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CONVENTIONAL MACHINING OF ESR 4340 STEEL.(U)

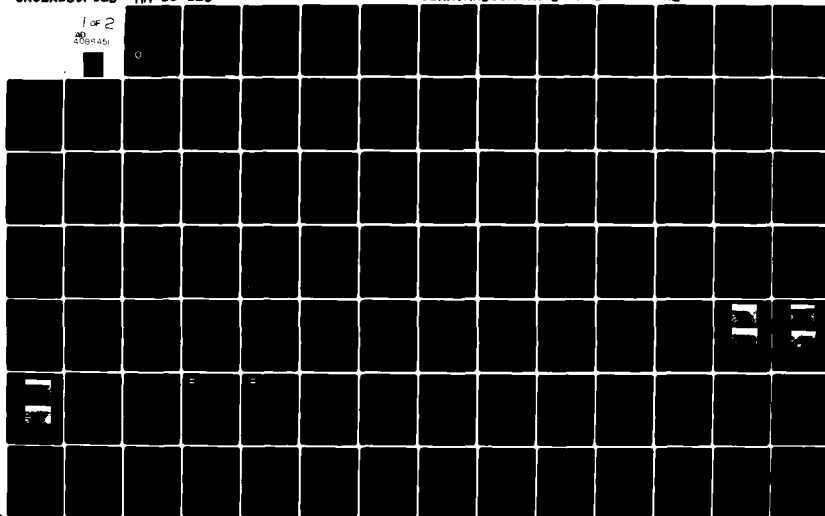
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MANUFACTURING METHODS AND TECHNOLOGY  
(MANTECH) PROGRAM

CONVENTIONAL MACHINING OF ESR 4340 STEEL

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Hughes Helicopters  
Division of the Summa Corporation  
Culver City, California 90230

July 1980

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| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br><br>This program involved the study of conventional machining of heat treated ESR 4340 steel (Rc 54-57). Initial effort involved a survey of available data regarding the machining of high strength steels with hardnesses of Rc 50 and above. A machining program was conducted, determining optimum tools and conditions for turning, drilling, face milling, end milling, and grinding operations. Effects of various parameters including cutting speeds, feeds, |                                                                                                                  |                                                      |

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depths of cut, and cutting fluids on tool life was determined. All the operations were found to be extremely difficult and application of conventional procedures is not feasible. Tool lives remained short despite reductions in speeds and feeds. Conventional grinding methods induced detrimental residual tensile stresses along the surface, resulting in cracking, lapping, and untempered martensitic structures. Low stress grinding techniques were found to be applicable to this material when proper dressing procedures and reduced rates were used.

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### SUMMARY

Hughes Helicopters (HH) under Army Contract DAAG 46-78-C-0046 has completed a study of the conventional machining of ESR 4340 steel. The objective of this program was to optimize procedures and develop an efficient machining specification. Metcut Research Associates, a leader in the research and development of metal removal technology, was the subcontractor.

The program conducted between September 1978 through March 1980 was sponsored by U. S. Army Aviation Research and Development Command (AVRADCOM), St. Louis, Missouri and monitored by U. S. Army Materials and Mechanics Research Center (AMMRC) Watertown, Massachusetts, under the direction of Mr. Arthur Ayvazian. The machining tests were conducted at Metcut under the direction of Mr. J. Kohls and Mr. J. Christopher. The project was coordinated by the HH project engineer, Mr. K. Niji, with the assistance of Mr. J. Leach of the Manufacturing Department.

ESR 4340 steel is presently being used for various critical parts on the YAH-64 for its high ballistic tolerance characteristics. Its advantageous qualities of high hardness and toughness creates great difficulties in machining. Because of its relatively new usage, there is no manufacturing source of information which presents an efficient machining method for this material. This program was designed to resolve that problem.

This program was initially conceived as an 18-month two-phase program. Phase I began with an initial survey of available data regarding the machining of ESR 4340 steel. A machining test program was then developed and conducted, studying the effects of various parameters in turning, drilling, milling, and grinding. Optimum tools and conditions were obtained for these operations. All of the operations were found to be extremely difficult and application of conventional procedures is not feasible. Tool lives remained short despite reductions in speeds and feeds. Conventional grinding methods induced detrimental residual tensile stresses along the surface, resulting in cracking, lapping, and untempered martensitic structures. Low stress grinding techniques, emphasizing wheel dressing procedures and reduced speeds and downfeeds, proved to be applicable to this material. In view of most of the machining results, Phase II involving the application of Phase I findings to the fabrication of YAH-64 components was cancelled. Studies involving alternative methods are now being considered.

