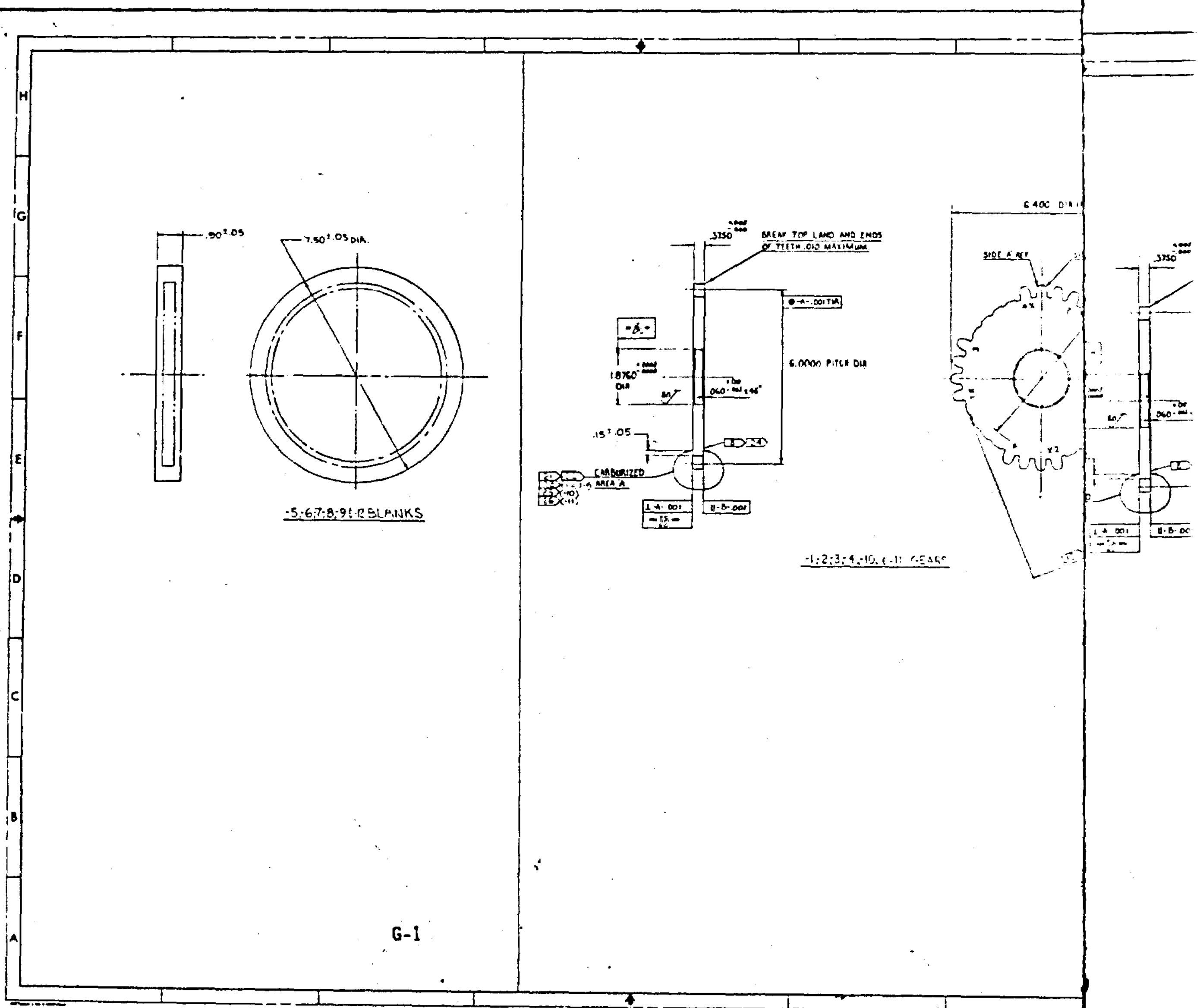
APPENDIX G SINGLE TOOTH BENDING FATIGUE TEST GEAR, DRAWING NUMBER SK29572



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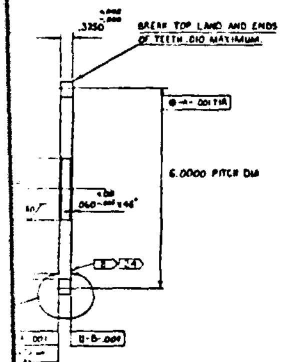
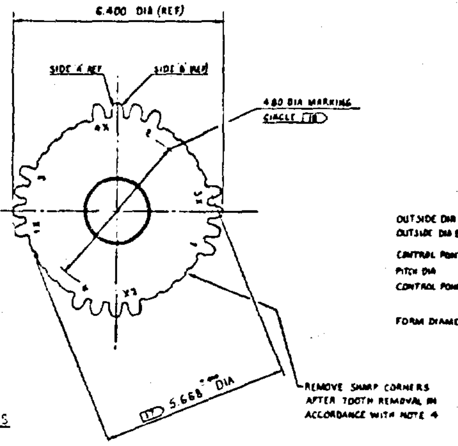
GEAR,





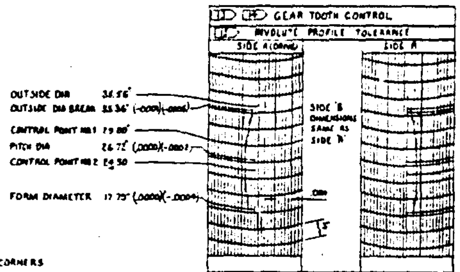
-1,-2,-3,-4,-10, & -11 GEARS

EXTERNAL SPUR GEAR DATA	
NUMBER OF TEETH	32
DIAMETRAL PITCH	5.3333
PRESSURE ANGLE	25°
PITCH DIAMETER	6.0000
OUTSIDE DIAMETER	6.400
ROOT DIAMETER	5.571
TIF DIAMETER	5.6935
MEASUREMENT OVER TWO PINS	[illegible]
FULL FILLET RADIUS	.074 MIN
PIN DIAMETER	.3456

REFERENCE DATA	
CIRCULAR TOOTH THICKNESS AT PITCH DIAMETER	.2905 MAX .2885 MIN
BACKLASH WITH MATING GEAR ON STANDARD CENTERS	.012 MAX .008 MIN
BASE CIRCLE DIAMETER	5.4378

GEAR TOOTH CONTROL

INVOLUTE PROFILE TOLERANCE

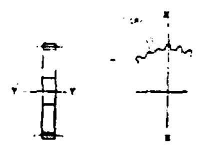


LEAD TOLERANCE PER INCH OF FACE WIDTH
A .0001 B .0001

TOTAL INDEX TOLERANCE
A .0009 B .0009

PITCH TOLERANCE
A .0005 B .0005

MAGNETIC PARTICLE INSPECTION REQUIREMENTS FOR -1,-2,-3,-4,& -10 GEARS.



MAGNETISM
1. AXIS X-X ACROSS TEETH - TURN 90° FOR SECOND SHOT MAGNETIZE 1800 AMPS
2. AXIS Y-Y CENTRAL CONDUCTOR MAGNETIZE 2000 AMPS

NOTES
1 ALL DIAMETERS ON A COMMON CEN[...] .010 TIR UNLESS OTHERWISE NOT[...]
2 MAXIMUM SURFACE ROUGHNESS [...]
3 RELATIVE AZIMUTH POSITION OF [...]
4 BREAK ALL SHARP EDGES NOT SPEC[...]
5 NITAL ETCH INSPECTION PER [...]
6 FLUORESCENT MAGNETIC PARTICLE [...]
7 FINISH ON TEETH 25 FLANKS AN[...]
8 MARK PART AND SERIAL NUMBER [...]
9 LEAD TOLERANCE APPLIES TO FULL [...] CROWNING OR END RELIEF TO BE [...]
10 PROOF DIAMETER OPTIONAL.
11 BILLET OR BAR SHALL HAVE A [...]
12 CARBURIZED TEST SAMPLES SHA[...]
13 PROFILE SHAPE WITHIN THE TOLERAN[...] CONVEX CURVATURE. NO STEPS O[...]
14 THE FULL CIRCULAR FILLET SHALL [...]
15 THE TOOTH PROFILES AND FILLETS S[...] WITH NO UNDERCUT PERMITTED
16
17 REMOVE TEETH AS SHOWN, PRIOR TO [...] THE DIAMETER INDICATED.
18 MARK BELOW TEETH IN POSITIONS [...] NOT IMPRESSION STAMP
19 MATERIAL 9310 STEEL PER [...]
20 MATERIAL [...]
21 HEAT TREATMENT
A. VACUUM CARBURIZE [...]
B. CARBURIZED CASE [...]
[illegible]
22 HEAT TREATMENT
[illegible]
23 [illegible]
VENDOR A: SUMMIT GEAR CO., PLYMOUTH [...]
VENDOR B: C.I. HAYES CO., CRANSTON [...]
24 [illegible]
25 [illegible]
26 [illegible]

CODE IDENT NO. 77272
DWG NO. 5K29551

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REVISED PER DCN	A
REVISED PER DCN	B

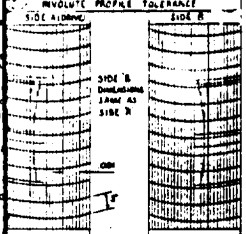
EXTERNAL SPUR GEAR DATA	
NUMBER OF TEETH	
DIAMETRAL	[illegible]
PRESSURE ANGLE	[illegible]
PITCH DIAMETER	6.0000
OUTSIDE DIAMETER	6.400
ROOT DIAMETER	5.571
[illegible] DIAMETER	5.6559
MEASUREMENT OVER TWO PINS	[illegible]
FULL FILLET RADIUS	.074 MIN
PIN DIAMETER	.3456

REFERENCE DATA	
CIRCULAR TOOTH THICKNESS AT PITCH DIAMETER	.2905 MAX .2885 MIN
BACKLASH WITH MATING GEAR ON STANDARD CENTERS	.012 MAX .008 MIN
BASE CIRCLE DIAMETER	5.4378

GEAR TOOTH CONTROL

INVOLUTE PROFILE TOLERANCE

SIDE A (DRIVE) SIDE B

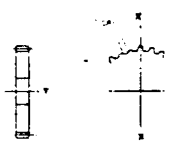


LEAD TOLERANCE PER INCH OF FACE WIDTH

TOTAL INDEX TOLERANCE

PITCH TOLERANCE

MAGNETIC PARTICLE INSPECTION REQUIREMENTS



NOTES

1. ALL DIAMETERS ON A COMMON CENTERLINE TO BE CONCENTRIC TO EACH OTHER WITHIN .010 TIR UNLESS OTHERWISE NOTED.
2. MAXIMUM SURFACE ROUGHNESS 125 EXCEPT AS NOTED.
3. RELATIVE AZIMUTH POSITION OF GEAR TEETH AND HOLES OPTIONAL UNLESS SPECIFIED.
4. BREAK ALL SHARP EDGES NOT SPECIFIED TO A RADIUS OR A CHAMFER OF .010 TO .020
5. NITAL ETCH INSPECTION PER BAC 5436
6. FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BAC 5424 CLASS A CRITICAL.
7. FINISH ON TEETH 25 FLANKS AND FILLETS (MAXIMUM)
8. MARK PART AND SERIAL NUMBER HERE. VIBRO ETCH. DO NOT IMPRESSION STAMP
9. LEAD TOLERANCE APPLIES TO FULL FACE WIDTH MINUS EDGE BREAKS. CROWNING OR END RELIEF TO BE AVOIDED.
10. PROOF DIAMETER OPTIONAL.
11. BILLET OR BAR SHALL HAVE A MINIMUM MECHANICAL REDUCTION OF 3 TO 1 FROM THE INGOT.
12. CARBURIZED TEST SAMPLES SHALL BE FACSIMILES OF GEAR TEETH.
13. PROFILE SHAPE WITHIN THE TOLERANCE BAND SHALL BE A SMOOTH AND GRADUAL CONVEX CURVATURE. NO STEPS OR GROOVES PERMITTED.
14. THE FULL CIRCULAR FILLET SHALL BE A SMOOTH CURVATURE WITH NO STEPS OR GROOVES.
15. THE TOOTH PROFILES AND FILLETS SHALL BE FINISH MACHINED BY FORM GRINDING WITH NO UNDERCUT PERMITTED.
16.
17. REMOVE TEETH AS SHOWN, PRIOR TO HEAT TREATMENT AND CARBURIZING, TO PROVIDE THE DIAMETER INDICATED.
18. MARK BELOW TEETH IN POSITIONS SHOWN WITH 1/8 HIGH CHARACTERS. VIBRO ETCH. DO NOT IMPRESSION STAMP.
19. MATERIAL: 9310 STEEL PER BMS 7-249 TYPE III.
20. MATERIAL: 5CR-14 MO 1.35W STEEL PER BMS 7-223 TYPE II.
21. HEAT TREATMENT
    - A. VACUUM CARBURIZE ENCLOSED AREAS — AREA A
    - B. CARBURIZED CASE HARDNESS ROCKWELL C — 60-64
    - C. EFFECTIVE CASE DEPTH AT ROCKWELL C 50 AFTER GRINDING — .030-.045
    - D. CORE HARDNESS ROCKWELL C — 36-44
    - E. DRAW AT 350°F ±25°F FOR FOUR HOURS AFTER FINAL GRIND.
    - F. PRIOR TO THE HEAT TREATMENT AND QUENCHING OPERATIONS, CARBON PASTE (NO CARB OR EQUIVALENT) SHALL BE APPLIED TO BOTH END FACES OF THE GEARS. THE GEARS SHALL BE STACKED WITH END PLATES AT THE TOP AND BOTTOM WITH AN APPLIED SPRING LOAD.
22. HEAT TREATMENT
    - A. VACUUM CARBURIZE ENCLOSED AREAS — AREA A
    - B. CARBURIZED CASE HARDNESS ROCKWELL C — 60-64
    - C. EFFECTIVE CASE DEPTH AT ROCKWELL C 50 AFTER GRINDING — .030-.045
    - D. CORE HARDNESS ROCKWELL C — 32-42
    - E. DRAW AT 300°F-325°F FOR FOUR HOURS AFTER FINAL GRIND.
    - F. PRIOR TO THE HEAT TREATMENT AND QUENCHING OPERATIONS, CARBON PASTE (NO CARB OR EQUIVALENT) SHALL BE APPLIED TO BOTH END FACES OF THE GEARS. THE GEARS SHALL BE STACKED WITH END PLATES AT THE TOP AND BOTTOM WITH AN APPLIED SPRING LOAD.
23. FOUR (4) TEST GEARS OF EACH DASH NUMBER ARE TO BE VACUUM CARBURIZED AND HARDENED BY EACH VENDOR
    VENDOR "A": SUMMIT GEAR CO., PLYMOUTH, MINN.
    VENDOR "B": C.I. HAYES CO., CRANSTON, R.I.
24. HEAT TREAT VENDORS ARE TO ADD APPROPRIATE IDENTIFYING SUFFIX "A" OR "B" TO SERIAL NUMBER.
25. EIGHT GEARS TO BE HEAT TREATED BY SUMMIT GEAR CO., PLYMOUTH, MINN.
26. ALL GEARS TO BE HEAT TREATED BY SUMMIT GEAR CO., PLYMOUTH, MINN.

ONE-HALF SCALE
COPY OF ORIGINAL DWG

PART NUMBER	DESCRIPTION	ZONE	MATERIALS AND SPECIFICATION	NOTE	FINISH	PT MK
SK29572-12	BLANK		FROM MILL HEAT G			
SK29572-11	TEST GEAR		MAKE FROM SK29572-[illegible] BLANK			
SK29572-10	TEST GEAR		MAKE FROM SK29572-[illegible] BLANK			
SK29572-9	BLANK		FROM MILL HEAT F			
SK29572-8	BLANK		FROM MILL HEAT D			
SK29572-7	BLANK		FROM MILL HEAT C			
SK29572-6	BLANK		FROM MILL HEAT B			
SK29572-5	BLANK		FROM MILL HEAT A			
SK29572-4	TEST GEAR		MAKE FROM SK29572-8 BLANK			
SK29572-3	TEST GEAR		MAKE FROM SK29572-7 BLANK			
SK29572-2	TEST GEAR		MAKE FROM SK29572-6 BLANK			
SK29572-1	TEST GEAR		MAKE FROM SK29572-5 BLANK			

LIST OF MATERIAL

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES ON
DECIMALS: .X ±.1 .XX ±.020 .XXX ±.005
ANGLES: ±.5°

TEST

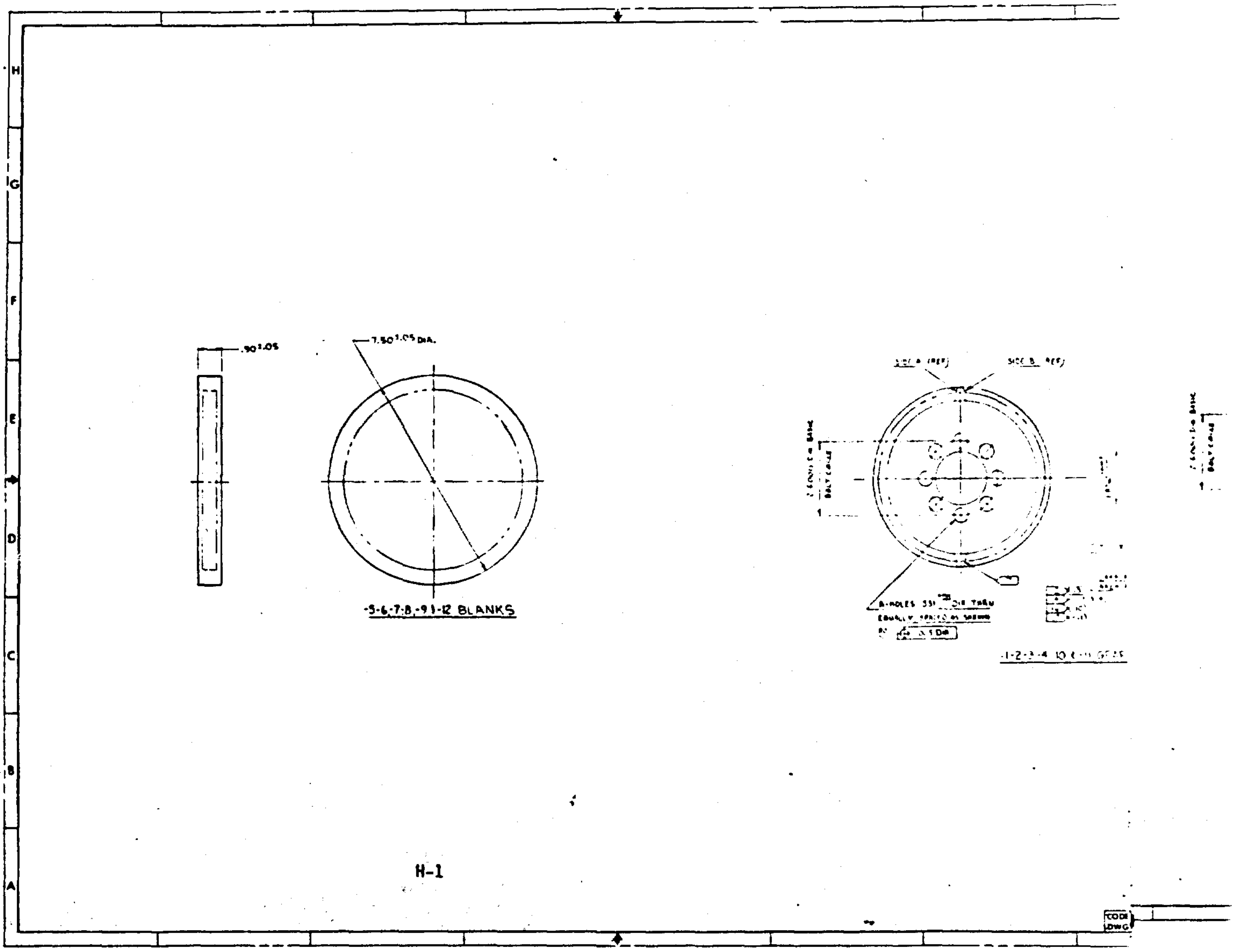
THE BOEING COMPANY

SMALL TOOTH FATIGUE TEST GEAR VACUUM CARB. PROGRAM

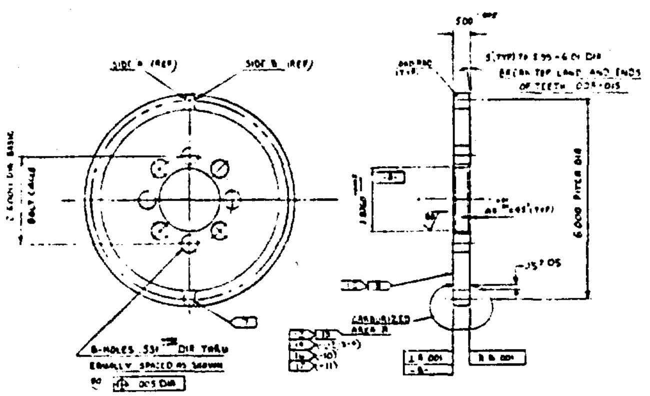
SK29572

Best Available Copy

APPENDIX H SCORING FATIGUE TEST GEAR DRAWING NUMBER SK29571



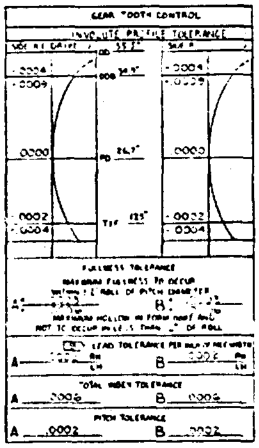
APPENDIX L ENGINEERING DRAWINGS OF SPIRAL BEVEL TEST GEAR (CONTINUED)