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## INTRODUCTION

Hughes Helicopters (HH), with the assistance of Metcut Research Associates as a major subcontractor, has completed a program studying conventional machining methods for ESR 4340 steel in an attempt to develop an efficient machining procedure. Hughes Helicopters is interested in the development of such a procedure for ESR 4340 steel since many of the components in the drive system, flight control system and hydraulic subsystem of the YAH-64 are made from this material. Figure 1 and Table I illustrate the areas where these parts are located. This material is being used to make these various parts specifically because of its high ballistic tolerance characteristics. Parts made of ESR 4340 steel tend to withstand the impact of a 12.7 mm armor piercing round or the explosive energy of a 23 mm HEI (high explosive incendiary) round that might completely fragment parts made of normal 4340 steel.

The low non-metallic inclusion content, the high density of the material, and the uniformity of structure provides ESR steel with its toughness quality, while still maintaining its high hardness (Rc 54-57 in the heat treated condition). Defects such as central porosity and line inclusion accumulations in rolled and forged plates are virtually eliminated. The uniform structure obtained from the electroslag remelt process produces a material whose yield strength and fracture toughness are similar in both transverse and longitudinal directions. These high properties in the short transverse direction permits reductions in plate thickness, subsequently reducing weight and material costs.

The qualities that make application of ESR steel so advantageous also create difficulties in machining the material. The desulfurization and oxide inclusion removal, which results in the clean steel, removes elements which enhance machinability. Because of its relatively new usage, there is no manufacturing specification which deals with the efficient machining of ESR 4340 steel.

After an initial survey of available information regarding the machining of ESR 4340 steel and other high hardness materials, tests were conducted to ascertain the effects of various parameters such as cutting speeds, feeds and fluids. An assortment of carbide tools, along with various ceramics for turning, and high speed steels for drilling, were obtained and studied during the course of the machining tests. A determination of optimum tools and conditions were made for turning, drilling, face milling, end milling, and grinding operations. The optimum tools and conditions are presented and discussed in this report.