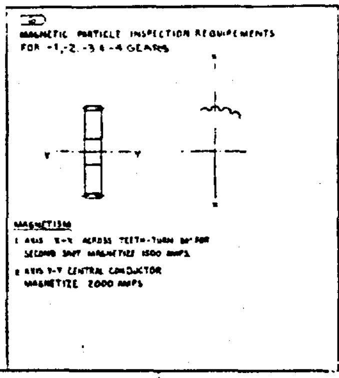


-1,-2,-3,-4,-10, & -11 GEAR

EXTERNAL SPUR GEAR DATA	
NUMBER OF TEETH	30
DIAMETRAL PITCH	5.000
PRESSURE ANGLE	25°
PITCH DIAMETER	6.0000
OUTSIDE DIAMETER	6.400
ROOT DIAMETER	5.446
TIF DIAMETER	[illegible]
MEASUREMENT OVER TWO PINS	[illegible]
MINIMUM FILLET RADIUS OF CURVATURE	.063
PIN DIAMETER	.3456

REFERENCE DATA	
CIRCULAR TOOTH THICKNESS AT PITCH DIAMETER	.2 36 MAX .3306 MIN
BACKLASH WITH MATING GEAR AT STANDARD CENTRES	[illegible] MAX .007 MIN
BASE CIRCLE DIAMETER	5.4378





NOTES

1. ALL DIAMETERS ON A COMMON CENTERLINE TO BE CONCENTRIC TO EACH OTHER WITHIN .00? TIR UNLESS OTHERWISE NOTED
2. MAXIMUM SURFACE ROUGHNESS 125 EXCEPT AS NOTED
3. RELATIVE AZIMUTH POSITION OF GEAR TEETH, SPLINE TEETH AND HOLE
4. BREAK ALL SHARP EDGES NOT SPECIFIED TO A RADIUS OR A CHAMFER
5. NITAL ETCH INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5
6. FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BOEING PROCESS
7. FINISH ON GEAR TEETH 25 FLANKS AND FILLETS (MAXIMUM
8. MARK PART AND SERIAL NUMBER HERE VIBRO ETCH DO NOT IMPRESSION
9. LEAD TOLERANCE APPLIES TO FULL FACE WIDTH MINUS EDGE BREAKS CROWNING OR END RELIEF TO BE AVOIDED
10. MATERIAL 5CR-1.4 MO 1.35W STEEL PER BMS 7-225 TYPE
11. MATERIAL 9310 STEEL PER BMS 7-249 TYPE III
12. HEAT TREATMENT:
    - A. VACUUM CARBURIZE ENCLOSED AREAS
    - B. CARBURIZED CASE HARDNESS, ROCKWELL C
    - C. EFFECTIVE CASE DEPTH AT ROCKWELL C50 AFTER
    - D. CORE HARDNESS, ROCKWELL C
    - E. DRAW AT 550°F-525°F FOR FOUR HOURS AFTER FINAL
13. HEAT TREATMENT:
    - A. VACUUM CARBURIZE ENCLOSED AREAS
    - B. CARBURIZED CASE HARDNESS, ROCKWELL C
    - C. EFFECTIVE CASE DEPTH AT ROCKWELL C50 AFTER
    - D. CORE HARDNESS, ROCKWELL C
    - E. DRAW AT 500°F-525°F FOR FOUR HOURS AFTER
14. TEN (10) TEST GEARS OF EACH DASH NUMBER ARE TO BE VA... HARDENED BY EACH VENDOR
    - VENDOR A: SUMMIT GEAR CO., PLYMOUTH, MINN.
    - VENDOR B: C.I. HAYES CO., CRANSTON, R.I.
15. HEAT TREAT VENDORS ARE TO ADD APPROPRIATE IDENTI... SERIAL NUMBER
16. ALL TWENTY GEARS TO BE HEAT TREATED BY SUMMIT
17. ALL GEARS TO BE HEAT TREATED BY SUMMIT GEAR CO.

CODE IDENT NO. 81205
DWG NO. SK29571

REVISIONS	
A	REVISED PER DCN
B	REVISED PER DCN

NOTES

1. ALL DIAMETERS ON A COMMON CENTERLINE TO BE CONCENTRIC TO EACH OTHER WITHIN .0010 TIR UNLESS OTHERWISE NOTED
2. MAXIMUM SURFACE ROUGHNESS 125 EXCEPT AS NOTED
3. RELATIVE AZIMUTH POSITION OF GEAR TEETH, SPLINE TEETH AND HOLES OPTIONAL UNLESS SPECIFIED
4. BREAK ALL SHARP EDGES NOT SPECIFIED TO A RADIUS OR A CHAMFER OF .010 TO .020
5. NITAL ETCH INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5436.
6. FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5424 CLASS A CRITICAL.
7. FINISH ON GEAR TEETH 25 FLANKS AND FILLETS (MAXIMUM).
8. MARK PART AND SERIAL NUMBER HERE VIBRO ETCH. DO NOT IMPRESSION STAMP
9. LEAD TOLERANCE APPLIES TO FULL FACE WIDTH MINUS EDGE BREAKS. CROWNING OR END RELIEF TO BE AVOIDED.
10. MATERIAL 5CR-1.4 MO 1.35W STEEL PER BMS 7-223 TYPE III.
11. MATERIAL 9310 STEEL PER BMS 7-249 TYPE III
12. HEAT TREATMENT:
    - A. VACUUM CARBURIZE ENCLOSED AREAS — AREA A
    - B. CARBURIZED CASE HARDNESS, ROCKWELL C — 60-64
    - C. EFFECTIVE CASE DEPTH AT ROCKWELL C50 AFTER GRINDING — .035-.055
    - D. CORE HARDNESS, ROCKWELL C — 36-44
    - E. DRAW AT 550°F ±25°F FOR FOUR HOURS AFTER FINAL GRIND.
13. HEAT TREATMENT:
    - A. VACUUM CARBURIZE ENCLOSED AREAS — AREA A
    - B. CARBURIZED CASE HARDNESS, ROCKWELL C — 60-64
    - C. EFFECTIVE CASE DEPTH AT ROCKWELL C50 AFTER GRINDING — .035-.055
    - D. CORE HARDNESS, ROCKWELL C — 32-42
    - E. DRAW AT 300°F-325°F FOR FOUR HOURS AFTER FINAL GRIND.
14. TEN (10) TEST GEARS OF EACH DASH NUMBER ARE TO BE VACUUM CARBURIZED AND HARDENED BY EACH VENDOR.
    - VENDOR 'A' - SUMMIT GEAR CO., PLYMOUTH, MINN.
    - VENDOR 'B' - C.I. HAYES CO., CRANSTON, R.I.
15. HEAT TREAT VENDORS ARE TO ADD APPROPRIATE IDENTIFYING SUFFIX 'A' OR 'B' TO SERIAL NUMBER.
16. ALL TWENTY GEARS TO BE HEAT TREATED BY SUMMIT GEAR CO.
17. ALL GEARS TO BE HEAT TREATED BY SUMMIT GEAR CO.

ONE-HALF SCALE
COPY OF ORIGINAL DWG.

LIST OF MATERIAL

PART OR IDENTIFYING NUMBER	NOMENCLATURE OR DESCRIPTION	MATERIAL AND SPECIFICATION		
SK29571-12	BLANK	10 FROM MILL HEAT G		
SK29571-11	TEST GEAR	MAKE FROM SK29571-12 BLANK	12 17	
SK29571-10	TEST GEAR	MAKE FROM SK29571-9 BLANK	12 17	
SK29571-9	BLANK	11 FROM MILL HEAT F		
SK29571-8	BLANK	11 FROM MILL HEAT D		
SK29571-7	BLANK	11 FROM MILL HEAT C		
SK29571-6	BLANK	10 FROM MILL HEAT B		
SK29571-5	BLANK	10 FROM MILL HEAT A		
SK29571-4	TEST GEAR	MAKE FROM SK29571-8 BLANK	13	VE
SK29571-3	TEST GEAR	MAKE FROM SK29571-7 BLANK	13	VE
SK29571-2	TEST GEAR	MAKE FROM SK29571-6 BLANK	12	VE
SK29571-1	TEST GEAR	MAKE FROM SK29571-5 BLANK	12	VE

THIS DRAWING INCLUDES INFORMATION PROPRIETARY TO THE BOEING-VERTOL CO. AND SHALL NOT WITHOUT PERMISSION OF THE BOEING-VERTOL CO. BE USED OR DUPLICATED BY ANYONE.

TEST

THE BOEING COMPANY
VERTOL DIVISION

GEAR, ROTATING TEST
VACUUM CARB. PROGRAM

J 81205 SK29571

Best Available Copy

APPENDIX I TELEDYNE VASCO ANALYSIS REPORT OF X2M MATERIAL

TELEDYNE VASCO

ANALYSIS REPORT

Customer: Boeing Vertol
P. O. Box 16858
Philadelphia, Pa. 19142

Stulen Machine Company
4693 Peoples Rd.
Pittsburgh, Pa. 15237

COPY

Your Order No. 8-4435-5-0080

Our Order No. V 297803

Brand: VIM-VAR Vasco X2 Modified Per Boeing Spec BMS 7-223C Type III Ultrasonic Insp.

SIZE	PIECES	WEIGHT	HEAT No.	DATE SHIPPED
8-1/4"rd. x 48"lg.	1	731#	5842-A	5-26-82

Macro Structure - Satisfactory to ASTM A-604 level detailed in Boeing Spec BMS 7-223C

Grain Size T = 5-1/2
B = 6

Magnetic Particle Inspection - T - F/S 0/0
B - F/S 0/0

J-K Rating:

	A Thin	A Heavy	B Thin	B Heavy	C Thin	C Heavy	D Thin	D Heavy
T	1/2	0	0	0	0	0	1	0
B	0	0	0	0	0	0	1-1/2	0

Ultrasonic Inspection prior to turning to the shipped size - Satisfactory to OII Procedure No. .00.05.258 Rev II as established between Boeing/Vertol Orbit Industries and Teledyne Vasco.

Orbit Certificate U1-3768 is attached.

Analysis

Heat No.	C	Si	Mn	S	P	W	Cr	V	Mo	Co	Ni
5842A	.15	.94	.37	.004	.013	1.47	4.85	.40	1.37		
Center of Ingot	.16										

Sworn and subscribed to before me
27 day of May 1982

Kathleen A. Weiss

KATHLEEN A. WEISS Notary Public

Certified Correct

[signature]

APPENDIX J STATISTICAL ANALYSIS METHOD FOR SINGLE TOOTH BENDING FATIGUE DATA

The data from the single tooth bending fatigue test program was analyzed statistically using the same Boeing Vertol computer program used for the earlier test programs. Since comparisons between the results obtained from the earlier programs and those obtained from this program have been made, it is essential that the analysis techniques be consistent.

The statistical analysis was based on the theory that for a particular material there is a definite bending (tensile) stress which the material will be able to withstand for an infinite number of cycles, without the occurrence of a failure. In other words, as long as the stress in a component is maintained at a level equal to or lower than the endurance limit, a failure will never occur. This is a reasonable approach sine, at this time, all Boeing Vertol transmission gears are designed for "infinite" life (i.e. at overhaul they are only removed from service if a defect is found). On the basis of this theory, it was assumed that the mean stress/life (S-N) curve takes the general form:

$$S = \bar{S} + \frac{\alpha}{N^{\gamma}} \quad (1)$$

where: S = stress at failure

$\bar{S}$ = endurance limit stress

α = material constant

γ = test gear specimen configuration constant (shape factor)

N = cycles at which failure occurs

After an empirical evaluation of the material constants, the stress at any number of cycles can be evaluated, using Equation (5), by calculating the $\bar{X}$ value based on an individual data point. In order to determine the mean ($\bar{S}$) stress for the entire group of data at a particular number of cycles (after the individual $\bar{X}$ value for each data point is calculated at these cycles), the individual $\bar{X}$ values are then summed up and divided by the number of data points (using Equation 6).

$$\bar{X} = \frac{X_F}{\left[1 + \frac{(\alpha/\bar{S})}{N_E{}^{Y}}\right]} \left[1 + \frac{\alpha/\bar{S}}{N_E{}^{Y}}\right] \tag{5}$$

$$\bar{S} = \frac{\Sigma\,\bar{X}}{n} \tag{6}$$

where: $\bar{S}$ = mean stress for total group of specimens at N_E cycles

$\bar{X}$ = stress at N_R cycles based on a particular data point

X_F = stress at failure for a particular data point

N_F = cycles at failure for a particular data point

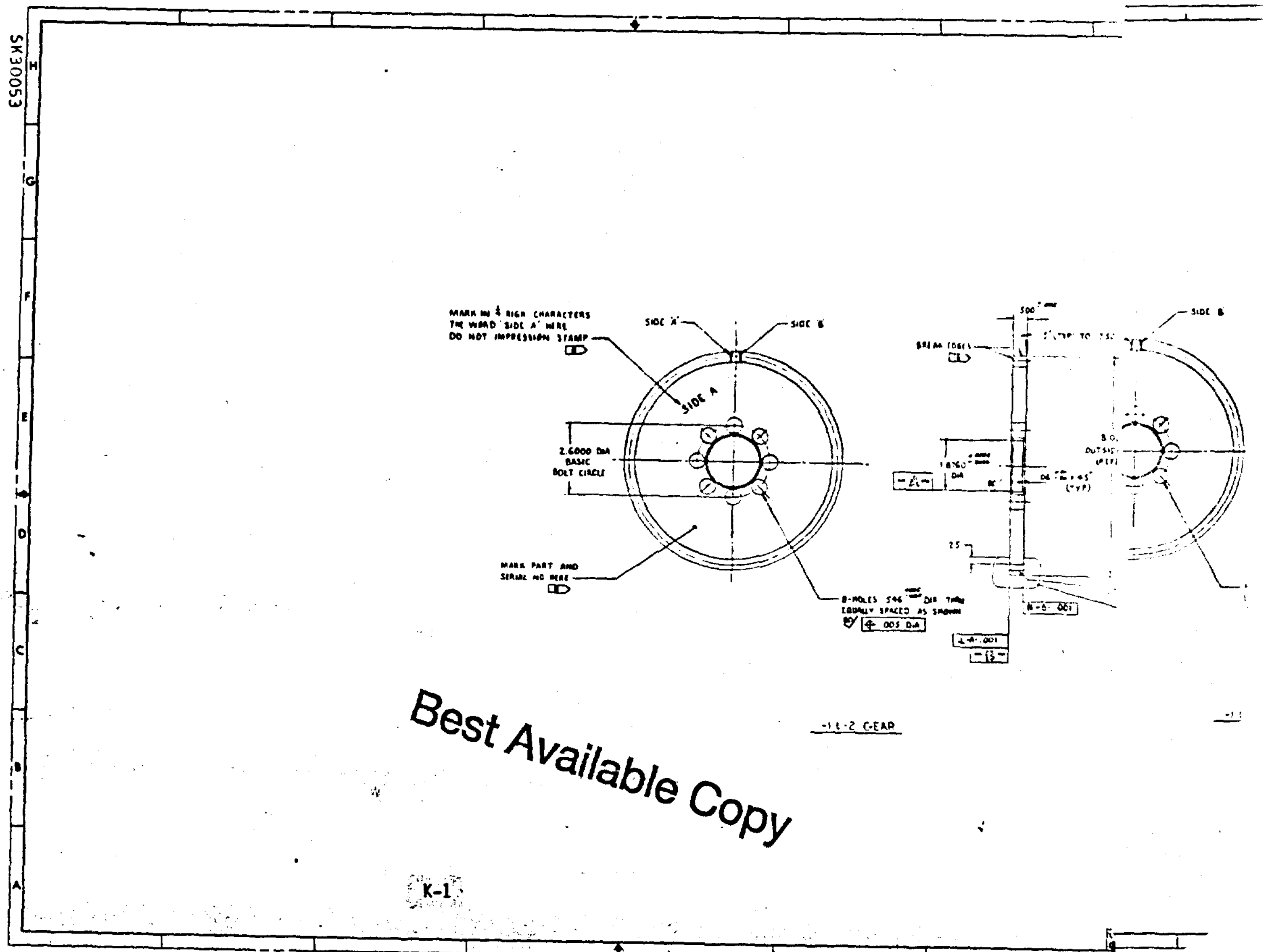
n = number of test data points

N_E = cycles at which data is to be evaluated

Y = test specimen shape constant

$\alpha/\bar{S}$ = test specimen material constant

The only unknowns are the test specimen shape and material constants. These factors have been evaluated and defined in the prior programs and those values, as shown in Table 1, will be used in this analysis.

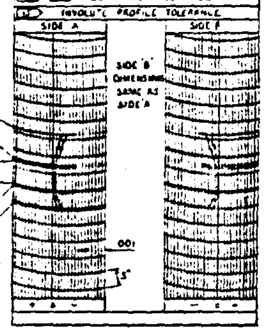

SK30053
MARK IN ⅛ HIGH CHARACTERS
THE WORD 'SIDE A' HERE
DO NOT IMPRESSION STAMP
SIDE 'A'
SIDE 'B'
SIDE A
2.6000 DIA
BASIC
BOLT CIRCLE
MARK PART AND
SERIAL NO HERE
8-HOLES .546 DIA THRU
EQUALLY SPACED AS SHOWN
.005 DIA
SIDE B
GEAR

REFERENCE DATA		
CIRCULAR TOOTH THICKNESS AT PITCH DIAMETER	.3109	MAX
	.3087	MIN
BACKLASH WITH MATING GEAR ON STANDARD CENTERS	.012	MAX
	.008	MIN
BASE CIRCLE DIAMETER (REF)	7.0476952	
LEAD TOLERANCE PER INCH OF FACE WIDTH	A .0001 RH .0001 LH	B .0001 RH .0001 LH
TOTAL INDEX TOLERANCE	A .0006	B .0006
PITCH TOLERANCE	A .0002	B .0002

EXTERNAL SPUR GEAR DATA	
NUMBER OF TEETH	40
DIAMETRAL PITCH	5.3333
PRESSURE ANGLE	20
PITCH DIAMETER	7.500
OUTSIDE DIAMETER	8.000
ROOT DIAMETER	[illegible]
FORM DIAMETER	7.5861
MEASUREMENT OVER TWO PINS	[illegible]
FULL FILLET RADIUS (REF)	.126
PIN DIAMETER	.3840

GEAR TOOTH CONTROL

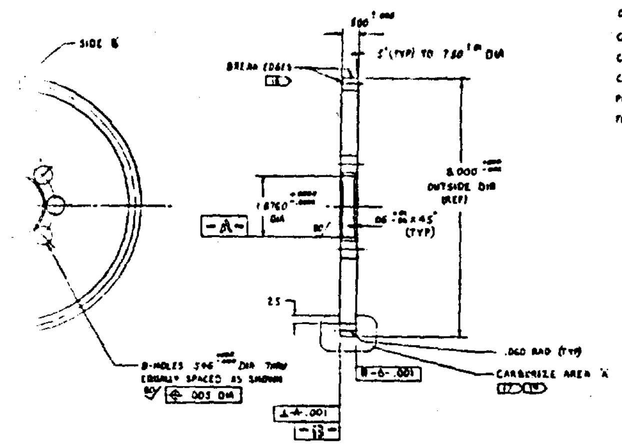
INVOLUTE PROFILE TOLERANCE



OUTSIDE DIAMETER	38.65° (-.0005)(-.0006)
CONTROL POINT NO.1	27.97° (.0000)(-.0002)
CONTROL POINT NO.2	24.97° (.0000)(-.0001)
CONTROL POINT NO.3	21.88° (.0000)(-.0001)
PITCH DIAMETER	20.00° (.0000)(-.0002)
FORM DIAMETER	17.97° (-.0005)(-.0006)

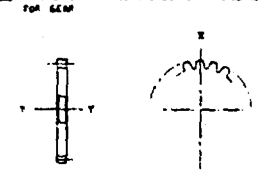
NOTES

1. ALL DIAMETERS ON A COMMON CENTERLINE TO BE CONC... UNLESS OTHERWISE NOTED
2. MAXIMUM SURFACE ROUGHNESS 125 EXCEPT AS NOTED
3. ALL ... AZIMUTH POSITION OF GEAR TEETH AND HOLES ...
4. BREAK ALL SHARP EDGES NOT SPECIFIED TO A RADIUS OF ...
5. NITAL ETCH INSPECTION PER BOEING PROCESS SPECIFICATION ...
6. FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BOEING ...
7. FINISH ON GEAR TEETH FLANKS 16 MAXIMUM BOTH SIDES ...
8. MARK PART AND SERIAL NUMBER HERE. VIBRO ETCH PER BO... DO NOT IMPRESSION STAMP.
9. LEAD TOLERANCE APPLIES TO FULL FACE WIDTH MINUS EDGE ...
10. BILLET OR BAR SHALL HAVE A MINIMUM MECHANICAL REDUCTI...
11. CARBURIZED TEST SAMPLES SHALL BE FACSIMILES OF GEA...
12. QUALITY CONTROL PER BOEING SPECIFICATION MS 14.02
13. PROFILE SHAPE WITHIN THE TOLERANCE BAND SHALL BE A S... NO STEPS OR GROOVES PERMITTED.
14. THE FULL CIRCULAR FILLET SHALL BE A SMOOTH CURVATURE ...
15. THE TOOTH PROFILES AND FILLETS SHALL BE FINISH MACHINED ...
16. BREAK ALL EDGES OF GEAR TEETH .005 TO .015.
17. HEAT TREATMENT
    - A. VACUUM CARBURIZE ENCLOSED AREAS ...
    - B. CARBURIZED CASE HARDNESS ROCKWELL C ...
    - C. EFFECTIVE CASE DEPTH AT ROCKWELL C50 AFTER ...
    - D. CORE HARDNESS ROCKWELL C ...
    - E. DRAW AT 550°F ± 25°F FOR FOUR HOURS AFTER ...
18. MATERIAL: 5 Cr - 1.8 Mo, 1.35 W STEEL PER BMS ...
19. HEAT TREATMENT:
    - A. VACUUM CARBURIZE ENCLOSED AREAS ...
    - B. CARBURIZED CASE HARDNESS ROCKWELL C ...
    - C. EFFECTIVE CASE DEPTH AT ROCKWELL C50 AFTER ...
    - D. CORE HARDNESS ROCKWELL C ...
    - E. DRAW AT 300°F - 325°F FOR FOUR HOURS AFTER FIN...
20. MATERIAL: 9310 STEEL PER BMS 7-249 TYPE III.



-112 GEAR

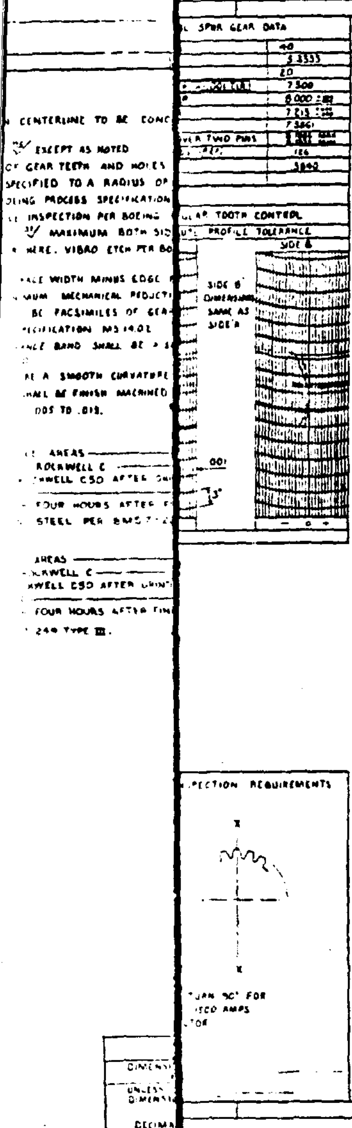
MAGNETIC PARTICLE INSPECTION REQUIREMENTS FOR GEAR



MAGNETISM
1. AXIS X-X ACROSS TEETH — TURN 90° FOR SECOND SHOT. MAGNETIZE 1500 AMPS
2. AXIS Y-Y CENTRAL CONDUCTOR MAGNETIZE 2000 AMPS

CODE IDENT NO. 77272
DWG NO. 3433053

Best Available Copy



REVISIONS		
A	REVISED PER DCN	

NOTES

1. ALL DIAMETERS ON A COMMON CENTERLINE TO BE CONCENTRIC TO EACH OTHER WITHIN .010 T.I.R. UNLESS OTHERWISE NOTED.
2. MAXIMUM SURFACE ROUGHNESS 63/ EXCEPT AS NOTED.
3. RELATIVE AZIMUTH POSITION OF GEAR TEETH AND HOLES OPTIONAL UNLESS SPECIFIED.
4. BREAK ALL SHARP EDGES NOT SPECIFIED TO A RADIUS OR CHAMFER OF .010 TO .020
5. NITAL ETCH INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5436.
6. FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5424 CLASS A CRITICAL.
7. FINISH ON GEAR TEETH FLANKS 32/ MAXIMUM BOTH SIDES.
8. MARK PART AND SERIAL NUMBER HERE. VIBRO ETCH PER BOEING PROCESS SPECIFICATION BAC 5307 TYPE 'VE'. DO NOT IMPRESSION STAMP.
9. LEAD TOLERANCE APPLIES TO FULL FACE WIDTH MINUS EDGE BREAKS CROWNING OR END RELIEF TO BE AVOIDED.
10. BILLET OR BAR SHALL HAVE A MINIMUM MECHANICAL REDUCTION OF 3 TO 1 FROM THE INGOT.
11. CARBURIZED TEST SAMPLES SHALL BE FACSIMILES OF GEAR TEETH.
12. QUALITY CONTROL PER BOEING SPECIFICATION MS 14.02
13. PROFILE SHAPE WITHIN THE TOLERANCE BAND SHALL BE A SMOOTH AND GRADUAL CONVEX CURVATURE. NO STEPS OR GROOVES PERMITTED.
14. THE FULL CIRCULAR FILLET SHALL BE A SMOOTH CURVATURE WITH NO STEPS OR GROOVES.
15. THE TOOTH PROFILES AND FILLETS SHALL BE FINISH MACHINED BY FORM GRINDING WITH NO UNDERCUT PERMITTED.
16. BREAK ALL EDGES OF GEAR TEETH .005 TO .015.
17. HEAT TREATMENT

	AREA A	AREA B
A. VACUUM CARBURIZE ENCLOSED AREAS		
B. CARBURIZED CASE HARDNESS ROCKWELL C	60-64	
C. EFFECTIVE CASE DEPTH AT ROCKWELL C50 AFTER GRINDING	.030-.045	
D. CORE HARDNESS ROCKWELL C	36-44	

E. DRAW AT 550°F ± 25°F FOR FOUR HOURS AFTER FINAL GRIND

18. MATERIAL: 5 Cr - 1.0 Mo, 1.35 W STEEL PER BMS 7-223 TYPE III.
19. HEAT TREATMENT:

	AREA A
A. VACUUM CARBURIZE ENCLOSED AREAS	
B. CARBURIZED CASE HARDNESS ROCKWELL C	60-64
C. EFFECTIVE CASE DEPTH AT ROCKWELL C50 AFTER GRINDING	.030-.045
D. CORE HARDNESS ROCKWELL C	32-42

E. DRAW AT 300°F - 325°F FOR FOUR HOURS AFTER FINAL GRIND.

20. MATERIAL: 9310 STEEL PER BMS 7-249 TYPE III.

ONE-HALF SCALE
COPY OF ORIGINAL DWG

PART NUMBER	DESCRIPTION	ZONE	MATERIAL AND SPECIFICATION	HT TR	FINISH
SK30053-2	TEST GEAR		20	19	16
SK30053-1	TEST GEAR		NOM & TEMP 18	17	16

LIST OF MATERIAL

DIMENSIONING AND TOLERANCING PER MIL-STD-8
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES
DECIMALS .X ± .1 .XX ± .02 .XXX ± .005
ANGLES ± .5°

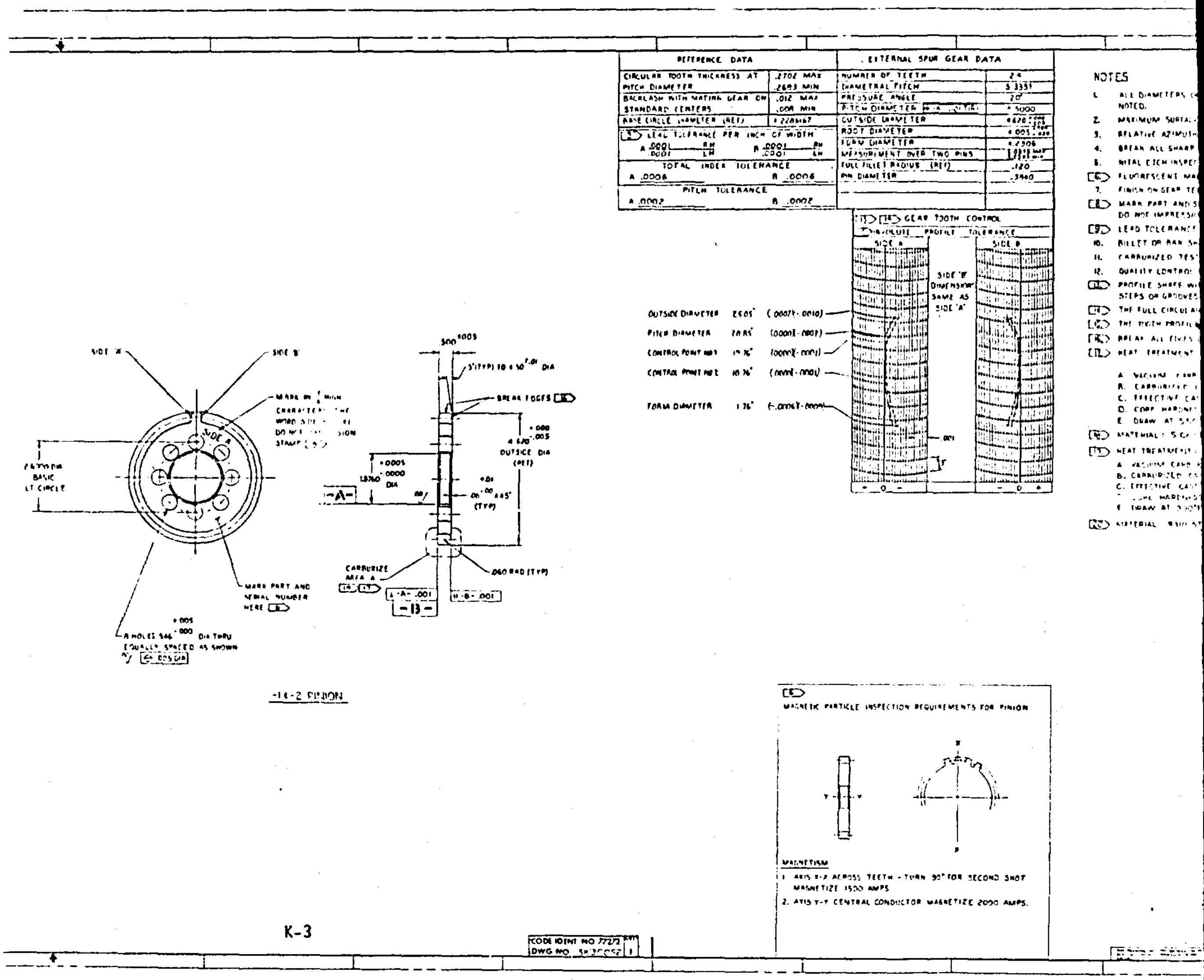
THE BOEING COMPANY
VERTOL DIVISION PHILADELPHIA PA
TEST GEAR
LOT RATIO VACUUM CARBURIZE ROTATING FATIGUE TEST
SK30053

SK30053 1 A

SK30023 (1)

Best Available Copy

APPENDIX K ENGINEERING DRAWINGS OF SPUR TEST GEARS (CONTINUED)

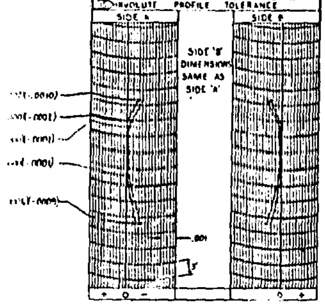


	EXTERNAL SPUR GEAR DATA	
.2702 MAX	NUMBER OF TEETH	24
.2683 MIN	DIAMETRAL PITCH	5.3333
.012 MAX	PRESSURE ANGLE	20°
[illegible] MIN	PITCH DIAMETER [illegible] .001 TIR	4.5000
[illegible]	OUTSIDE DIAMETER	4.820 [illegible]
[illegible] WIDTH	ROOT DIAMETER	4.005 [illegible]
[illegible] RH	FORM DIAMETER	4.2306
[illegible] LH	MEASUREMENT OVER TWO PINS	[illegible]
ANCE	FULL FILLET RADIUS (REF)	.120
.0006	PIN DIAMETER	.3940
.0002		

13 14 GEAR TOOTH CONTROL

INVOLUTE PROFILE TOLERANCE

SIDE A — SIDE B



NOTES

1. ALL DIAMETERS ON A COMMON CENTERLINE TO BE CONCENTRIC TO EACH OTHER WITHIN .010 T.I.R. UNLESS OTHERWISE NOTED.
2. MAXIMUM SURFACE ROUGHNESS 125 EXCEPT AS NOTED.
3. RELATIVE AZIMUTH POSITION OF GEAR TEETH AND HOLES OPTIONAL UNLESS SPECIFIED.
4. BREAK ALL SHARP EDGES NOT SPECIFIED TO A RADIUS OR CHAMFER OF .010 TO .020
5. NITAL ETCH INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5436.
6. FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5424 CLASS A CRITICAL.
7. FINISH ON GEAR TEETH FLANKS 32 MAXIMUM BOTH SIDES.
8. MARK PART AND SERIAL NUMBER HERE. VIBRO ETCH PER BOEING PROCESS SPECIFICATION BAC 5307 TYPE "VE". DO NOT IMPRESSION STAMP.
9. LEAD TOLERANCE APPLIED TO FULL FACE WIDTH MINUS EDGE BREAKS.
10. BILLET OR BAR SHALL HAVE A MINIMUM MECHANICAL REDUCTION OF 3 TO 1 FROM THE INGOT.
11. CARBURIZED TEST SAMPLES SHALL BE FACSIMILES OF GEAR TEETH.
12. QUALITY CONTROL PER BOEING SPECIFICATION MS 14.02
13. PROFILE SHAPE WITHIN THE TOLERANCE BAND SHALL BE A SMOOTH AND GRADUAL CONVEX CURVATURE. NO STEPS OR GROOVES PERMITTED.
14. THE FULL CIRCULAR FILLET SHALL BE A SMOOTH CURVATURE WITH NO STEPS OR GROOVES.
15. THE TOOTH PROFILES AND FILLETS SHALL BE FINISH MACHINED BY FORM GRINDING WITH NO UNDERCUT PERMITTED.
16. BREAK ALL EDGES OF GEAR TEETH .005 TO .015.
17. HEAT TREATMENT

	AREA A	AREA B
A. VACUUM CARBURIZE ENCLOSED AREAS	AREA A	AREA B
B. CARBURIZED CASE HARDNESS ROCKWELL C	60-64	
C. EFFECTIVE CASE DEPTH AT ROCKWELL C50 AFTER GRINDING	.030-.045	
D. CORE HARDNESS ROCKWELL C	36-44	

E. DRAW AT 550°F ±25°F FOR FOUR HOURS AFTER FINAL GRIND.

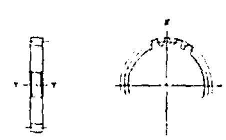
18. MATERIAL: 5 Cr-1.4 Mo, 1.35 W STEEL PER BMS 7-223 TYPE III.
19. HEAT TREATMENT:

A. VACUUM CARBURIZE ENCLOSED AREAS	AREA A
B. CARBURIZED CASE HARDNESS ROCKWELL C	60-64
C. EFFECTIVE CASE DEPTH AT ROCKWELL C50 AFTER GRINDING	.030-.045
D. CORE HARDNESS ROCKWELL C	32-42

E. DRAW AT 300°F-325°F FOR FOUR HOURS AFTER FINAL GRIND.

20. MATERIAL: 9310 STEEL PER BMS 7-249 TYPE III.

6. MAGNETIC PARTICLE INSPECTION REQUIREMENTS FOR PINION.



MAGNETISM

1. AXIS X-X ACROSS TEETH - TURN 90° FOR SECOND SHOT MAGNETIZE 1500 AMPS.
2. AXIS Y-Y CENTRAL CONDUCTOR MAGNETIZE 2000 AMPS.

ONE-HALF SCALE
COPY OF ORIGINAL DWG

PART NUMBER	DESCRIPTION	ZONE	MATERIALS AND SPECIFICATION	HT TR	FINISH	ET MK
SK30052-2	TEST PINION		20	19		[illegible]
SK30052-1	TEST PINION		HOH E TEMP 18	17		[illegible]

LIST OF MATERIALS

DIMENSIONING AND TOLERANCING PER MIL-STD-8

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

TOLERANCES

DIMENSIONS .X ±.1 .XX ±.01 .XXX ±.005

ANGLES ±.5°

THE BOEING COMPANY VERTOL DIVISION PHILADELPHIA PA.

TEST PINION

1:1 RATIO, VACUUM CARBURIZE ROTATING FATIGUE TEST

J 77272 SK30052

REVISIONS: A REVISED PER DCN

SK30052 | A

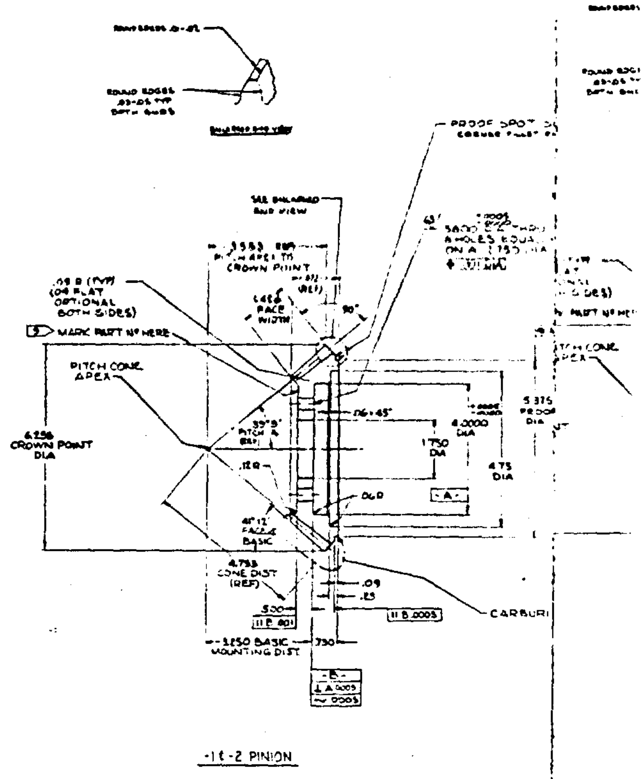
Best Available Copy

APPENDIX L ENGINEERING DRAWINGS OF SPIRAL BEVEL TEST GEAR

SK 30051

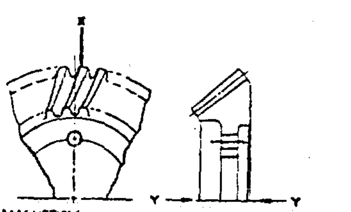
SPIRAL BEVEL GEAR DATA	
NUMBER OF TEETH	35
PITCH	5.8330
PRESSURE ANGLE	22° 30'
SPIRAL ANGLE (MEAN)	26° 0' LH
PITCH DIAMETER (A .001 T.I.R.)	6.000
SHAFT ANGLE (BASIC)	90° 0'
PITCH ANGLE (BASIC)	39° 9'
ROOT ANGLE (BASIC)	37° 38'
FILLET RADIUS (REF)	.020 - .030
PITCH TOLERANCE (AGMA CLASS 13)	.0002
TOTAL INDEX TOLERANCE (AGMA CLASS 13)	.0011
BACKLASH CONTRIBUTION OF GEAR WITH ZERO BACKLASH MASTER (NORMAL)	.0025 MIN .0035 MAX
WHOLE DEPTH	.315

REFERENCE DATA	
CIRCULAR TOOTH THICKNESS AT PITCH DIAMETER	.293
ADDENDUM (REF)	.164
DEDENDUM (REF)	.151
NORMAL CHORDAL THICKNESS AT PITCH DIAMETER	.235
NORMAL CHORDAL ADDENDUM	.162
BACKLASH WITH MATING GEAR ON STANDARD MOUNTING DISTANCE (NORMAL)	.005 MIN .007 MAX
NUMBER OF TEETH IN MATING GEAR	43
LOAD SIDE OF TOOTH	CONCAVE
GLEASON SUMMARY - 26 GENERATOR	146.656
GLEASON SUMMARY - 463 GRINDER	14[illegible].656
PART NUMBER OF MATING GEAR	SK 30050



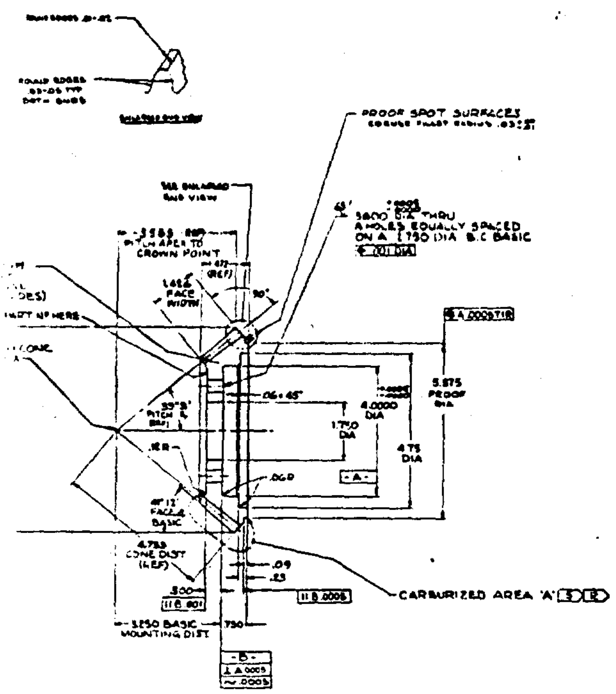
-1 & -2 PINION

(6) FLUORESCENT MAGNETIC PARTICAL INSPECTION PER BOEING SPEC BAC 5424 CLASS A CRITICAL.