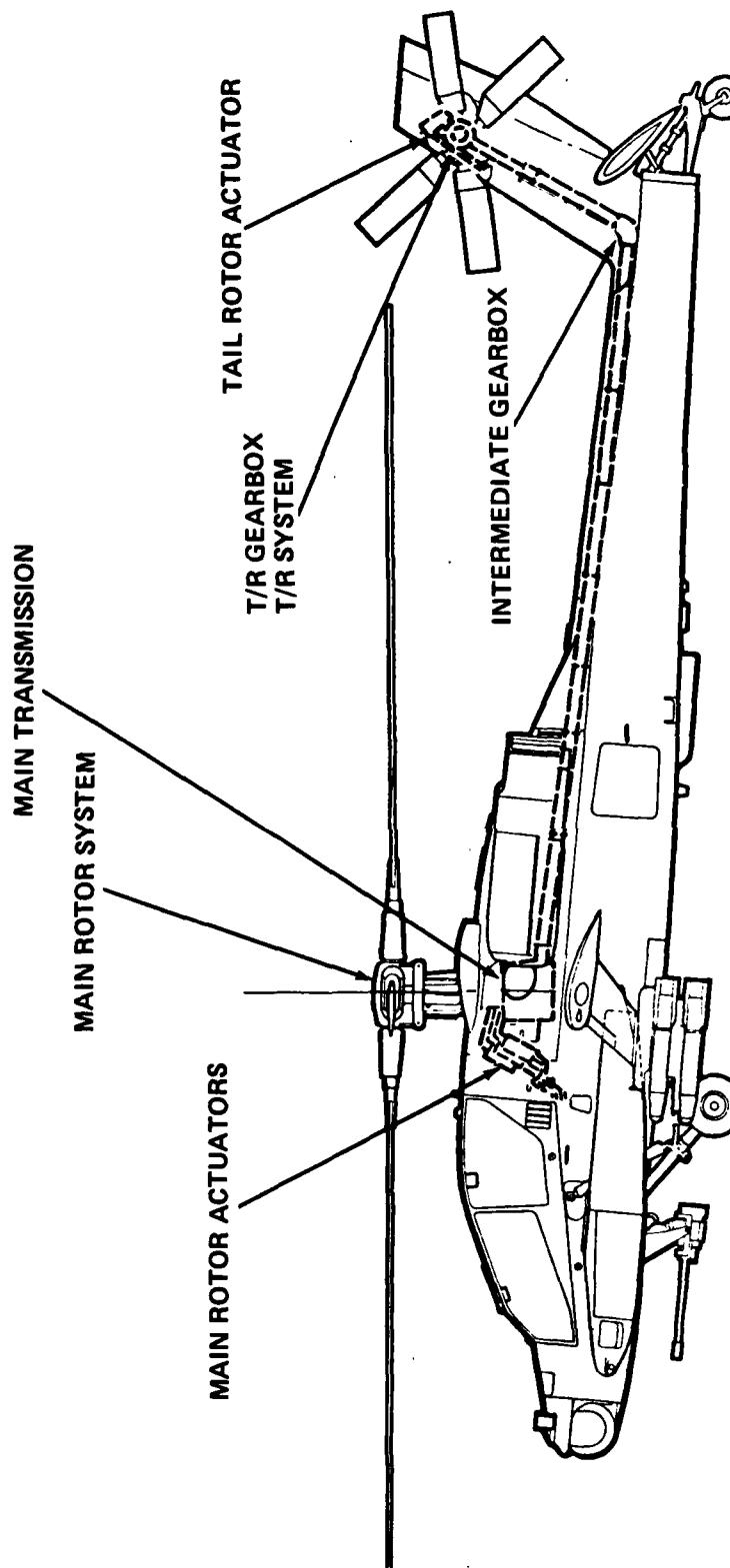


Figure 1. Critical Areas Where ESR 4340 Steel is Used on the YAH-64

TABLE I. ESR STEEL YAH-64 HELICOPTER COMPONENT PARTS

| Name                                   | Part Number | No. of Pieces | Finished Weight (lb) |
|----------------------------------------|-------------|---------------|----------------------|
| <u>DRIVE</u>                           |             |               |                      |
| <u>Main Transmission</u>               |             |               |                      |
| Intermediate Gear Bearing Retainer     | 7-113100122 | 1             | 2.3                  |
| T/R Helical Pinion Retainer            | 7-113100125 | 1             | 0.9                  |
| Rotor Brake Adapter                    | 7-113100131 | 2             | 2.4                  |
| Input Pinion Bearing Adapter           | 7-113100132 | 2             | 2.4                  |
| Intermediate Gear Roller Bearing Liner | 7-113100143 | 1             | 3.0                  |
| Input Bevel Gear Bearing Liner         | 7-113100144 | 2             | 5.8                  |
| Input Bevel Gear Bearing Sleeve        | 7-113100145 | 2             | 6.2                  |
| T/R Helical Gear Sleeve                | 7-113100146 | 1             | 0.5                  |
| Gen. Roller Bearing Sleeve             | 7-113100148 | 2             | 0.2                  |
| Gen. Ball Bearing Sleeve               | 7-113100149 | 2             | 0.5                  |
| Rotor Brake Roller Bearing Sleeve      | 7-113100150 | 2             | 1.0                  |
| Input Pinion Thrust Bearing Sleeve     | 7-113100154 | 2             | 6.8                  |
| Input Pinion Roller Bearing Sleeve     | 7-113100155 | 2             | 1.0                  |
| Hydraulic Pump Gear Bearing Sleeve     | 7-113100156 | 8             | 1.3                  |
| <u>Intermediate Gearbox</u>            |             |               |                      |
| Roller Bearing Output Sleeve           | 7-113300143 | 1             | 0.4                  |
| Duplex Ball Bearing Sleeve             | 7-113300144 | 2             | 4.2                  |
| Roller Bearing Input Sleeve            | 7-113300147 | 1             | 0.4                  |
| <u>Tail Rotor Gearbox</u>              |             |               |                      |
| Input Gear Sleeve                      | 7-113400143 | 1             | 2.6                  |
| Input Gear Roller Bearing Sleeve       | 7-113400144 | 1             | 0.6                  |
| Output Gear Roller Bearing Sleeve      | 7-113400145 | 1             | 1.3                  |
| Output Gear Sleeve                     | 7-113400146 | 1             | 2.5                  |