MAGNETISM
1- AXIS X-X ACROSS TEETH - TURN 90° FOR SECOND SHOT 1800-2200 AMPS.
2- AXIS Y-Y CENTRAL CONDUCTOR FOR TEETH 2000-2400 AMPS.
3- COIL 500-800 AMPS.

Best Available Copy



-1, -2 PINION

NOTES:

1. ALL DIAMETERS ON A COMMON CENTER LINE TO BE CONCENTRIC TO EACH OTHER WITHIN .005 TIR UNLESS OTHERWISE NOTED.
2. MAXIMUM SURFACE ROUGHNESS EXCEPT AS NOTED.
3. FINISH ON GEAR TEETH: MIN MAX ON FLANKS ON FILLETS.
4. BREAK ALL SHARP EDGES NOT SPECIFIED TO A RADIUS OR CHAMFER OF .010 TO .020.
5. HEAT TREATMENT:
   - A. VACUUM CARBURIZE ENCLOSED AREAS — AREA 'A'
   - B. CARBURIZED CASE HARDNESS ROCKWELL C — 60-64
   - C. EFFECTIVE CASE DEPTH AT ROCKWELL C50 AFTER GRINDING — .035-.045
   - D. CORE HARDNESS ROCKWELL C — 36-44
   - E. DRAW AT 550°F±25°F FOR FOUR HOURS AFTER FINAL GRIND.
6. FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BOEING PROCESS SPECIFICATION BAC5424, CLASS A CRITICAL.
7. RELATIVE AZIMUTH POSITION OF GEAR TEETH AND HOLES OPTIONAL UNLESS SPECIFIED.
8. NITAL ETCH INSPECTION PER BOEING PROCESS SPECIFICATION BAC5436. DO NOT GRIT BLAST.
9. MARK PART AND SERIAL NUMBER HERE. VIBRO ETCH PER BOEING SPECIFICATION BAC5307 TYPE VE. DO NOT IMPRESSION STAMP. CHARACTERS 1/16 HIGH.
10. BILLET OR BAR SHALL HAVE A MINIMUM MECHANICAL REDUCTION OF 3 TO 1 FROM THE INGOT.
11. MATERIAL: 5 Cr - 1.4 Mo - 1.35 W STEEL PER BMS 7-223 TYPE III.
12. HEAT TREATMENT:
   - A. VACUUM CARBURIZE ENCLOSED AREAS — AREA A
   - B. CARBURIZED CASE HARDNESS ROCKWELL C — [illegible]
   - C. EFFECTIVE CASE DEPTH AT ROCKWELL C50 AFTER GRINDING — [illegible]
   - D. CORE HARDNESS ROCKWELL C — [illegible]
   - E. DRAW AT 300°F - 325°F FOR FOUR HOURS AFTER FINAL GRIND.
13. MATERIAL: 9310 STEEL PER BMS 7-249 TYPE III.

SK23408	SSG STAND	-2	A
SK23408	SSG-S	-1	-

CODE IDENT NO. 77272

DWG NO. SK30051

BASIC PART CODE

	REVISIONS	
A	REVISED PER DCN	

METERS ON A COMMON CENTER LINE TO BE CONCENTRIC
H OTHER WITHIN .005 TIR UNLESS OTHERWISE NOTED.
MUM SURFACE ROUGHNESS EXCEPT AS NOTED.
ON GEAR TEETH: MIN MAX ON FLANKS ON FILLETS.
ALL SHARP EDGES NOT SPECIFIED TO A RADIUS OR
FER OF .010 TO .020.
TREATMENT:

UUM CARBURIZE ENCLOSED AREAS	AREA 'A'
RBURIZED CASE HARDNESS ROCKWELL C	60-64
ECTIVE CASE DEPTH AT ROCKWELL C50	
ER GRINDING	.030-.045
HARDNESS ROCKWELL C	36-44

AT 550°F ±25°F FOR FOUR HOURS AFTER FINAL GRIND.
ESCENT MAGNETIC PARTICLE INSPECTION PER BOEING
SS SPECIFICATION BAC 5424, CLASS A CRITICAL.
E AZIMUTH POSITION OF GEAR TEETH AND HOLES OPTIONAL UNLESS SPECIFIED.
CH INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5436. DO NOT GRIT BLAST.
RT AND SERIAL NUMBER HERE, VIBRO ETCH PER BOEING SPECIFICATION BAC 5307
DO NOT IMPRESSION STAMP. CHARACTERS 3/16" HIGH.
H BAR SHALL HAVE A MINIMUM MECHANICAL REDUCTION OF 3 TO 1 FROM THE INGOT

A. 5 Cr - 1.4 Mo - 1.35 W STEEL PER BMS 7-223 TYPE III.
EATMENT

UUM CARBURIZE ENCLOSED AREAS	AREA 'A'
RBURIZED CASE HARDNESS ROCKWELL C	60-64
CTIVE CASE DEPTH AT ROCKWELL C50 AFTER GRINDING	.030-.045
HARDNESS ROCKWELL C	32-42

AT 300°F - 325°F FOR FOUR HOURS AFTER FINAL GRIND.
9310 STEEL PER BMS 7-240 TYPE III.

S.S.G. STAND	-2		A
S.S.G. STAND	-1		

ONE HALF SCALE
COPY OF ORIGINAL DWG

PART OR IDENTIFYING NUMBER	NOMENCLATURE OR DESCRIPTION	ZONE	MATERIAL & SPECIFICATION
SK30051-2	PINION		
SK30051-1	PINION		

THE BOEING COMPANY
VERTOL DIVISION PHILADELPHIA, PA.

PINION, SPIRAL BEVEL, TEST
VACUUM CARBURIZE

J 77272 SK30051

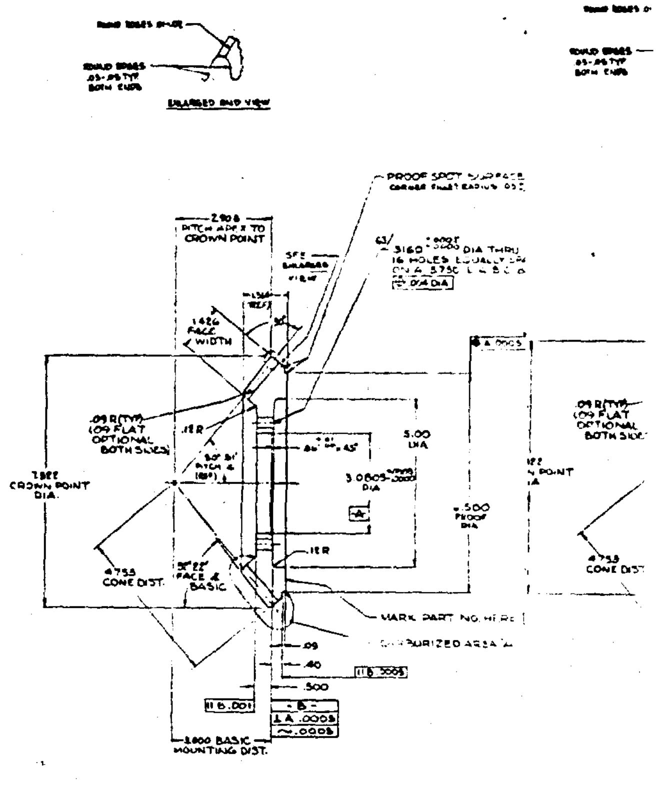
SK30051 A

Best Available Copy

SK 30050

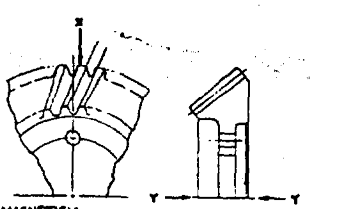
SPIRAL BEVEL GEAR DATA	
NUMBER OF TEETH	43
PITCH	5.8330
PRESSURE ANGLE	22° 30' 0"
SPIRAL ANGLE (MEAN)	26° 0' RH
PITCH DIAMETER ⌀A .001 TIR	7.372
SHAFT ANGLE (BASIC)	90° 0'
PITCH ANGLE (BASIC)	50° 51'
ROOT ANGLE (BASIC)	48° 48'
FILLET RADIUS (REF)	.040 - .050
PITCH TOLERANCE (AGMA CLASS 12)	.0002
TOTAL INDEX TOLERANCE (AGMA CLASS 12)	.0011
BACKLASH CONTRIBUTION OF GEAR WITH ZERO BACKLASH MASTER (NORMAL)	.0025 MIN .0035 MAX
WHOLE DEPTH	.315

REFERENCE DATA	
CIRCULAR TOOTH THICKNESS AT PITCH DIAMETER	.236
ADDENDUM (REF)	.119
DEDENDUM (REF)	.196
NORMAL CHORDAL THICKNESS AT PITCH DIAMETER	.193
NORMAL CHORDAL ADDENDUM	.118
BACKLASH WITH MATING GEAR ON STANDARD MOUNTING DISTANCE (NORMAL)	.005 MIN .007 MAX
NUMBER OF TEETH IN MATING GEAR	35
LOAD SIDE OF TOOTH	CONVEX
GLEASON SUMMARY - 26 GENERATOR	146.656
GLEASON SUMMARY - 463 GRINDER	146.656
PART NUMBER OF MATING GEAR	SK 30051



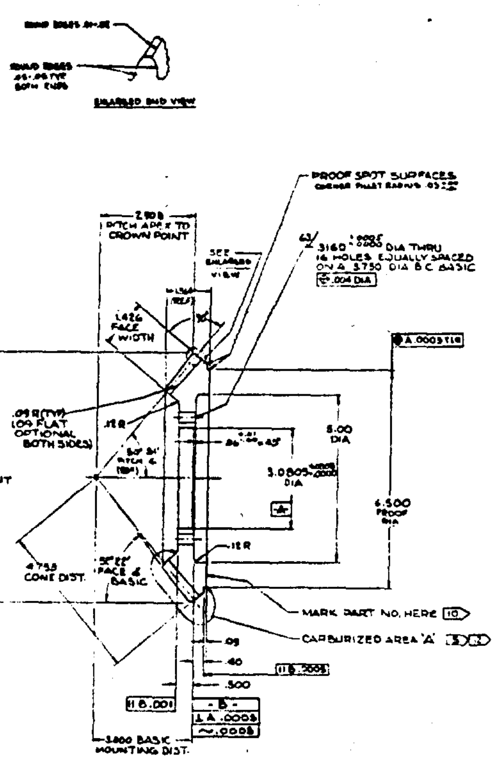
-1(-2 GEAR

FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BOEING SPEC BAC 5424 CLASS A CRITICAL.



MAGNETISM
1- AXIS X-X ACROSS TEETH - TURN 90° FOR SECOND SHOT 1800-2200 AMPS.
2- AXIS Y-Y CENTRAL CONDUCTOR FOR TEETH 2000-2400 AMPS
3- COIL 500-800 AMPS

Best Available Copy



-14-2 GEAR

NOTES:

1. ALL DIAMETERS ON A COMMON CENTER LINE TO BE CONCENTRIC TO EACH OTHER WITHIN .005 TIR UNLESS OTHERWISE NOTED
2. MAXIMUM SURFACE ROUGHNESS 125/ EXCEPT AS NOTED.
3. FINISH ON GEAR TEETH 16/ MIN 32/ MAX ON FLANKS 32/ ON FILLETS.
4. BREAK ALL SHARP EDGES NOT SPECIFIED TO A RADIUS OR CHAMFER OF .010 TO .020
5. HEAT TREATMENT:
   - A. VACUUM CARBURIZE ENCLOSED AREAS — AREA 'A'
   - B. CARBURIZED CASE HARDNESS ROCKWELL C — 60-64
   - C. EFFECTIVE CASE DEPTH AT ROCKWELL C50 AFTER GRINDING — .030-.045
   - D. CORE HARDNESS ROCKWELL C — 36-44
   - E. DRAW AT 550°F ± 25°F FOR FOUR HOURS AFTER FINAL GRIND.
6. FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5424, CLASS A CRITICAL.
7. MATERIAL: 5 Cr - 1.4 Mo - 1.35 W STEEL PER BMS 7-223 TYPE III.
8. RELATIVE AZIMUTH POSITION OF GEAR TEETH AND HOLES OPTIONAL UNLESS SPECIFIED
9. NITAL ETCH INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5436 DO NOT GRIT BLAST
10. MARK PART AND SERIAL NUMBER HERE VIBRO ETCH PER BOEING SPECIFICATION BAC 5307 TYPE 'VE' DO NOT IMPRESSION STAMP CHARACTERS 3/16 HIGH.
11. BILLET OR BAR SHALL HAVE A MINIMUM MECHANICAL REDUCTION OF 3 TO 1 FROM THE INGOT
12. HEAT TREATMENT:
    - A. VACUUM CARBURIZE ENCLOSED AREAS — AREA 'A'
    - B. CARBURIZED CASE HARDNESS ROCKWELL C — 60-64
    - C. EFFECTIVE CASE DEPTH AT ROCKWELL C50 AFTER GRINDING — .030-.045
    - D. CORE HARDNESS ROCKWELL C — 32-42
    - E. DRAW AT 300°F - 325°F FOR FOUR HOURS AFTER FINAL GRIND
13. MATERIAL: 9310 STEEL PER BMS 7-249 TYPE III.

CODE IDENT NO 77272

REVISIONS		
A	REVISED PER DCN	

METERS ON A COMMON CENTER LINE TO BE CONCENTRIC
OTHER WITHIN .005 TIR UNLESS OTHERWISE NOTED.
M SURFACE ROUGHNESS 125 EXCEPT AS NOTED.
ON GEAR TEETH: 15 MIN 17 MAX ON FLANKS 32 ON FILLETS.
ALL SHARP EDGES NOT SPECIFIED TO A RADIUS OR CHAMFER TO .020

REATMENT:

M CARBURIZE ENCLOSED AREAS	AREA 'A'
RIZED CASE HARDNESS ROCKWELL C	60-64
TIVE CASE DEPTH AT ROCKWELL C50 GRINDING	.030-.045
HARDNESS ROCKWELL C	36-44

AT 550°F ± 25°F FOR FOUR HOURS AFTER FINAL GRIND.
SCENT MAGNETIC PARTICLE INSPECTION PER BOEING SPECIFICATION BAC 5424, CLASS A CRITICAL.
AL: 5 Cr - 1.4 Mo, 1.35 W STEEL PER BMS 7-223 TYPE III.

AZIMUTH POSITION OF GEAR TEETH AND HOLES OPTIONAL UNLESS SPECIFIED
INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5436. DO NOT GRIT BLAST
AND SERIAL NUMBER HERE VIBRO ETCH PER BOEING SPECIFICATION BAC 5307
DO NOT IMPRESSION STAMP CHARACTERS 3/16 HIGH.
BAR SHALL HAVE A MINIMUM MECHANICAL REDUCTION OF 3 TO 1 FROM THE INGOT.

ATMENT:

M CARBURIZE ENCLOSED AREAS	AREA 'A'
RIZED CASE HARDNESS ROCKWELL C	60-64
TIVE CASE DEPTH AT ROCKWELL C50 AFTER GRINDING	.030-.045
HARDNESS ROCKWELL C	37-42

AT 300°F - 325°F FOR FOUR HOURS AFTER FINAL GRIND
AND STEEL PER BMS 7-249 TYPE III.

ONE HALF SCALE COPY OF ORIGINAL DWG

PART OR IDENTIFYING NUMBER	NOMENCLATURE OR DESCRIPTION	ZONE	MATERIAL & SPECIFICATION			
SK30050-2	GEAR		13	12		10
SK30050-1	GEAR		7	5		6

LIST OF MATERIAL

THE BOEING COMPANY
VERTOL DIVISION PHILADELPHIA PA

GEAR, SPIRAL BEVEL
TEST
VACUUM CARBURIZE

J 77272 SK30050

SK30050 1 A

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APPENDIX M FORMULA FOR DETERMINING EFFECTIVE CASE DEPTH (R/C 50) ON X2M CARBURIZING STEEL

FORMULA FOR DETERMINING EFFECTIVE CASE DEPTH

(R_c 50) ON X-2 CARBURIZING STEEL

STANLEY E. CASPER

CORPORATE METALLURGIST

C. I. HAYES INC.

9/23/82

FORMULA FOR DETERMINING EFFECTIVE CASE DEPTH

(R_c 50) ON X-2 CARBURIZING STEEL

INTRODUCTION

The carburization of hi-chrome materials requires one to address the problem of the tenacious oxide which serves to block carbon diffusion.

Vacuum carburization allows one to reduce the oxide at a relatively high temperature before cooling to a suitable carburization temperature. The choice of the latter is dependent on the complexity of the part (case uniformity) and the ability to break up the carbides. Generally, the higher temperature one carburizes hi-chrome alloys, the more difficult it is to dissolve the carbides.

After carburization it is desirable to diffuse at a temperature at least 50° F. higher in order to accelerate carbide solution.

The possibility of interrupting the process to do some intermediate machining always remains, therefore, allowances must be made for the "diffusion" that occurs during the final hardening process.

All of these factors constitute a multi-phase carburize and diffusion technique.

PHASE 1	Carburize (And diffuse if same temp.)
PHASE 2	Diffuse should temperature change
PHASE 3	Diffuse and harden sequence usually followed by a re-heat

2.

FORMULA: TWO PHASE PROCESS (See glossary on page M-11 for definition of symbols.)

$$d = k\sqrt{t}$$ Phase 1

$$t_2 = \left(\frac{d}{k_2}\right)^2$$

$$d_2 = k_2\sqrt{t_2 + c + t_3}$$ Phase 2

$$\therefore$$

$$d_2 = \frac{k\sqrt{t}}{\sqrt{t_2}}\left(\sqrt{t_2 + c + t_3}\right)$$

THREE PHASE PROCESS

$$d = k\sqrt{t}$$ Phase 1

$$t_2 = \left(\frac{d}{k_2}\right)^2$$ Phase 2

$$d_2 = k_2\sqrt{t_2 + t_3}$$

$$t_4 = \left(\frac{d_2}{k_3}\right)^2$$ Phase 3

$$d_3 = k_3\sqrt{t_4 + c + t_5}$$

$$\therefore$$

$$d_3 = \frac{\frac{k\sqrt{t}}{\sqrt{t_2}}\left(\sqrt{t_2 + t_3}\right)}{\sqrt{t_4}}\left[\sqrt{t_4 + c + t_5}\right]$$

3.