TABLE I. ESR STEEL YAH-64 HELICOPTER COMPONENT PARTS (CONT)

| Name                                  | Part Number | No. of Pieces | Finished Weight (lb) |
|---------------------------------------|-------------|---------------|----------------------|
| <u>FLIGHT CONTROL AND ROTOR GROUP</u> |             |               |                      |
| <u>Main Rotor</u>                     |             |               |                      |
| Rotating SP Bearing Retainer          | 7-211511204 | 1             | 7.0                  |
| Adj Pitch Link Barrels                | 7-211511136 | 4             | 5.1                  |
| Pitch Link Rod Ends                   | 7-211511137 | 4             | 8.4                  |
| <u>Tail Rotor</u>                     |             |               |                      |
| Rotating Swashplate                   | 7-211527003 | 1             | 7.8                  |
| Swashplate Bearing Retainer           | 7-211527016 | 1             | 3.3                  |
| <u>HYDRAULIC SUBSYSTEM</u>            |             |               |                      |
| <u>Main Rotor Actuators</u>           |             |               |                      |
| Longitudinal                          |             | 1             | 49.1                 |
| Lateral                               |             | 1             | 38.6                 |
| Collective                            |             | 1             | 44.4                 |
| <u>Tail Rotor Actuator</u>            |             | 1             | 32.6                 |
| SHIPSET TOTAL                         | 26          | 53            | 242.6                |

### DISCUSSION

This effort was originally planned as a two phase program. The first phase would primarily involve testing by Metcut to determine best conditions for achieving high machining efficiency. The second phase would apply this information to the fabrication of small YAH-64 components.

The first task in Phase I involved a survey by Hughes Helicopters and Metcut reviewing current manufacturing procedures being followed regarding ESR 4340. Little or no attempt was being made to finish machine parts by any of the vendors or subcontractors. Major Hughes Helicopters subcontractors working on the AAH program using ESR 4340 steel, included Aircraft Gear (T/R gearbox components), Bendix (drive train components) Bertea (hydraulic actuators), and Litton (main transmission components). The procedure most commonly followed, primarily involved rough machining in the annealed state, then slow grinding of 0.050 - 0.070 inches of material to finished dimensions after heat treatment. Most of the data gathered was obtained through a literature survey conducted at Metcut's Machinability Data Center. Data regarding the machining of high hardness metals (50R<sub>C</sub> and above) have been compiled in a form similar to the data sheets in the Machining Data Handbook and are presented as Appendix A. Data for turning (carbide and ceramic), drilling, face milling, end milling, tapping, and grinding have been gathered and grouped by operation and hardness ranges. The information was to be used to find a starting point for tools and parameter values for our efforts in machining ESR 4340 steel.

The initial step in the program was to fabricate test specimens. The ESR process involves remelting a consumable electrode at atmospheric pressure in a superheated molten slag bath which protect the molten metal from atmospheric contamination. Electricity is passed through the slag, generating enough heat to melt the end of the electrode which is immersed in the slag. The ESR ingot grows through progressive solidification of the molten metal in a water cooled mold. The solidification characteristics are greatly influenced by the size, shape and temperature of the molten metal pool. After the ingots are solidified, they are forged to various standard rounds and round corner squares. HMS 6-1121 is the Hughes specification for ESR 4340 and is included as Appendix B. The material then had to be machined into the various test sample sizes (3 inch diameter bars for the turning tests and

various rectangular sizes for the other tests). After machining to test sizes, the material then had to be heat treated prior to testing. The heat treat process is a long one, involving normalizing, tempering and austenitizing in a vacuum furnace. The specific times and temperatures involved are presented in an excerpt from the Hughes Helicopters heat treatment specification, Appendix C. Due to the necessity of a vacuum furnace and the long time required, the heat treat process is a costly one. The difficulties incurred in obtaining acceptable ESR 4340 material for this program were increased due to the great and immediate demand required for the fabrication of actual YAH-64 parts.

The program required evaluation of material from two different heats in the turning operation. The other machining tests were to be conducted on material from the heat which was harder to turn. Some material from a previously purchased heat (No. 9087-4) was used for part of the turning tests. Heat treated hardnesses for this residual material did not meet minimum requirements. The specification called for 54-57 Rc, while the material could only reach 51-53 Rc hardnesses, even after re-heat treatment of the material. This was thought to be due to the fact that its carbon content was barely on the minimum end of the requirements. The material was still used in testing because of the difficulties in readily obtaining test material. It was also determined that the maximum thickness permitted for through-hardening was 3 inches. Thicker material resulted in a hardness reduction, not only in the core area, but towards the surface of the material as well. The bulk of the test material came from a newly purchased heat, No. 49103. This material was heat treated at Ironbound Inc., in New Jersey. Tensile specimens were heat treated along with the test material to verify the heat treatment. The mechanical properties of both transverse and longitudinal tensile specimens were found to meet minimum requirements. Hardness measurements taken on the new heat material indicate little hardness reduction, usually ranging about 54-55 Rc.

Initially, turning tests were conducted on 3 inch diameter bars from both the residual heat and the new heat. Using various carbide and ceramic inserts, determination of the best tool was made. For each tool, relations between cutting speeds, feeds, depths of cut and tool lives were analyzed in an attempt to establish the most efficient tool. A tool life limit of about 30 minutes was set for the turning tests due to limited amounts of material and time. The data obtained for turning is presented in Table II. Effects of cutting speeds on tool life for various carbide and ceramic inserts are illustrated in Figures 2 and 3. The feeds and speeds were rather low and tool lives quite short for the carbide inserts. At 0.050 inch depth of cut, the carbide grades generally had a tool life of less than 10 minutes for feeds of 0.005 inch and speeds greater than 150 fpm. Speeds lower than 150 fpm were generally not

TABLE II. DATA FROM TURNING (Heat 49103)

| Insert           | Cutting Speed<br>(ft/min) | Feed<br>(in. / rev) | Depth of Cut<br>(in. ) | Tool Life<br>(min:sec) |
|------------------|---------------------------|---------------------|------------------------|------------------------|
| Carboloy<br>514  | 175                       | 0.005               | 0.050                  | 1:50                   |
|                  | 150                       | 0.005               | 0.050                  | 9:00                   |
| Carboloy<br>545  | 175                       | 0.005               | 0.050                  | 10:36                  |
|                  | 150                       | 0.005               | 0.050                  | 26:40                  |
| Carboloy<br>350  | 250                       | 0.005               | 0.050                  | 0:42                   |
|                  | 200                       | 0.005               | 0.050                  | 6:24                   |
|                  | 175                       | 0.005               | 0.050                  | 12:55                  |
|                  | 150                       | 0.005               | 0.050                  | 0.004" wear @ 30:00    |
|                  | 125                       | 0.005               | 0.050                  | 0.002" wear @ 10:00    |
|                  |                           |                     |                        |                        |
| Carboloy<br>883  | 250                       | 0.005               | 0.050                  | 1:50                   |
|                  | 225                       | 0.005               | 0.050                  | 5:00                   |
|                  | 200                       | 0.005               | 0.050                  | 5:00                   |
|                  | 175                       | 0.005               | 0.050                  | 7:10, 7, 3:10          |
|                  | 150                       | 0.005               | 0.050                  | 8:30                   |
|                  | 125                       | 0.005               | 0.050                  | 10:00                  |
| B & W<br>Ceramic | 1000                      | 0.005               | 0.050                  | 0:21                   |
|                  | 800                       | 0.005               | 0.050                  | 1:08                   |
|                  | 800                       | 0.0025              | 0.050                  | 1:00                   |
|                  | 700                       | 0.005               | 0.050                  | 1:09                   |
|                  | 600                       | 0.005               | 0.050                  | 2:37                   |
| NPC-A<br>Ceramic | 1000                      | 0.005               | 0.050                  | 0:22                   |
|                  | 800                       | 0.005               | 0.050                  | 0:50, 3:50             |
|                  | 800                       | 0.0025              | 0.050                  | 9:14                   |
|                  | 700                       | 0.005               | 0.050                  | 1:25                   |
|                  | 600                       | 0.005               | 0.050                  | 1:32                   |
| Sandvik<br>315   | 250                       | 0.005               | 0.050                  | 0:10                   |
|                  | 175                       | 0.005               | 0.050                  | 2:40                   |
|                  | 150                       | 0.005               | 0.050                  | 3:20                   |
| Kendex           | 500                       | 0.005               | 0.050                  | 21:00                  |
| K-090            | 525                       | 0.005               | 0.050                  | 34:00                  |
| Ceramic          | 550                       | 0.005               | 0.050                  | 1:55                   |