FORMULA - continued

ALTERNATE EXPRESSION - TWO PHASE PROCESS

$$d_2 = k_2 \left[\frac{k^2 t}{k_2^2} + c + t_3 \right]^{1/2}$$

THREE PHASE PROCESS

$$d_3 = k_3 \sqrt{ \left[\frac{k_2 \sqrt{\frac{k^2 t}{k_2^2} + t_3}}{k_3} \right]^2 + c + t_5 }$$

SUBSTANTIATION:

Assume on X-2

The diffusion constant "k" is 95% of 9310 (data for 9310 previously submitted)

TEMP.	9310	X-2
1650° F.	k=.016	k=.015
1700° F.	k=.020	k=.019
1750° F.	k=.024	k=.023
1800° F.	k=.030	k=.0285
1850° F.	k=.035	k=.033
1900° F.	k=.040	k=.038
1950° F.	k=.045	k=.043

TEST RUN ON 9/20/82:

Carburize at 1800° F. for 150 minutes
Diffuse at 1800° F. for 315 minutes

TOTAL....465 minutes

Phase 1

$$d = k\sqrt{t} = .0285\sqrt{\frac{465}{60}} = .0793"$$

The parts were gas quenched and annealed to simulate intermediate machining. They were then reheated to 1850° F. for 30 minutes and oil quenched.

Phase 2

$$t_2 = \left(\frac{d}{k_2}\right)^2 = \left(\frac{.0793}{.033}\right)^2 = 5.775 \text{ hrs.}$$

$$d_2 = k_2\sqrt{t_2 + c + t_3} = .033\sqrt{5.775 + .17 + 5}$$

$$d_2 = .084"$$

Actual .086" - .090"

TEST RUN ON 8/30/82

Carburize at 1800^{o} F. for....150 minutes

Diffuse at 1800^{o} F. for......255 minutes
TOTAL...... 405 minutes

Phase 1

$$d = k\sqrt{t} = .0285\sqrt{\frac{405}{60}} = .074"$$

The parts were gas quenched and annealed to simulate intermediate machining. They were then reheated to 1550^{o} for 30 minutes and oil quenched.

Phase 2

$$t_2 = \left(\frac{d}{k_2}\right)^2 = \left(\frac{.074}{.033}\right)^2 = 5.03$$

$$d_2 = k_2\sqrt{t_2 + c + t_3} = .033\sqrt{5.03 + .17 + .5}$$

$$d_2 = .079"$$

Actual .075" - .080"

TEST RUN ON 8/20/32

Carburize at 1750° F. for......90 minutes
Diffuse at 1750° F. for.........5 minutes
TOTAL......95 minutes

Phase 1

$$d = k\sqrt{t} = .023\sqrt{\frac{95}{60}} = .029''$$

The parts were gas quenched and annealed for simulation purposes. They were reheated to 1850° F. for 30 minutes and oil quenched.

Phase 2

$$t_2 = \left(\frac{d}{k_2}\right)^2 = \left(\frac{.029}{.033}\right)^2 = .772 \text{ hours}$$

$$d_2 = k_2\sqrt{t_2 + c + t_3} = .033\sqrt{.772 + .17 + .5}$$

$$d_2 = .040''$$

Actual parts revealed .048". Since this error was greater than 10% a check was made on furnace temperature. It was discovered that a temperature error of 30° F. existed, whereby the parts actually saw 1780° F. and 1880° F., respectively.

A recalculation substituting

k as .026

k_2 as .036

$$d_2 = .045''$$

TEST RUN ON 6/16/82

Carburize at 1750° F. for......90 minutes
Diffuse at 1750° F. for.........4 minutes
TOTAL......94 minutes

Phase 1

$$d = k\sqrt{t} = .023\sqrt{\frac{94}{60}} = .029"$$

The parts were gas quenched and annealed. They were reheated to 1550° F. for 20 minutes and oil quenched.

Phase 2

$$t_2 = \left(\frac{d}{k_2}\right)^2 = \left(\frac{.029}{.033}\right)^2 = .772 \text{ hours}$$

$$d_2 = k_2\sqrt{t_2 + c + t_3} = .033\sqrt{.772 + .17 + .333}$$

$$d_2 = .0373$$

Actual .038"

TEST RUN ON 6/18/82

SAME CYCLE AS ABOVE

Actual .040"

TEST RUN ON 11/14/79

Carburize at 1650^{0} F. for 30 minutes

Phase 1

$$d = k\sqrt{t} = .015\sqrt{.5} = .0106''$$

Parts were heated to 1850^{0} F. and soaked 40 minutes (this was not a reheat, no constant applied).

Phase 2

$$t_2 = \left(\frac{d}{k_2}\right)^2 = \left(\frac{.0106}{.033}\right)^2 = 0.10 \text{ hours}$$

$$d_2 = k_2\sqrt{t_2 + t_3} = .033\sqrt{.10 + .67} = .029''$$

The parts were gas quenched, reheated to 1850^{0} F. for 40 minutes and oil quenched.

Phase 3

$$t_4 = \left(\frac{d_2}{k_3}\right)^2 = \left(\frac{.029''}{.033}\right)^2 = .77 \text{ hours}$$

$$d_3 = k_3\sqrt{t_4 + c + t_5} = .033\sqrt{.77 + .17 + .67} = .042''$$

*Actual .036"

*NOTE: This is not within the ± 10%. Impossible to determine if furnace problem existed because of date of test. Sample examination indicated a lean case indicating some problem (most likely temperature) as in 8/20/82 test.

This will be rechecked when time allows.

TEST RUN ON 6/22/79

Carburize at 1650° F. for 17 minutes

Phase 1

$$d = k\sqrt{t} = .015\sqrt{.283} = .008''$$

Parts were heated to 1950° F. for 40 minutes. (No reheat utilized, therefore no constant was used).

Phase 2

$$t_2 = \left(\frac{d}{k_2}\right)^2 = \left(\frac{.008''}{.043}\right)^2 = .035 \text{ hours}$$

$$d_2 = k_2\sqrt{t_2 + t_3} = .043\sqrt{.035 + .67} = .036$$

Actual .040"

TEST RUN ON 5/30/79

Same as 6/22/79

GLOSSARY OF SYMBOLS

d - Initial effective case depth in thousandths of an inch formed in first carburize and/or diffuse at any single temperature

k - Diffusion constant for temperature used in PHASE 1

t - Time in hours for the first carburize and/or diffusion at any single temperature

t_2 - Time in hours required to create "d" at new PHASE 2 diffusion temperature

k_2 - Diffusion constant for temperature used in PHASE 2

d_2 - Effective case depth in thousandths of an inch formed after diffusion in PHASE 2

t_3 - Time of diffusion in hours in PHASE 2

c - Reheat constant in hours, i.e., one inch cross section heated to 1800° F. - 1950° F. is .17

t_4 - Time in hours required to create d_2 at a new PHASE 3 temperature

k_3 - Diffusion constant for temperature used in PHASE 3

d_3 - Effective case depth in thousandths of an inch formed after diffusion in PHASE 3

t_5 - Time of diffusion in hours in PHASE 3

APPENDIX N HAYES VACUUM CARBURIZING EVALUATIONS FOR 9310

AISI 9310 HARDNESS SURVEY

.002..............R_c66.5

.005..............R_c65

.010..............R_c63.5

.015..............R_c63.5

.020..............R_c63.5

.025..............R_c65

.030..............R_c62.5

.040..............R_c63.5

.050..............R_c63.5

.060..............R_c62.5

.070..............R_c58

.080..............R_c54

.085..............R_c50.5

.090..............R_c48

As before Roy, I would appreciate your carbon data to correlate with our Leco.

Thank you.

Very truly yours,

C. I. HAYES INC.

S.E. Casper

Stanley E. Casper
Corporate Metallurgist

SEC:esc

Mr. Roy Cunningham
September 22, 1982
Page 4

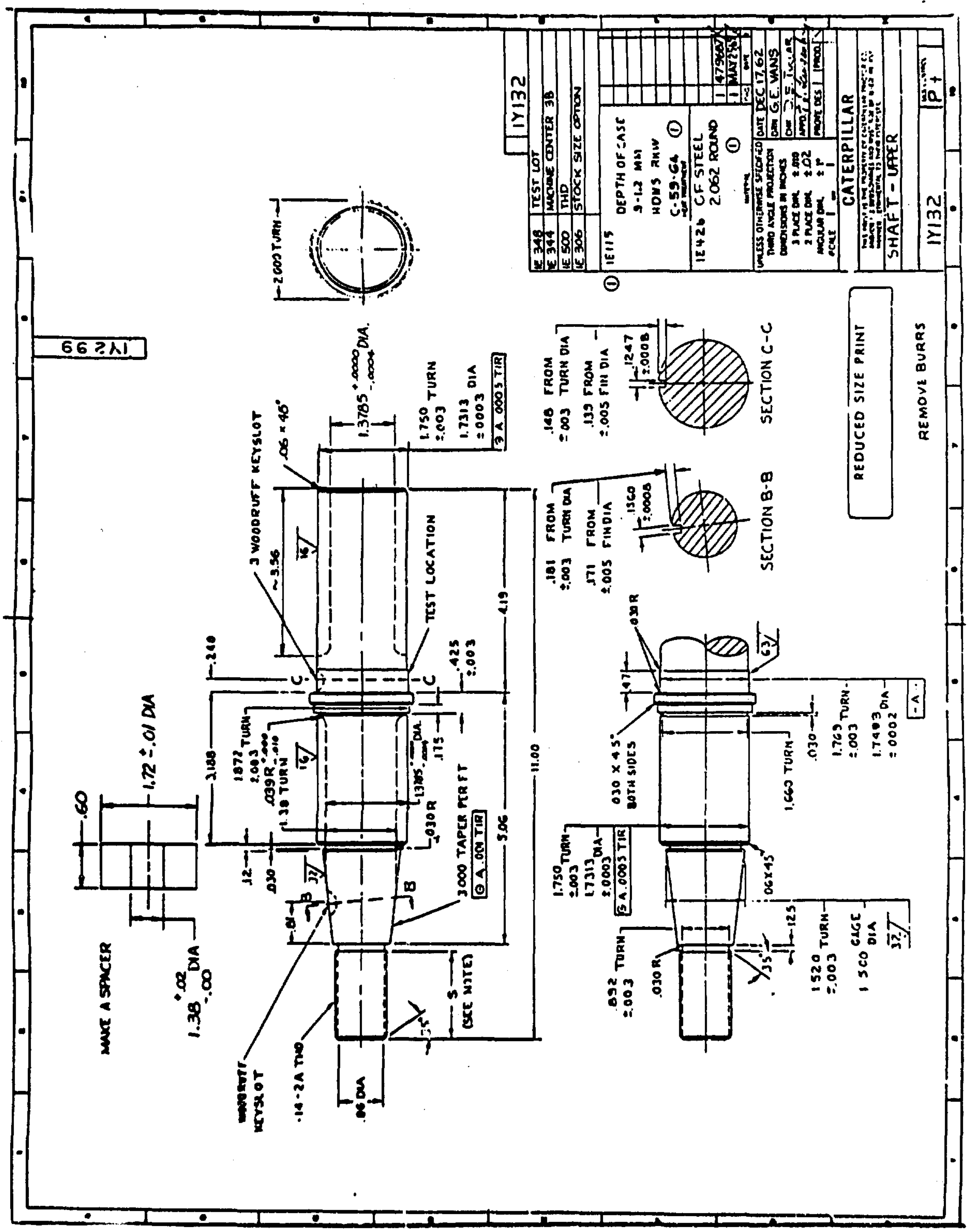
On August 26, 1982, a test run was made on AISI 9310 to confirm the charts already submitted to Boeing.

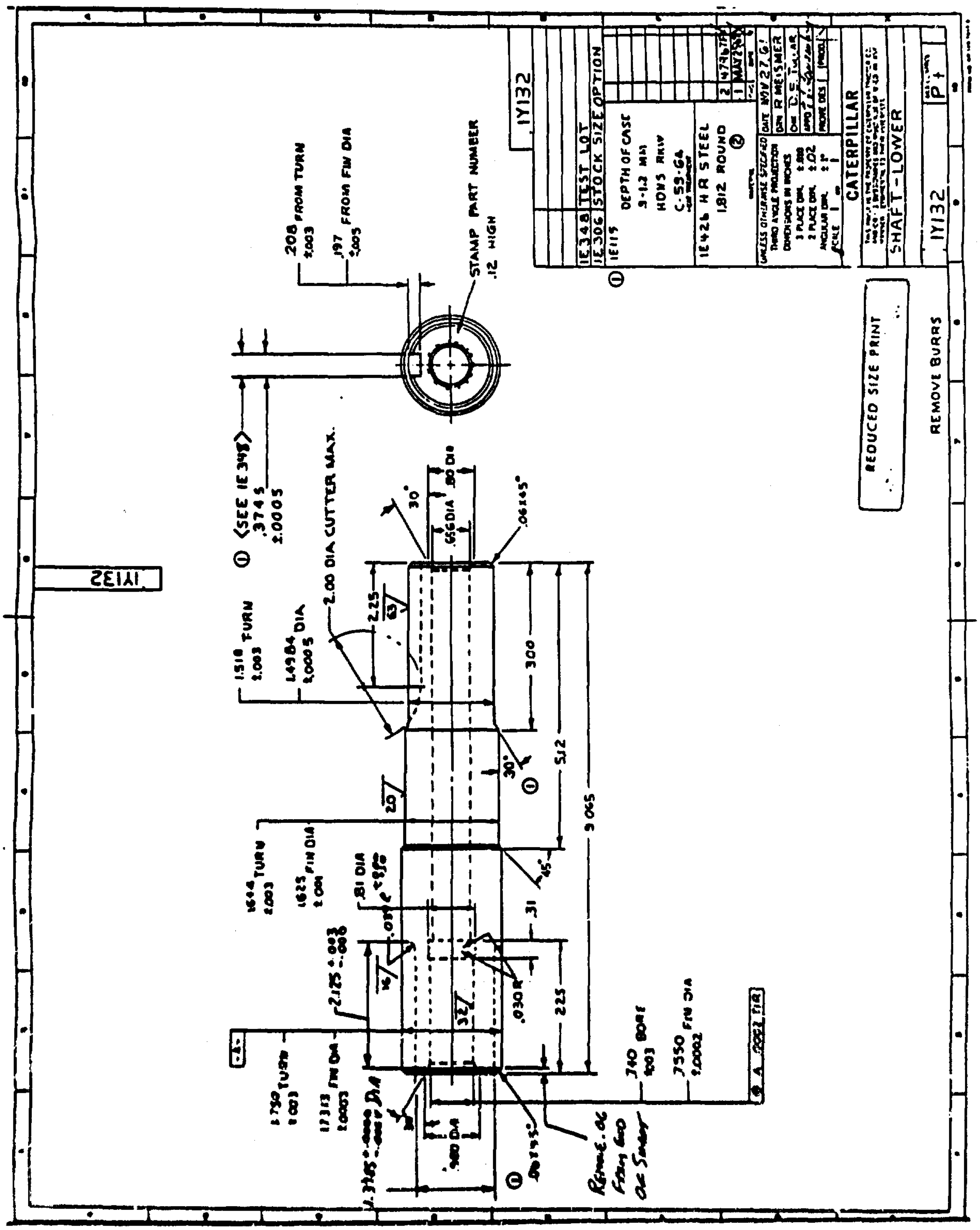
The object of this test was to produce .085" effective case depth.

The cycle was:

Heat to 1900° F.	
Soak at 1900° F.	30 minutes
Carb at 1900° F.	60 minutes
CH_4 - 250 Torr 7[illegible]CF/hr.	
Diff. at 1900° F.	210 minutes
Gas Quench	
Reheat to 1550° F.	
Soak at 1550° F.	40 minutes
Oil quench	
Freeze at -120° F.	120 minutes

APPENDIX O GEARED ROLLER TEST MACHINE DRAWINGS





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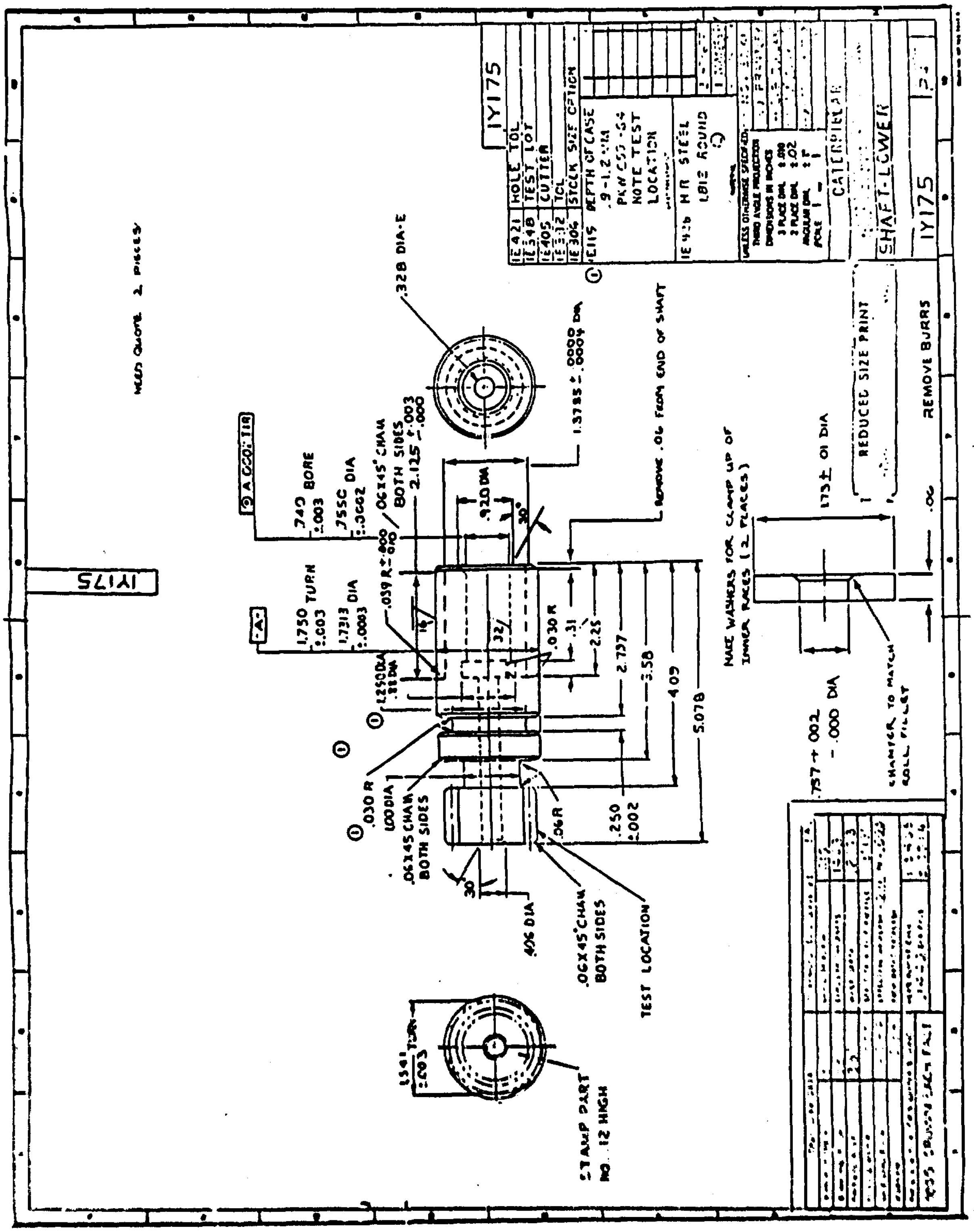
APPENDIX O GEARED ROLLER TEST MACHINE DRAWINGS (CONTINUED)