TABLE II. DATA FROM TURNING (Heat 9087) (CONT)

| Insert                                                                                                                                    | Cutting Speed<br>(ft/min) | Feed<br>(in. / rev) | Depth of Cut<br>(in. ) | Tool Life<br>(min:sec) |
|-------------------------------------------------------------------------------------------------------------------------------------------|---------------------------|---------------------|------------------------|------------------------|
| Carboloy<br>883                                                                                                                           | 100                       | 0.010               | 0.100                  | 22:00                  |
|                                                                                                                                           | 175                       | 0.005               | 0.050                  | 7:10                   |
| Carboloy<br>350                                                                                                                           | 175                       | 0.005               | 0.050                  | 30:00                  |
| Carboloy<br>545                                                                                                                           | 175                       | 0.005               | 0.050                  | 30:00                  |
| NPC-A<br>Ceramic                                                                                                                          | 1000                      | 0.005               | 0.050                  | 4:00                   |
|                                                                                                                                           | 900                       | 0.005               | 0.050                  | 0:24                   |
|                                                                                                                                           | 800                       | 0.005               | 0.050                  | 0:25                   |
|                                                                                                                                           | 500                       | 0.005               | 0.050                  | 2:51                   |
|                                                                                                                                           | 600                       | 0.0025              | 0.050                  | 25:45                  |
| B&W<br>Ceramic                                                                                                                            | 1000                      | 0.005               | 0.050                  | 0:37                   |
|                                                                                                                                           | 900                       | 0.005               | 0.050                  | 1:00                   |
|                                                                                                                                           | 800                       | 0.005               | 0.050                  | 2:26                   |
| Kendex                                                                                                                                    | 500                       | 0.005               | 0.050                  | 29:16                  |
| K-090                                                                                                                                     | 550                       | 0.005               | 0.050                  | 8:22                   |
| Ceramic                                                                                                                                   | 600                       | 0.005               | 0.050                  | 2:18, 4:10             |
| Tool geometry for all turning inserts as follows:                                                                                         |                           |                     |                        |                        |
| Back Rake: $-5^{\circ}$ SCEA: $15^{\circ}$ Side Relief: $5^{\circ}$<br>Side Rake: $-5^{\circ}$ ECEA: $15^{\circ}$ End Relief: $5^{\circ}$ |                           |                     |                        |                        |