APPENDIX P
GEARED ROLLER RAW TEST DATA FOR AISI 9310

Heat Treat	Specimen I.D.	Start Date	Oil Temp	Roll RPM	Load (lbs)	Hertz stress (ksi)	Hrs to Failure	Cycles to Failure	Comments
Summit heat treat at 1,900°F	14	1/26/83	200°F	1,000	2,605	450	14.3	858,000	
	12	1/27/83	200°F	920	2,605	450	63.8	3,521,760	
	10	1/27/83	200°F	1,000	2,605	450	30.7	1,842,000	
	15	1/27/83	200°F	920	2,605	450	29.1	1,606,320	
	13	2/6/83	200°F	920	2,605	450	17.3	954,960	
TEST STOPPED									
Hayes heat treat at 1,900°F	15	1/25/83	200°F	1,000	2,605	450	21.1	726,000	
	9	1/25/83	200°F	920	2,605	450	12.5	690,000	
	3	1/25/83	200°F	920	2,605	450	3.3	– ←	Oil jet clog -
	12	2/6/83	200°F	1,000	2,605	450	28.0	1,680,000	invalid data
	13	2/6/83	200°F	920	2,605	450	19.1	1,054,320	
TEST STOPPED									
Summit heat treat at 1,900°F	2	1/20/83	200°F	920	2,605	450	16.2	894,240	
	3	1/20/83	200°F	1,000	2,605	450	16.9	1,014,000	
	1	1/21/83	200°F	920	2,605	450	17.1	943,920	
	4	1/21/83	200°F	1,000	2,605	450	18.3	1,098,000	
	5	1/21/83	200°F	920	2,605	450	23.4	1,291,680	Cracked
	6	1/24/83	200°F	920	2,605	450	5.1	– ←	slave roll -
	7	1/24/83	200°F	920	2,605	450	12.9	712,080	invalid data
TEST STOPPED									
Hayes heat treat at 1,900°F	1	1/24/83	200°F	1,000	2,605	450	12.1	726,000	
	12	1/26/83	200°F	920	2,605	450	22.05	1,217,160	
	14	1/26/83	200°F	920	2,605	450	6.5	358,800	
	7	1/31/83	200°F	920	2,605	450	9.8	540,960	
	10	1/31/83	200°F	920	2,605	450	17.5	966,000	
	13	2/2/83	200°F	920	2,605	450	22.8	1,258,560	
TEST STOPPED									
Summit heat treat at 1,800°F	1	9/22/83	200°F	920	2,605	450	18.9	1,043,280	
	2	9/26/83	200°F	920	2,605	450	14.2	783,840	
	3	9/27/83	200°F	920	2,605	450	29.0	1,600,800	
	4	9/30/83	200°F	920	2,605	450	22.9	1,264,080	
	5	10/3/83	200°F	920	2,605	450	29.4	1,622,880	
	6	10/5/83	200°F	920	2,605	450	11.4	629,280	
	7	10/7/83	200°F	920	2,605	450	22.8	1,258,560	
	8	10/11/83	200°F	920	2,605	450	47.6	2,627,520	Roller
	9	10/14/83	200°F	920	2,605	450	60.6	3,345,120	slipped
	10	10/19/83	200°F	920	2,605	450	160.0	– ←	invalid data
TEST STOPPED									

APPENDIX Q SINGLE TOOTH BENDING FATIGUE TEST RAW DATA

SINGLE TOOTH FATIGUE TEST
VASCO X2M RAW DATA
HEAT TREATER "A" (SUMMIT GEAR)

	STRESS	CYCLES	SERIAL NUMBER	TOOTH NUMBER	LOADING STEADY	LOADING ALTERNATING	
VASCO SK29572-1							
(MILL HEAT:	274,114	27,000	001A	2	5100	5000	
5842A, TELEDYNE	187,266	17,000	002A	1	3500	3400	
VASCO)	165,554	37,000		2	3100	3000	
	154,698	56,000		3	2900	2800	
	138,414	55,000		4	2600	2500	
	208,978	22,000	003A	1	3900	3800	
	198,122	35,000		2	3700	3600	
	187,266	35,000		3	3500	3400	
	168,268	63,000		4	3100	3000	
	241,546	32,000	004A	2	4500	4400	
	230,690	26,000		3	4300	4200	
	219,834	27,000		4	4100	4000	
VASCO	214,406	20,000	001A	1	4000	3900	
SK29572-2	203,550	32,000		2	3800	3700	
	192,694	39,000		3	3600	3500	
(MILL HEAT:	181,838	87,000		4	3400	3300	
86510, CARTECH)	170,982	29,000	002A	1	3200	3100	
	160,126	228,000		2	3000	2900	
	142,270	8,215,000		3	2800	2700*	
	154,698	231,000		4	2900	2800	
	160,126	11,954,000	003A	1	3000	2900*	
	181,838	95,000		2	3400	3300	
	170,982	5,563,000		3	3200	3100	
	187,266	3,979,000		4	3500	3400	
	208,978	13,000	004A	1	3900	3800	
	203,550	9,000		2	3800	3700	
	198,122	19,000		3	3700	3600	
	192,694	20,000		4	3600	3500	

*RUNOUT, NO FAILURE

SINGLE TOOTH FATIGUE TEST
VASCO X2M RAW DATA
HEAT TREATER "B" (C. I. HAYES)

	STRESS	CYCLES	SERIAL NUMBER	TOOTH NUMBER	LOADING STEADY	LOADING ALTERNATING ±	
VASCO	214,406	8,349,000	001B	1	4000	4000	
SK29572-1	241,546	6,434,000		2	4300	4200*	
	252,402	97,000		3	4700	4600	
(MILL HEAT:	246,974	9,000		4	4600	4500	
5842A, TELEDYNE	214,406	4,758,000	002B	1	4000	3900	
VASCO)	214,406	3,037,000		2	4000	3900	
	214,406	1,230,000		3	4000	3900	
	241,546	10,000		4	4500	4400	
	214,406	21,000	003B	1	4000	3900	
	214,406	13,000		2	4000	3900	
	203,550	7,000		3	3800	3700	
	187,266	6,000,000		4	3500	3400*	
	208,978	23,000	004B	1	3900	3800	
	176,410	8,351,000		2	3300	3200*	
	198,122	39,000		3	3700	3600	
	187,266	173,000		4	3500	3400	
VASCO	187,266	8,606,000	001B	1	3500	3400*	
SK29572-2	214,406	6,890,000		2	4000	3900	
	241,546	34,000		3	4500	4500	
(MILL HEAT:	230,690	29,000		4	4300	4300	
86510, CARTECH)	241,546	3,379,000	002B	1	4500	4400	
	246,974	67,000		2	4600	4500	
	252,402	127,000		3	4700	4600	
	236,118	28,000		4	4400	4300	
	241,546	42,000	003B	1	4500	4400	
	230,690	25,000		2	4300	4200	
	219,834	35,000		3	4100	4000	
	203,550	6,794,000		4	3800	3700*	
	219,834	17,000	004B	1	4100	4000	
	214,406	33,000		3	4000	3900	
	208,978	29,000		4	3900	3800	

*RUNOUT, NO FAILURE

SINGLE TOOTH BENDING FATIGUE TEST
9310 RAW DATA

	HEAT TREATER A (SUMMIT GEAR)		SERIAL NUMBER	TOOTH NUMBER	LOADING LB	
	STRESS	CYCLES			STEADY	ALTERNATING
SK 29572-10 (MILL HEAT 87385-2 CARTECH)	230,690	6,616,000*	001A	1	4,300	4,200*
	252,402	91,000		2	4,700	4,600
	246,974	8,645,000*		3	4,600	4,500*
	257,830	6,520,000*		4	4,800	4,700*
	263,258	1,213,000	003A	1	4,900	4,800
	274,114	617,000		2	5,100	5,000
	284,970	190,000		3	5,300	5,200
	290,398	28,000		4	5,400	5,300
	284,970	2,255,000	004A	1	5,300	5,200
	290,398	58,000		2	5,400	5,300
	279,542	4,215,000		3	5,200	5,100
	295,326	1,037,000		4	5,500	5,400

*RUNOUT, NO FAILURE

VACUUM CARBURIZING PROGRAM - PHASE IV
7000 ● 53249 ● 00400 ● 000000
SINGLE TOOTH BENDING FATIGUE
<u>SUMMARY SHEET</u>

SPECIMEN		TEST DATES		APPLIED LOAD LB STEADY & ALTERNATING	FATIGUE CYCLES x10[6]	REMARKS	APPLIED STRESS
NO.	TOOTH	START	STOP				
001A	NO. 1	11-26-85	11-26-85	4,700 ± 4,600	0.084	FAILURE	228,676
	NO. 2	11-27-85	11-27-85	4,000 ± 3,900	0.022	FAILURE	194,251
	NO. 3	12-4-85	12-4-85	4,700 ± 4,600	0.520	FAILURE	228,676
	NO. 4	12-6-85	12-9-85	3,800 ± 3,700	5.327	FAILURE	184,416
003A	NO. 1	12-10-85	12-13-85	3,500 ± 3,400	6.658	FAILURE	169,663
004A	NO. 1	11-27-85	11-27-85	4,000 ± 3,900	0.141	FAILURE	194,251
	NO. 3	11-27-85	12-3-85	4,000 ± 3,900	5.767	FAILURE	194,251

APPENDIX R SCORE TEST RAW DATA

ROTATING SCORING TEST

9310 RAW DATA

	HEAT TREATER A (SUMMIT GEAR)	
	S/N	TF
SK 29571-1	10A/9A	389.
(MILL HEAT 87885-2	"	388.
CARTECH)	5A/4A	408.
	"	409.
	7A/2A	444.
	"	435.
	3A/17A	406.
	"	439.
	18A/16A	414.
	"	440.
	21A/19A	422.
	"	411.
	15A/13A	420.
	"	421.
	12A/11A	424.
	"	442.
	8A/14A	413.
	"	420.
	22A/20A	436.
	"	430.

ROTATING SCORING TEST

VASCO X2M RAW DATA

	HEAT TREATER "A" (SUMMIT GEAR)		HEAT TREATER "B" (C.I. HAYES)	
	S/N	T_F	S/N	T_F
SK29571-1 (MILL HEAT: 5842A, TELEDYNE VASCO)	9A/5A	519	9B/8B	470
	"	513	"	489
	6A/7A	538	10B/4B	465
	"	550	"	466
	3A/1A	550	6B/5B	485
	"	506	"	505
	2A/4A	532	7B/3B	461
	"	527	"	484
	10A/8A	552	3B/1B	500
	"	542	"	483
SK29571-2 (MILL HEAT: 86[illegible]10, CARTECH)	8A/9A	531	5B/4B	459
	"	496	"	472
	5A/6A	523	3B/2B	468
	"	531	"	441
	1A/7A	523	8B/1B	471
	"	543	"	458
	3A/4A	523	7B/6B	459
	"	519	"	495
	2A/10A	538	10B/9B	467
	"	532	"	500

APPENDIX S SPIRAL BEVEL INPUT PINION GEAR DRAWING

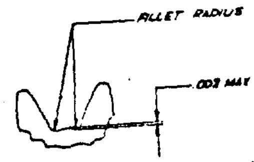
INVOLUTE SPLINE DATA	FIT	
TYPE FILLET ROOT SIDE FIT	—	
CLASS	32	
NO. OF TEETH	24/32	
DIAMETRAL PITCH	2.0000	
PITCH DIA	2.0625 +.0000 -.0020	
MAJOR DIA	1.8750 +.0000 -.0010	
MINOR DIA	30°	
PRESSURE ANGLE	1.7321	
BASE CIRCLE DIA (REF)	.0937	
CIRCULAR TOOTH THICKNESS MINIMUM DIMENSIONAL	.0967	
MAX EFF WITH GAUGE	.1200	
MEASURING PIN DIA	2.1747	
PIN DIM MIN	.015	
FILLET RADIUS MIN	1.9995	
TIF DIA MAX	—	
MAX OUT OF ROUNDNESS	.0016	
TOTAL INDEX TOLERANCE		
INVOLUTE PROFILE TOL. ERROR AT PITCH POINT	+.0003-.0003	
LEAD TOLERANCE	[illegible]	

GEAR DATA

TYPE	SPIRAL BEVEL
NUMBER TEETH	13
DIAMETRAL PITCH	4.050
PITCH DIAMETER	6.404
PRESSURE ANGLE	22° 30'
ADDENDUM (REF)	.228
CIRCULAR THICKNESS AT PITCH DIA (REF)	.376-.381
WHOLE DEPTH	.389-.399
DEDENDUM (REF)	.161
CLEARANCE	—
MAX TOOTH TO TOOTH SPACING ERROR	.0003
MAX CUMULATIVE SPACING ERROR	.0015
PIN DIMENSION	—
MEASURING PIN DIA	—
FILLET RADIUS	.045-.055
TIF DIA	—
BASE CIRCLE DIA	—
MAX INVOLUTE PROFILE ERROR	—
MAX LEAD ERROR IN/IN	—
SHAFT ANGLE	90° 0'
SPIRAL/HELIX ANGLE	35° 0'
HAND OF SPIRAL/HELIX	RH
PITCH ANGLE	30° 31'
DRIVER OR DRIVEN	DRIVER
DIRECTION OF ROTATION	CCW
SPEED – RPM	—
BACKLASH CONTRIBUTION OF GEAR WITH MASTER IN PLANE OF ROTATION	.003-.003
PART NO OF MATING GEAR	11405744
NUMBER TEETH – MATING GEAR (REF)	56
NORMAL CORRECTED ADDENDUM (REF)	.230
LOAD SIDE OF TOOTH (REF)	CONCAVE
BACKLASH WITH MATING GEAR ON STAND MTG DIST (PLANE OF ROTATION) (REF)	.006-.016
NORMAL CHORDAL THICKNESS AT PITCH DIA (REF)	.310-.314
GLEASON SUMMARY (NO. 2 GENERATOR)	129 445 (REF)
GLEASON SUMMARY (NO 16 HYPOID GEN)	132 088 (REF)

NOTES

1. BEVEL GEAR TEETH TO BE GROUND TO MATCH MASTER WITHIN THE FOLLOWING LIMITS:
   A. CENTRAL LOAD AND COAST PATTERN LIMITS:
      a) LENGTHWISE POSITION: LOCATION OF ENDS OF PATTERN ALONG LENGTH OF TOOTH SHALL MATCH MASTER WITHIN ±10% OF THE FACE WIDTH FROM EITHER END OF TOOTH.
      b) LENGTH: LENGTH OF PATTERN SHALL MATCH MASTER WITHIN ±10% OF FACE WIDTH OF TOOTH.
      c) DEPTH POSITION: DISTANCE FROM TOP OF TOOTH TO TOP OF PATTERN SHALL MATCH MASTER WITHIN ±.04
   B. ADDITIONAL LOAD SIDE PATTERN LIMITS:
      TOE VERT ±.0015 HORIZ ±.00
      HEEL VERT ±.003 HORIZ ±.00
      PROFILE VERT ±.000 HORIZ ±.003
      TOTAL VERT ±.003 HORIZ ±.00
      BIAS ±.003



TYPICAL NORMAL SECTION THROUGH BEVEL GEAR TEETH

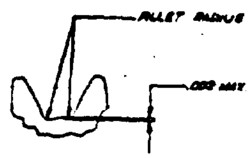
NOTES

...EAR TEETH TO BE GROUND
...H MASTER WITHIN THE
...NG LIMITS:

...LOAD AND COAST PATTERN LIMITS:
...VERSE POSITION (LOCATION OF
...OF PATTERN ALONG LENGTH OF
... SHALL MATCH MASTER WITHIN
...OF THE FACE WIDTH FROM EITHER
...OF TOOTH.
...TH: LENGTH OF PATTERN SHALL MATCH
...R WITHIN ...% OF FACE WIDTH OF TOOTH.
... POSITION: DISTANCE FROM TOP OF
... TO TOP OF PATTERN SHALL MATCH
... WITHIN ±.04

...LOAD SIDE PATTERN LIMITS:

...EPT ±.0015	HORIZ ±.00
...EPT ±.003	HORIZ ±.00
...EPT ±.000	HORIZ ±.003
...EPT ±.003	HORIZ ±.00
...003	



...PICAL NORMAL SECTION
...AR TEETH ...

NOTES:

1 BREAK ALL SHARP EDGES NOT SPECIFIED TO A RADIUS OR CHAMFER OF .010 TO .025

2 PART NO. 114D5245-1,-5 & -7 IS A CRITICAL PART AND REQUIRES ALL TESTS AND RECORDS SPECIFIED THEREFOR IN BOEING PROCESS SPEC MS 14.00

3 ALL DIAMETERS ON A COMMON CENTERLINE TO BE CONCENTRIC TO EACH OTHER WITHIN .010 T.I.R.

4 – MAXIMUM SURFACE ROUGHNESS 125/ EXCEPT AS NOTED.

5 – FINISH ON GEAR TEETH 25/ FLANKS AND 32/ FILLETS. SURFACE FINISH REQUIREMENTS TO BE MET AFTER FINAL PROCESSING

6 – RELATIVE AZIMUTH POSITION OF GEAR TEETH, SPLINE TEETH AND HOLES OPTIONAL UNLESS SPECIFIED.

7 – HEAT TREATMENT

A. CARBURIZE ENCLOSED AREAS PER BOEING SPEC. MS 12.02.

	A
B. CARBURIZED CASE HARDNESS ROCKWELL C	59-64
C. EFFECTIVE CASE DEPTH AFTER GRINDING	.030-.050
D. CORE HARDNESS ROCKWELL C 24	32-42
E. CORE STRENGTH PSI (REF)	142000-194000

F DRAW FOR 4 HOURS AT 300°-325°F AFTER FINAL GRIND

8 – SEE ZONE H11

9 NITAL ETCH INSPECTION PER BOEING SPEC MS 14.04 PRIOR TO SHOTPEENING

10 FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BOEING SPEC BAC 5424, CLASS A

11 SHOTPEEN ENCLOSED AREA PER BOEING SPEC MS 21.01
A SHOT SIZE 110
B ARC HEIGHT .008-.012 ALMEN A2
C COVERAGE 200%

12 MATERIAL – 9310 FORGING STEEL
MATL SPEC – BMS 7-6

13 MAKE FROM 114D5245-F3 FORGING

14 MAKE FROM 114D5245-F2, F3 OR RMF4 FORGINGS

15 FINISH BLACK OXIDE TREATMENT PER BOEING SPEC MS 8.17

16 HANDLE PART PER VERTOL SPEC PS-172.

17 [illegible]

18 SHOT PEENING PERMISSIBLE IN GROOVE & .375 DIA BRG PUSH-OUT HOLES NOT MANDATORY. DO NOT MASK.

19 114D5245 GEARS TO BE STATICALLY BALANCED TO .02 IN-OUNCE REMOVE MATERIAL FROM INDICATED AREA

20 MARK ACTUAL MOUNTING DISTANCE AND BACKLASH HERE

21 ALL THREADS PER FEDERAL HANDBOOK H-28 AND MIL-S-7742

22. QUALITY CONTROL REQUIRED IN ACCORDANCE WITH BOEING PROCESS SPEC MS 14.02.

23

24 CORE HARDNESS VARIATION IS NOT TO EXCEED FOUR ROCKWELL C POINTS FOR A PART NUMBER IN A MILL HEAT LOT.

25 NO MRB ACTION PERMITTED ON THESE DIMENSIONS.

26 MATERIAL-9310 FORGING STEEL PER BMS7-249 TYPE I.

27 MAKE FROM 114D5245-F6 OR -RMF8 FORGING.

28 MAKE FROM 114D5245-F6 FORGING.

114D5200	CH-47C			-7			J
114D5200	CH-47C			-5			F
114D5200	CH-47BC			-1			
			APPLICATION				

CODE IDENT NO 77272 DWG NO 114D5245 | 1

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EDGES NOT SPECIFIED TO A RADIUS OR CHAMFER

...-7 IS A CRITICAL PART AND REQUIRES ALL ...DOCS SPECIFIED THEREFOR IN BOEING ... MS 14.00

ON A COMMON CENTERLINE TO BE CONCENTRIC WITHIN .010 T.I.R.

...URFACE ROUGHNESS 125/ EXCEPT AS NOTED.

...EAR TEETH 25/ FLANKS AND 32/ FILLETS. ...N REQUIREMENTS TO BE MET AFTER FINAL PROCESSING

...ZIMUTH POSITION OF GEAR TEETH, SPLINE ...HOLES OPTIONAL UNLESS SPECIFIED

...MENT

...IZE ENCLOSED AREAS PER ... SPEC MS 12.02

	A
...IZED CASE HARDNESS ROCKWELL C	59-64
...VE CASE DEPTH AFTER GRINDING	.030-.050
...HARDNESS ROCKWELL C (24)	32-42
...STRENGTH PSI (REF)	148000-194000

...FOR 4 HOURS AT 300°-325F ... FINAL GRIND

...INSPECTION PER BOEING SPEC MS 14.04 PRIOR ...

... MAGNETIC PARTICLE INSPECTION PER ... BAC 5424 CLASS A

...ENCLOSED AREA PER BOEING SPEC MS 21.01 ...E 110 ...T .008-.012 ALMEN A2 ...E 200%

... FORGING STEEL ... BMS 7-6

...4D5245-F3 FORGING

114D5245-F2, F3 OR RMF4 FORGINGS

...OXIDE TREATMENT PER BOEING SPEC MS 8.17 ... PER VERTOL SPEC PS-173.

...PERMISSIBLE IN GROOVE ¢ .375 DIA BRG PUSHOUT ...MANDATORY. DO NOT MASK.

...TO BE STATICALLY BALANCED TO .02 IN-OUNCE ...FROM INDICATED AREA

... MOUNTING DISTANCE AND BACKLASH HERE ... PER FEDERAL HANDBOOK H-28 AND MIL-S-7742

...REQUIRED IN ACCORDANCE WITH BOEING ... MS 14.02.

...VARIATION IS NOT TO EXCEED FOUR ROCKWELL C POINTS ...BER IN A MILL HEAT LOT.

...PERMITTED ON THESE DIMENSIONS.

... FORGING STEEL PER BMS 7-249 TYPE I.

...5245-F6 OR -RMF8 FORGING.

...5245-F6 FORGING.

REVISIONS

LTR	DESCRIPTION	DATE	APPROVED
A	[illegible]		
B	INC ADV EO 3A 2012 [illegible]		
C	(1) EO 4A CANCELLED WILL NEVER BE REL (2) ADDED CH-47B REQ ... (3) ADDED NOTE 23		
D	INC ADV EO 5A REV NOTE 5		
E	INC ADV EO 7A REV NOTE ... (2) 7A REV NOTE 8 ... (4) 9A REV PITCH DIA OF GEAR DATA (5) 10A SOR ... WAS .50 R		
F	INC ADV EO 11A ADDED -5, ... SHOT PEEN CALLOUTS (2) REM NOTE 23 (NAS) EFF ...		
G	REPLACED PROPRIETARY NOTE.		
H	(1) INC ADV EO 12A ADDED (24) REV (7) DCE (2) ELR 64716 REV NOTE 8 B ADDED HORIZ PROFILE TOL ±.003		
J	INC ADCN (1)(5) ADDED (25) ... MARK ... MTG CALLOUT REV GEAR DATA TABLE ... EFF CH-47C ... ADDED -F6, -7, -RMF8 (26), (27) ... (28) REV (2)		

CUSTOMER SIGNATURE ON RECORD ONE-HALF SCALE COPY OF ORIGINAL DWG

CUSTOMER SIGNATURE ON RECORD ONE-HALF SCALE COPY OF ORIGINAL DWG

LIST OF MATERIAL

PART OR IDENTIFYING NUMBER	NOMENCLATURE OR DESCRIPTION	ZONE	MATERIAL AND SPECIFICATION				
114D5245-RMF8	FORGING		(28)	(25)		VE	J
114D5245-7	GEAR (2)		(27)	(7)		VE	J
114D5245-F6	FORGING		(26)			VE	J
114D5245-5	GEAR (2)		(14)	(7)	(15)	VE	F
114D5245-RMF4	FORGING		(12)	(25)		VE	
114D5245-F3	FORGING		(12)			VE	
114D5245-F2	FORGING		(12)	(25)		VE	
114D5245-1	GEAR (2)		(4)	(7)	(15)	VE	

CH-47C	-7	J
CH-47C	-5	F
CH-47B	-1	
APPLICATION		

THE BOEING COMPANY VERTOL DIVISION

GEAR, SPIRAL BEVEL PINION — COMBINING XMSN.

114D5245

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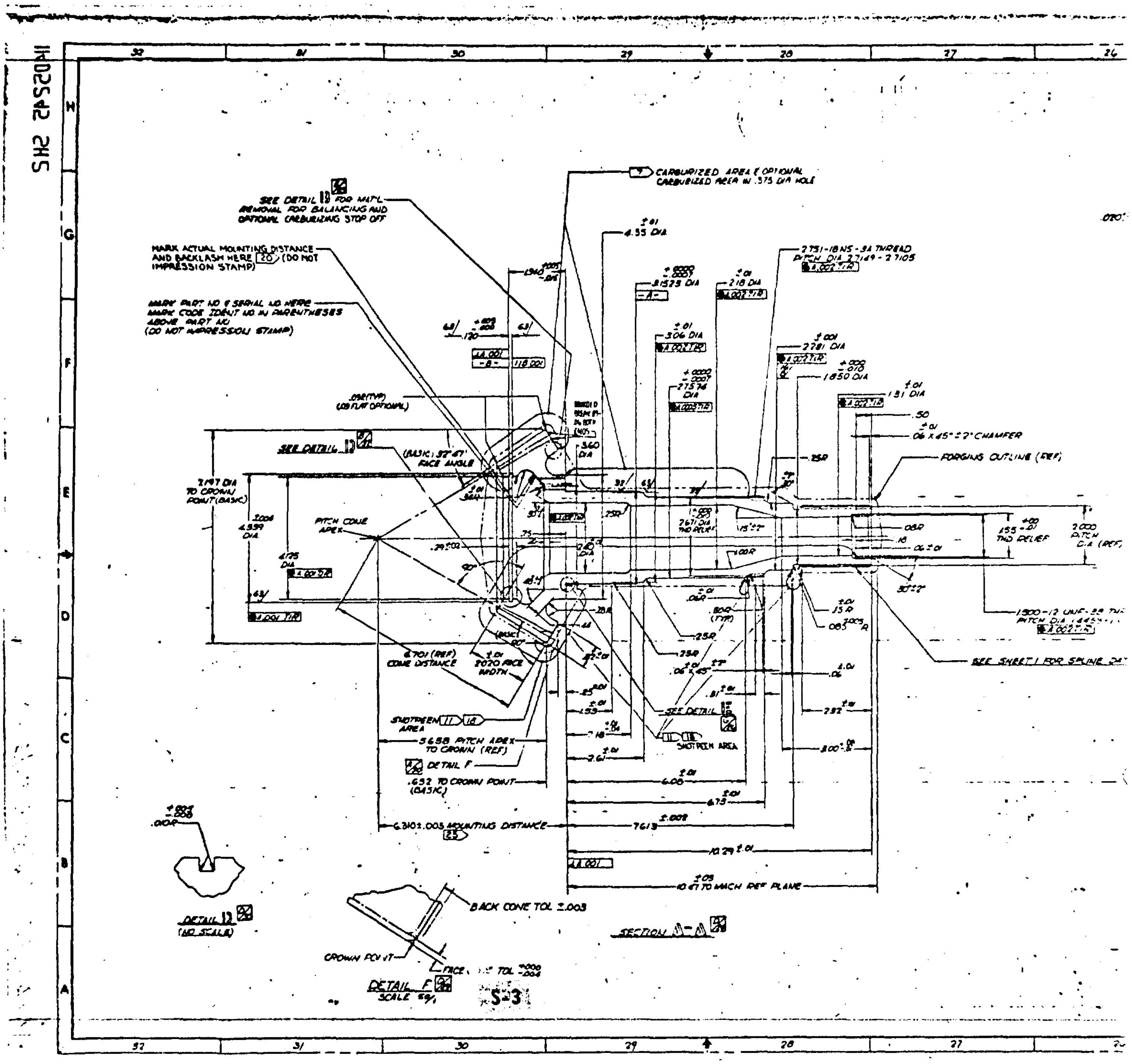
APPENDIX S SPIRAL BEVEL INPUT PINION GEAR DRAWING (CONTINUED)



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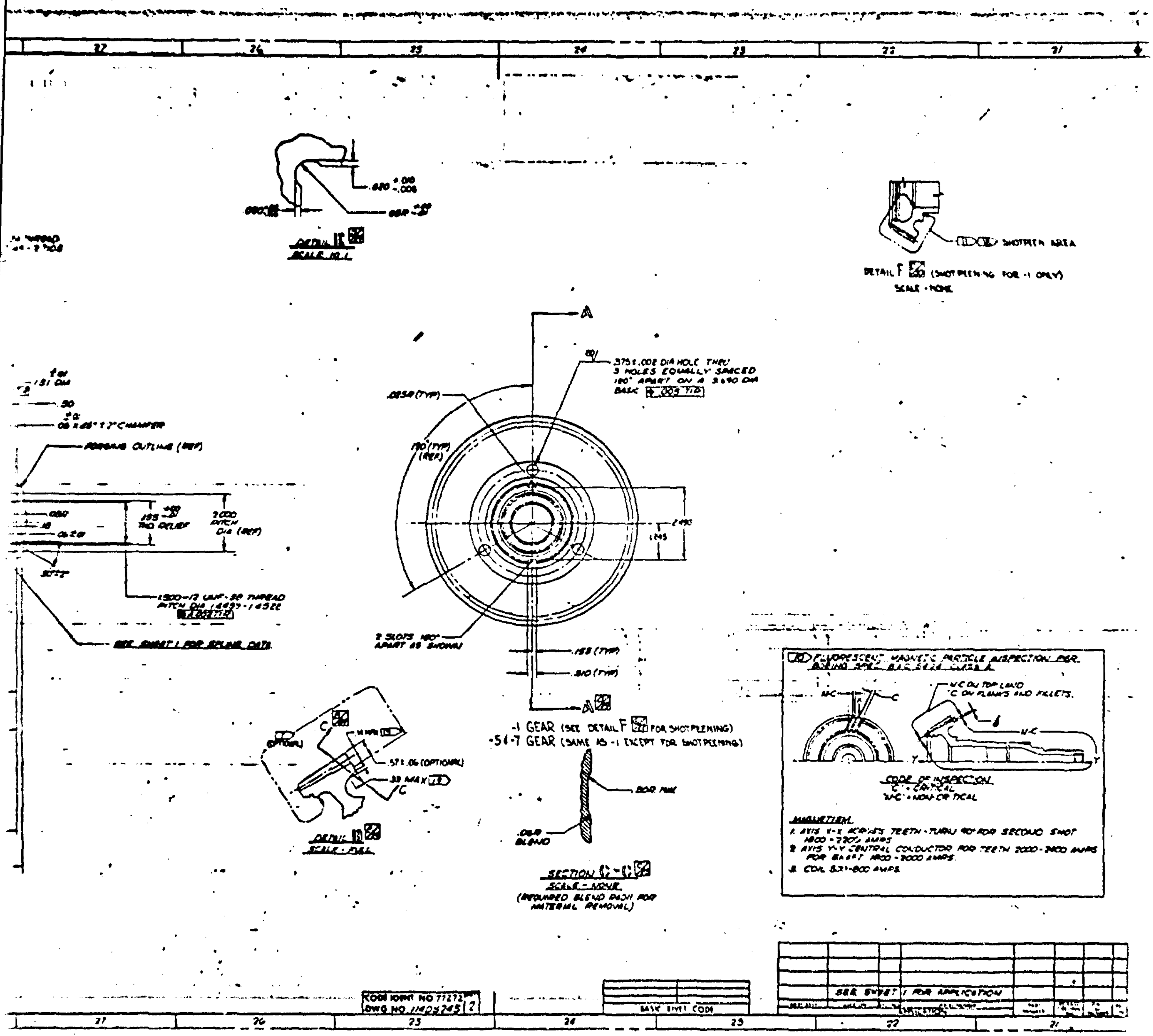

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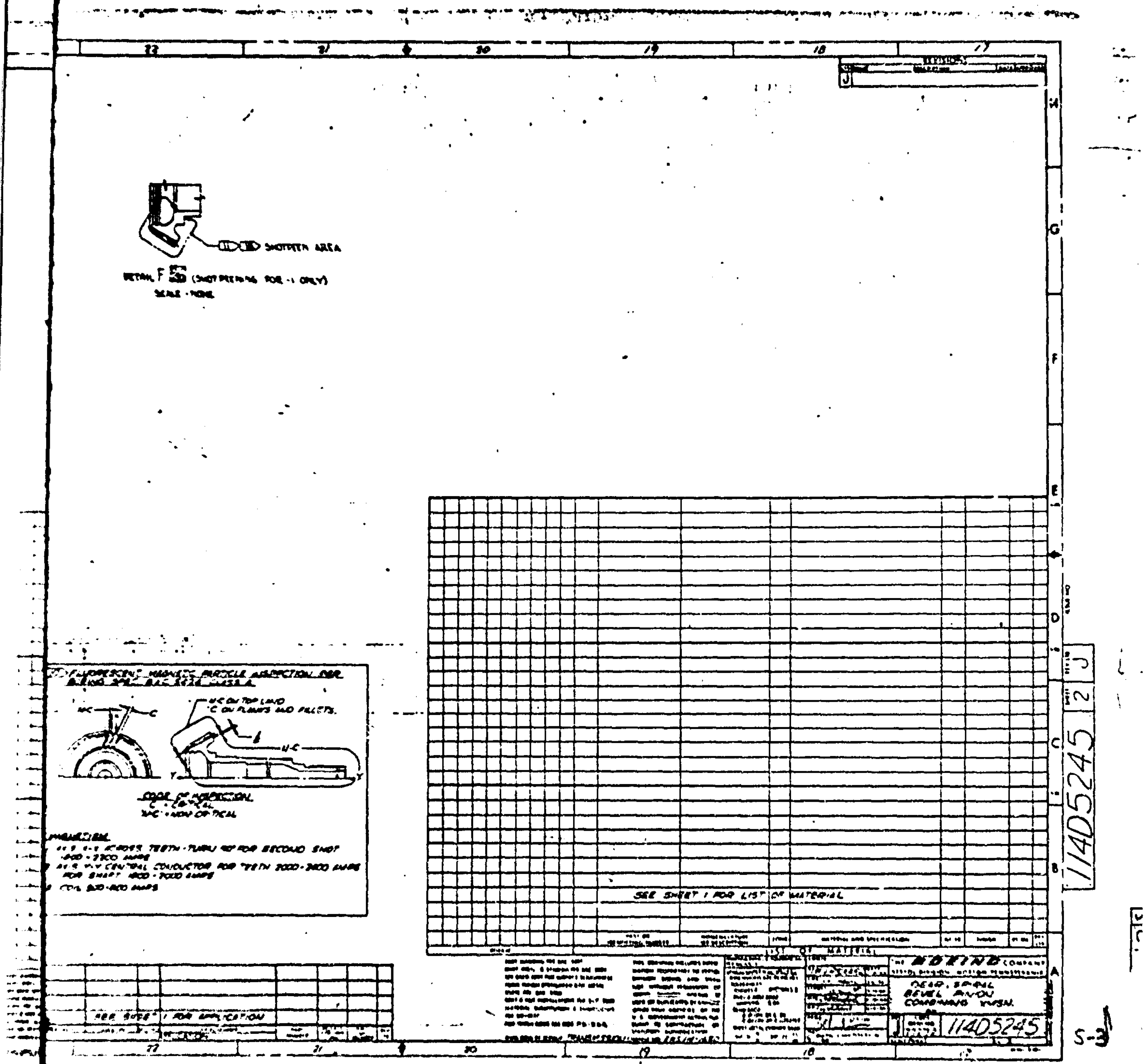

S-3

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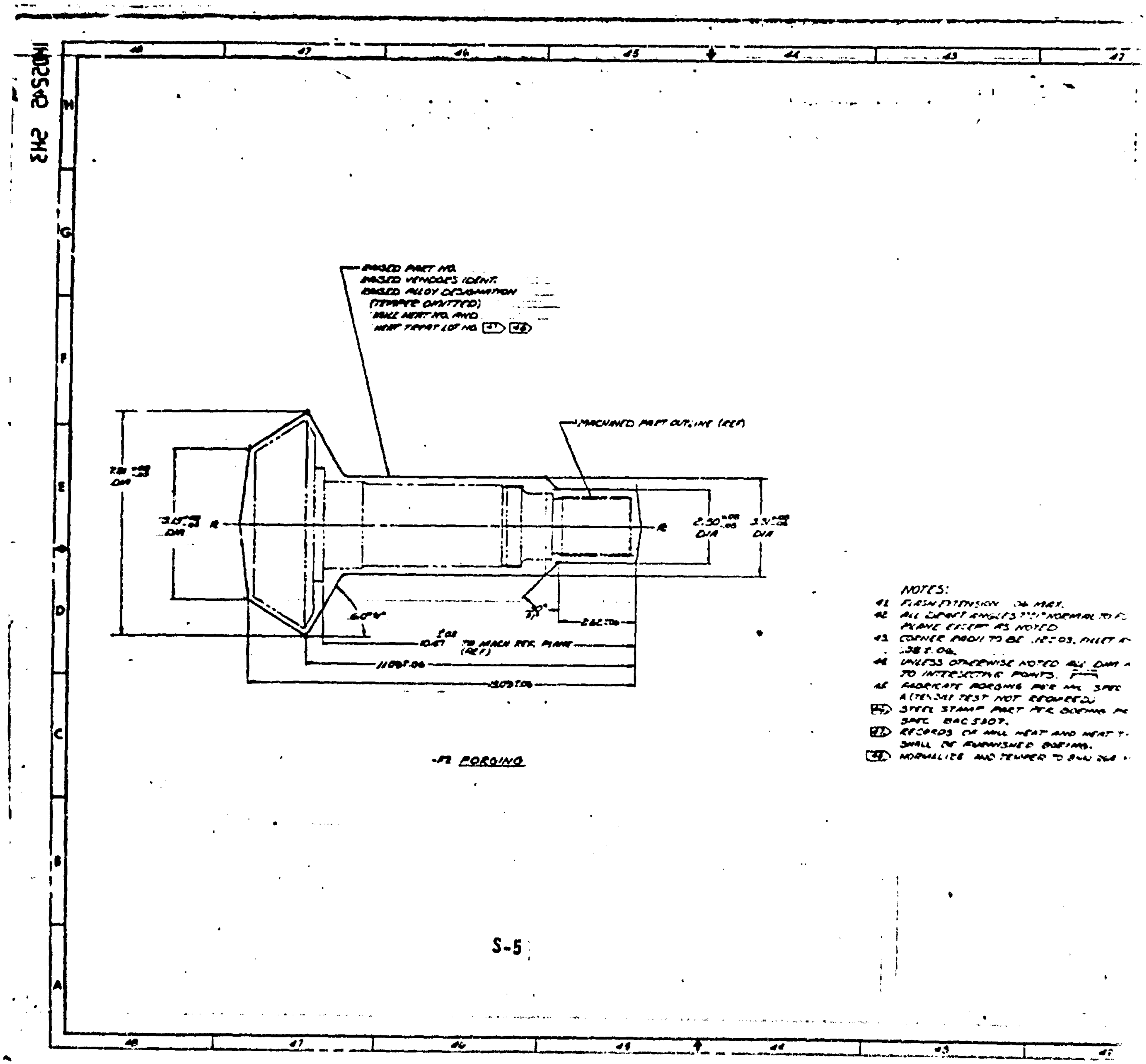
APPENDIX S SPIRAL BEVEL INPUT PINION GEAR DRAWING (CONTINUED)



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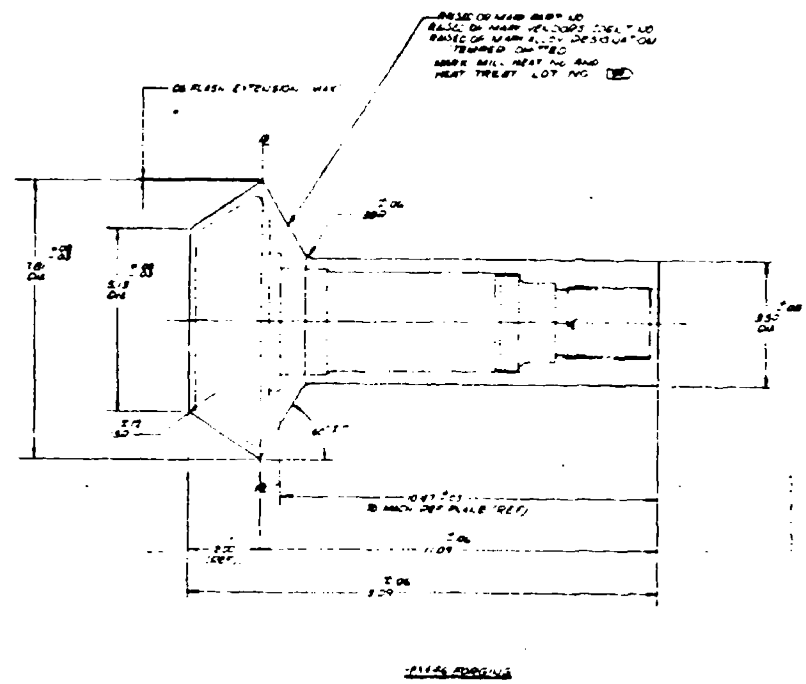
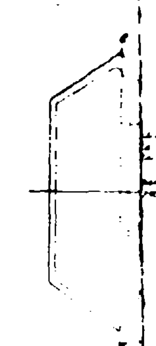
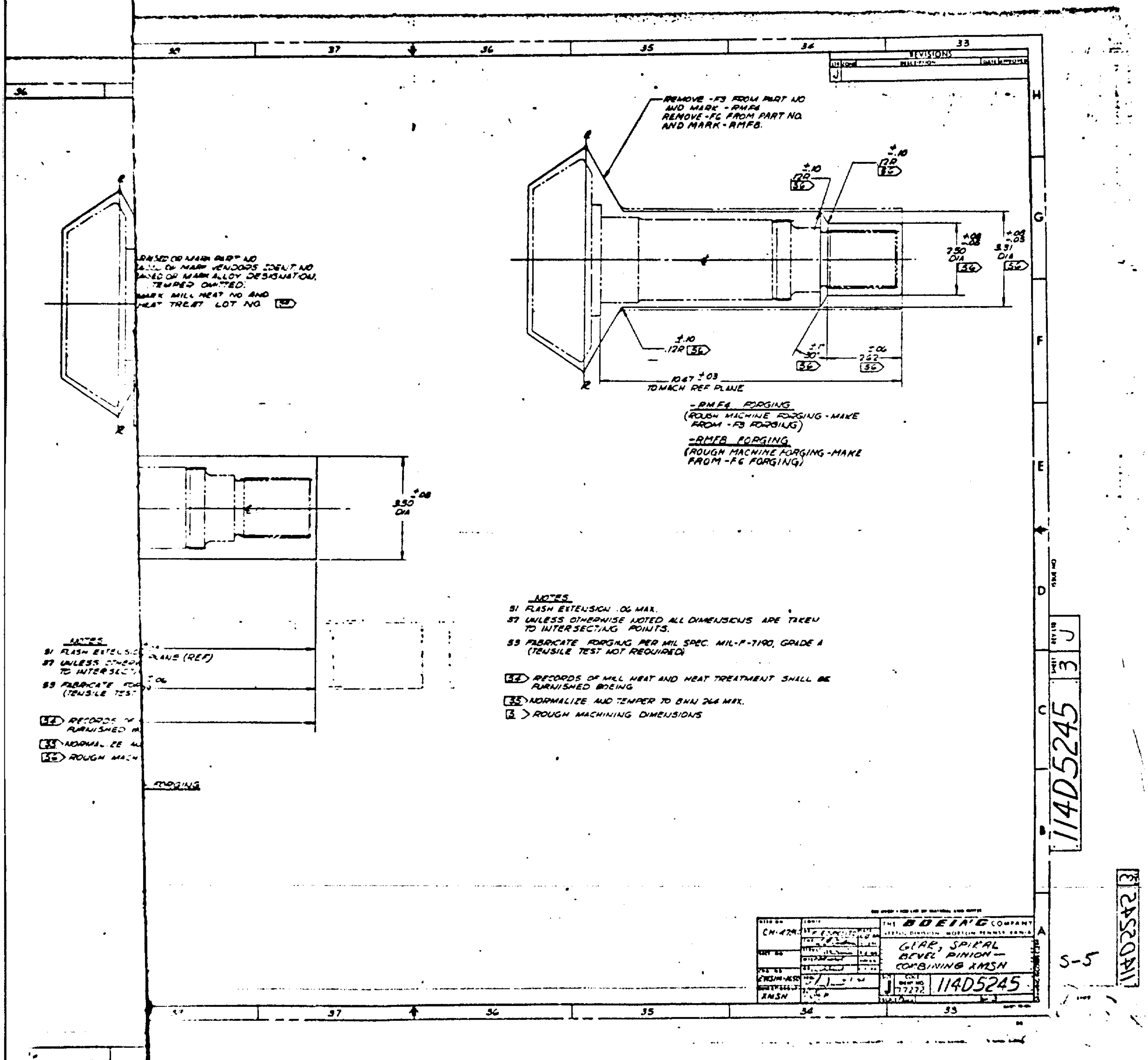


NOTES:

1. FLASH EXTENSION .06 MAX
2. ALL DRAFT ANGLES 7° NORMAL TO FORGING PLANE EXCEPT AS NOTED
3. CORNER RADII TO BE .12 ± .03, FILLET RADII TO BE .38 ± .06.
4. UNLESS OTHERWISE NOTED ALL DIMS ARE TAKEN TO INTERSECTING POINTS
5. FABRICATE FORGING PER MIL SPEC MIL F ... TENSILE TEST NOT REQUIRED.
6. STEEL STAMP PART PER BOEING PROCESS SPEC BAC 5307.
7. RECORDS OF MILL HEAT AND HEAT TREATMENT SHALL BE FURNISHED BOEING.
8. NORMALIZE AND TEMPER TO BHN 269 MAX





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APPENDIX T BOEING HELICOPTERS MATERIALS ENGINEERING LABORATORY REPORT 88-164

MATERIALS ENGINEERING LABORATORY REPORT

MELR NO. 89-164
DATE February 1, 1990

Subject: CH-47C, Combining Transmission Spiral Bevel Input Pinion Gear, P/N 114D5245-10, S/N M5373; Metallurgical Evaluation of Vacuum Carburized Gear

Material: 9310 Steel per BMS 7-249, Type III, Vacuum Carburized

Reference: Army Contract DAAG46-82-C-0034, "Aircraft Quality High Temperature Carburizing."

Enclosures: I-II -- Photographic Documentation of Subject Pinion Gear
III, IV & V -- Test Data

I. OBJECTIVE

The objective of this investigation was to metallurgically evaluate the subject gear to determine if it conformed to the metallurgical requirements of the engineering drawing.

II. BACKGROUND

The subject pinion gear was manufactured by Litton Precision Gear per the requirements of the engineering drawing with the exception that the pinion was vacuum carburized rather than conventionally carburized, see Reference. Vacuum carburizing was accomplished by Summit Gear Corp in Plymouth, Minnesota. The gear was subsequently bench tested in a CH-47C combining transmission at Boeing Helicopters, and then submitted to the Materials Engineering Laboratory for metallurgical evaluation.

III. TEST RESULTS

The as-received spiral bevel pinion gear, P/N 114D5245-10, S/N M5373, is shown in Figure 1. The location of the input pinion gear in a CH-47C combining transmission is illustrated in Figure 2.

Visual and magnetic particle inspection of the gear did not reveal any discrepancies.

The test data obtained from the subject pinion gear are contained in Enclosure III. The residual stress profile, which was obtained using X-ray diffraction techniques, is presented in Enclosure IV. Carbon profile data, which was obtained using the scanning electron microscope and the associated wavelength dispersive spectrometer, is contained in Enclosure V.

FORM 10840 (4/88)

During this evaluation, the only discrepancy noted was that the effective case depths on the flanks of two bevel gear teeth exceeded the requirements of the engineering drawing by 0.001 and 0.002 inch (see Enclosure III). This discrepancy, however, is within the tolerances permitted by Boeing Specification MS 14.02.

NOTE: Although the subject pinion gear was vacuum carburized, rather than conventionally carburized, the carburized areas were evaluated per the requirements of D210-12023-1, i.e., the specification controlling the conventionally carburized pinion gear. In all areas evaluated, the subject pinion gear conformed to the metallurgical requirements of D210-12023-1. For example: The case displayed light discontinuous carbides (Class A-acceptable), there was no evidence of decarburization, there was no visible retained austenite, etc. A typical case and core microstructure is shown in Figures 3 and 4.

IV. CONCLUSION

In the areas evaluated, the subject CH-47C Spiral Bevel Pinion Gear, P/N 114D5245-10, S/N M5373, conformed to the requirements of the engineering drawing and related specifications.

Prepared by ______________
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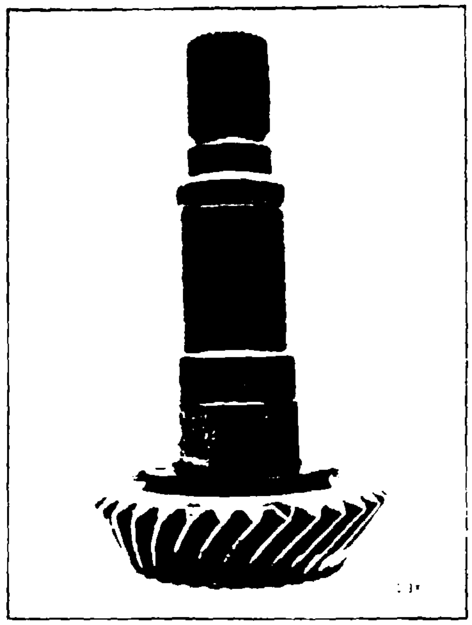
____
C. Yearwood

Reviewed by ______________
J. Kachelries

Approved by ______________
R. Cunningham



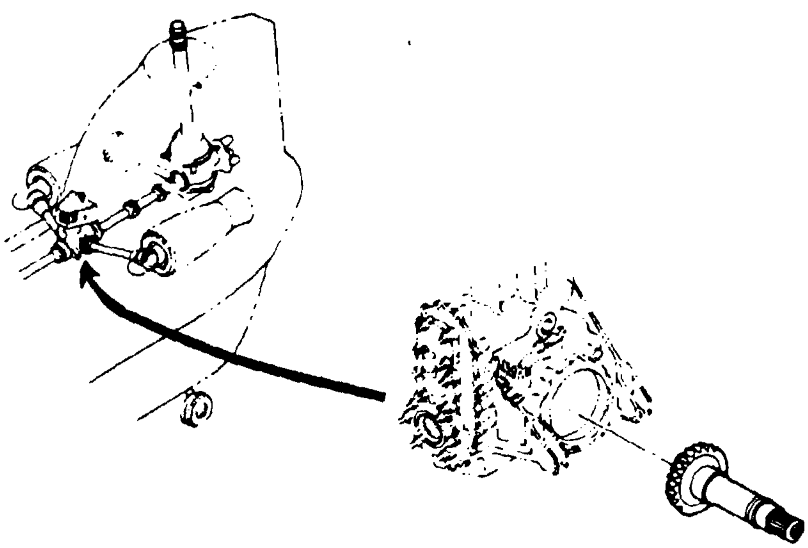


FIGURE 3 400X
TYPICAL VACUUM CARBURIZED CASE MICROSTRUCTURE. AREA SHOWN IS IN ROOT FILLET OF GEAR TOOTH. STRUCTURE IS PRIMARILY TEMPERED MARTENSITE.

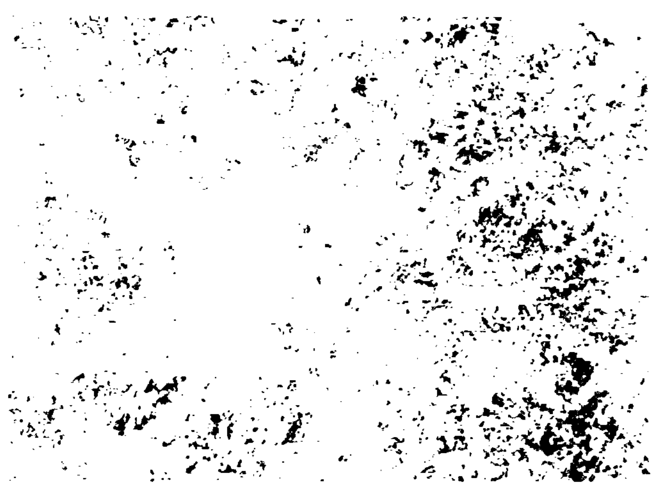


FIGURE 4 100X
TYPICAL CORE MICROSTRUCTURE. STRUCTURE IS PRIMARILY TEMPERED MARTENSITE.

ENCLOSURE III

Boeing Helicopters

MELR 89-164

PART NUMBER	SERIAL NUMBER	PART NAME
114D5245-10	M5373	SPIRAL BEVEL PINION GEAR

MAGNAGLO	NITAL ETCH	GRAIN SIZE
No Indications	No Indications	ASTM #5
RETAINED AUSTENITE	**CARBIDE NETWORK**	
None Observed	Class A	Decarburization--None Observed

INCLUSIONS (ASTM E-45)		TYPE A-SULPHIDE	TYPE B-ALUMINA	TYPE C-SILICATE	TYPE D-OXIDE
	RESULTS	AT-0 AH-0	BT-0 BH-0	CT-0 CH-0	DT-0.5 DH-0
	REQM'TS.	AT-1.5max AH-0	BT-1.5max BH-0	CT-1.5max CH-0	DT-1.5max DH-1.0

CHEMICAL ANALYSIS

	CARBON	MANGANESE	PHOSPHOROUS	SULPHUR	SILICON	NICKEL	CHROMIUM	MOLYBDENUM	COPPER
RESULTS	0.10	0.67	0.005	0.0016	0.27	3.37	1.39	0.15	0.03
REQM'TS.	0.07-0.13	0.40-0.70	0.010max	0.010max	0.20-0.35	3.00-3.50	1.00-1.40	0.08-0.18	0.35max

EFFECTIVE CASE DEPTH AND SURFACE HARDNESS

GEAR AND TEETH SPLINES

POSITION			ECD Rc 50 REQUIRED 0.030-0.050	SURFACE *HARDNESS Rc 59-64
Tooth Toe 0°	FLANKS	1	0.050	64
		2	0.051	64
	ROOT FILLETS	3	0.039	64
		4	0.044	64
	ROOT	5	0.048	64
Tooth Toe 180°	FLANKS	1	0.046	64
		2	0.047	64
	ROOT FILLETS	3	0.038	64
		4	0.039	63
	ROOT	5	0.043	64
Tooth Heel 0°	FLANKS	1	0.052	63
		2	0.043	64
	ROOT FILLETS	3	0.040	64
		4	0.030	64
	ROOT	5	0.041	64
Tooth Heel 180°	FLANKS	1	0.043	63
		2	0.044	64
	ROOT FILLETS	3	0.036	63
		4	0.030	62
	ROOT	5	0.040	63

BEARING SURFACES

POSITION	EFFECTIVE CASE DEPTH Rc 58	EFFECTIVE CASE DEPTH Rc 50 0.030-0.050	SURFACE *HARDNESS Rc 59-64
2.7574 inch dia 0°	0.030	0.044	64
2.7574 inch dia 180°	0.032	0.047	64
3.1523 inch dia 0°	0.033	0.048	64
3.1523 inch dia 180°	0.030	0.048	63

ROOT FILLET DIMENSIONS

	DRIVE SIDE	REQ'D	NON-DRIVE SIDE	REQ'D
0°	0.045 inch	0.045-0.055 inch	0.045 inch	0.045-0.055 inch

CORE HARDNESS OF BEARING SURFACES

Location		Core Actual	Hardness (R/C) Required
2.7574 in dia	0°	41	32-42
	180°	40	32-42
3.1523 in dia	0°	40	32-42
	180°	40	32-42

ENCLOSURE IV

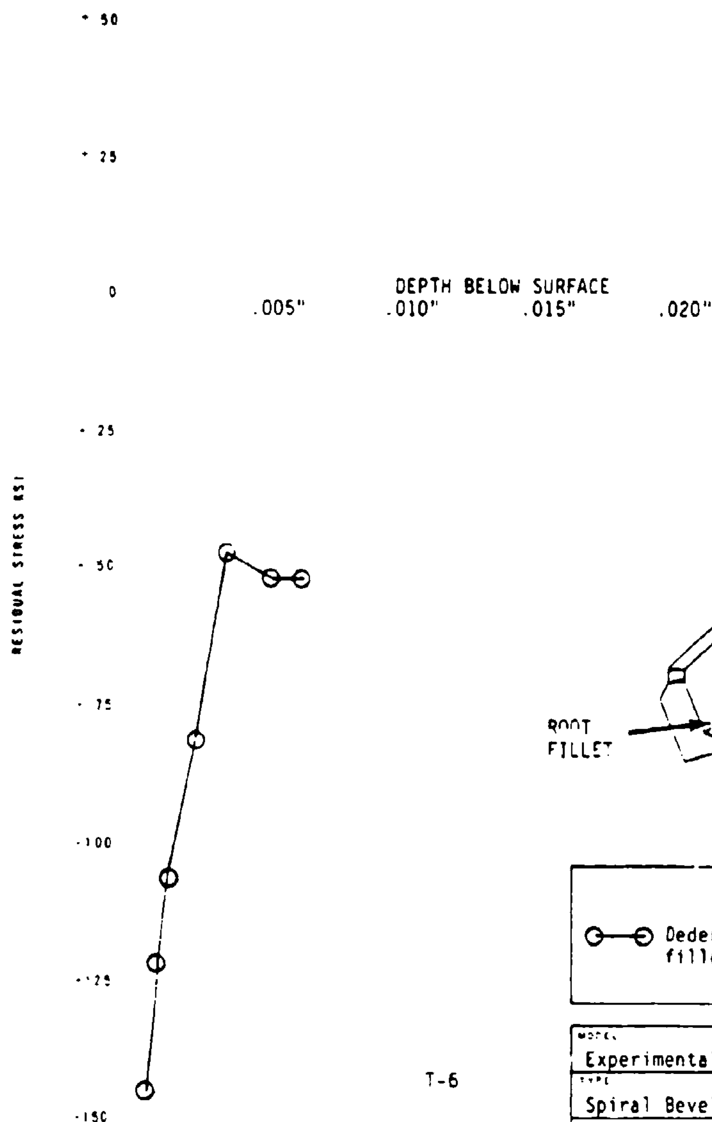
X-RAY DIFFRACTION

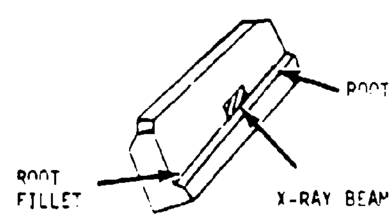
RESIDUAL STRESS PROFILE

PAGE	OF

PREPARED BY	CHECKED BY	DATE	MODEL	REPORT NO.
C.D. YEARWOOD		12/1/89		89-164

PART NAME	SPIRAL BEVEL PINION GEAR, COMBINING TRANSMISSION		
PART NUMBER	114D5245-10	SERIAL NUMBER	M5373





LEGEND

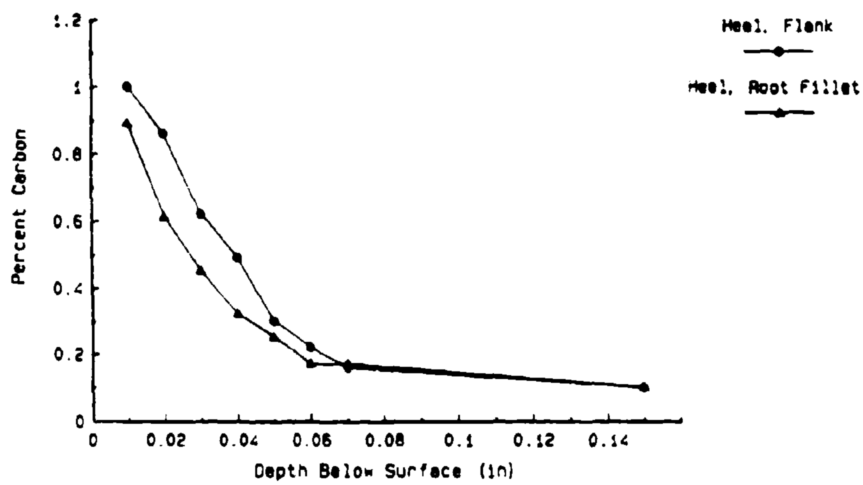
O—O Dedendum, near root fillet.

MODEL	ALLOY
Experimental	VIM-VAR 9310 Steel per BMS 7-249III
TYPE	**HEAT TREAT**
Spiral Bevel	Vacuum Carburized
SURFACE CONDITION Shot Peened S110 shot, .008"-.012", 200%	

T-6

FORM 4247C (6/84)

MELR 89-164
ENCLOSURE V



CARBON CONTENT IN PINION GEAR TEETH AS A FUNCTION OF DEPTH BELOW THE TOOTH SURFACE.

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1	ATTN: Dale Weires, Metallurgist
	Speco Corporation, Baker Road, Springfield OH 45501
1	ATTN: Harry Hartzell, Chief Metallurgist
	Summit Gear, 3131 Vicksburg Lane, Plymouth MN 55447
1	ATTN: Dave Tim
1	C.I. Hayes, 800 Wellington Ave, Cranston RI 02910
	Vacuum Industries, Inc., 5 Middlesex Avenue, Somerville MA 02145
1	ATTN: Mr. John H. Durant
1	McDonnell Douglas Co., Surface Combustion, Maumee OH 43537
1	Pratt & Whitney, 400 Main Street, East Hartford CT 06108
	Textron Lycoming, 550 Main Street, Stratford CT 06497
1	ATTN: Dr. L. Fiedler
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1	ATTN: Mr. P. K. Pearson
	Director, U.S. Army Materials Technology Laboratory, Watertown, MA 02172-0001
2	ATTN: SLCMT-TML
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1	Dr. Eric B. Kula
1	Dr. R. P. I. Adler
6	Dr. Martin G. H. Wells
1	Mr. Jonathan S. Montgomery