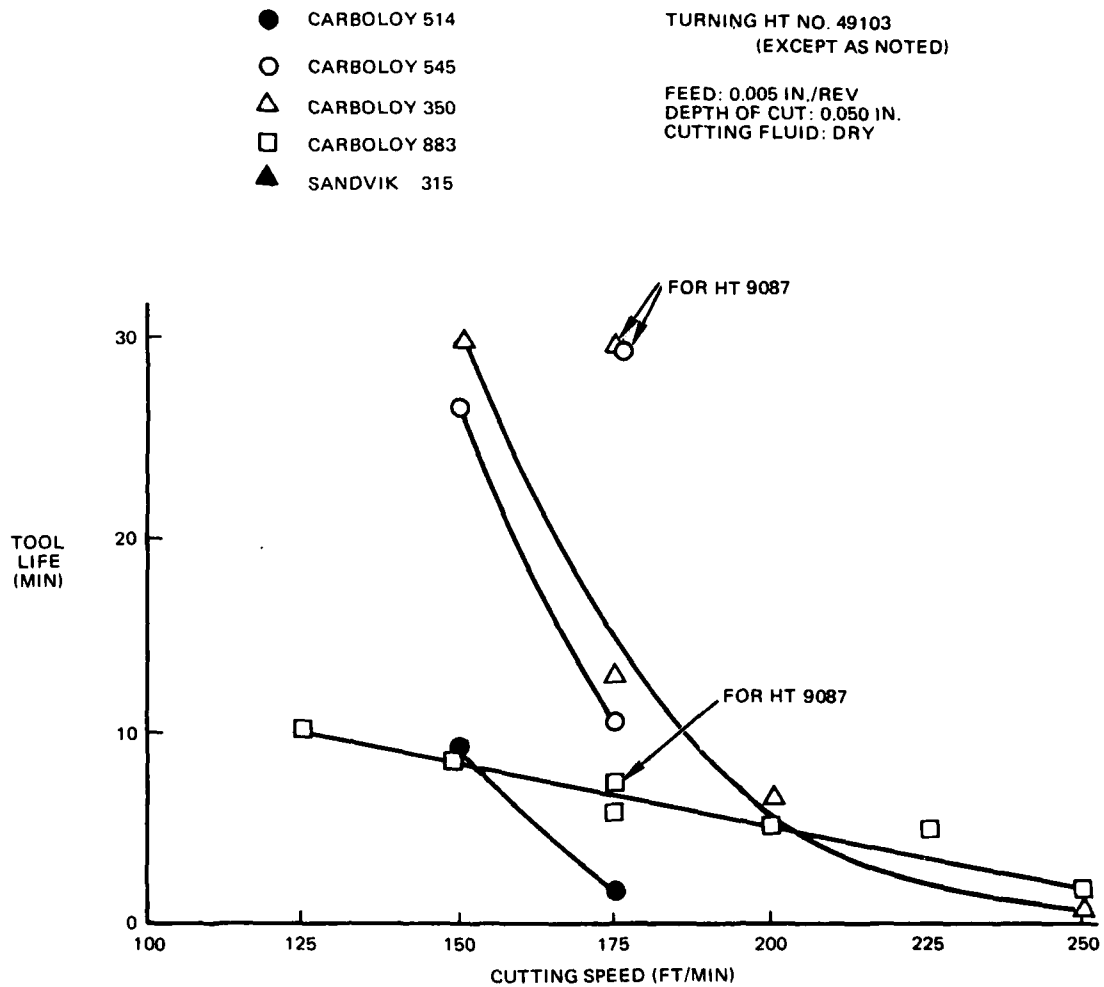


Figure 2. Effect of Cutting Speed and Tool Material (Carbide Inserts)

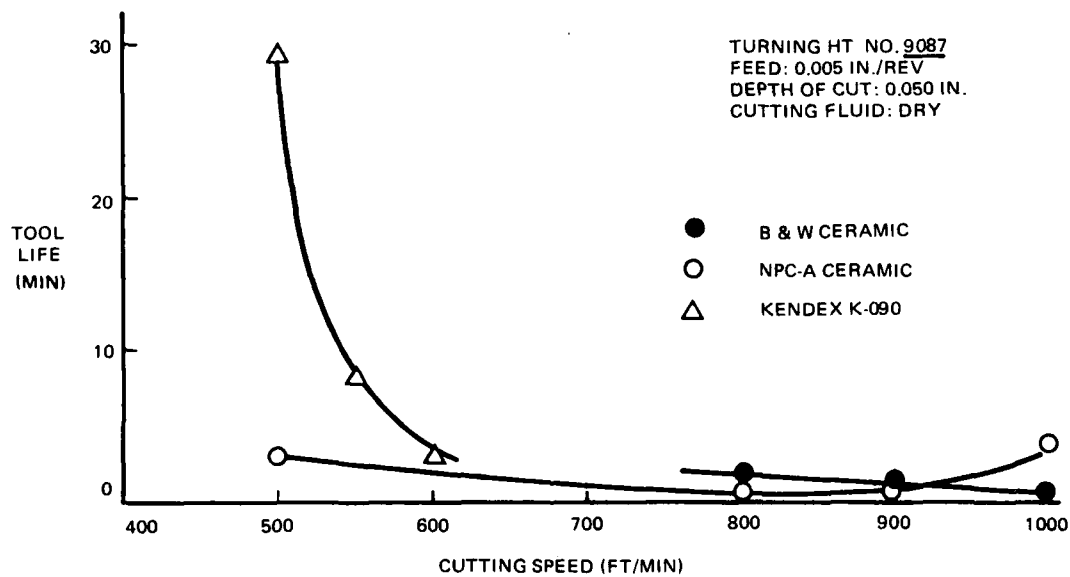
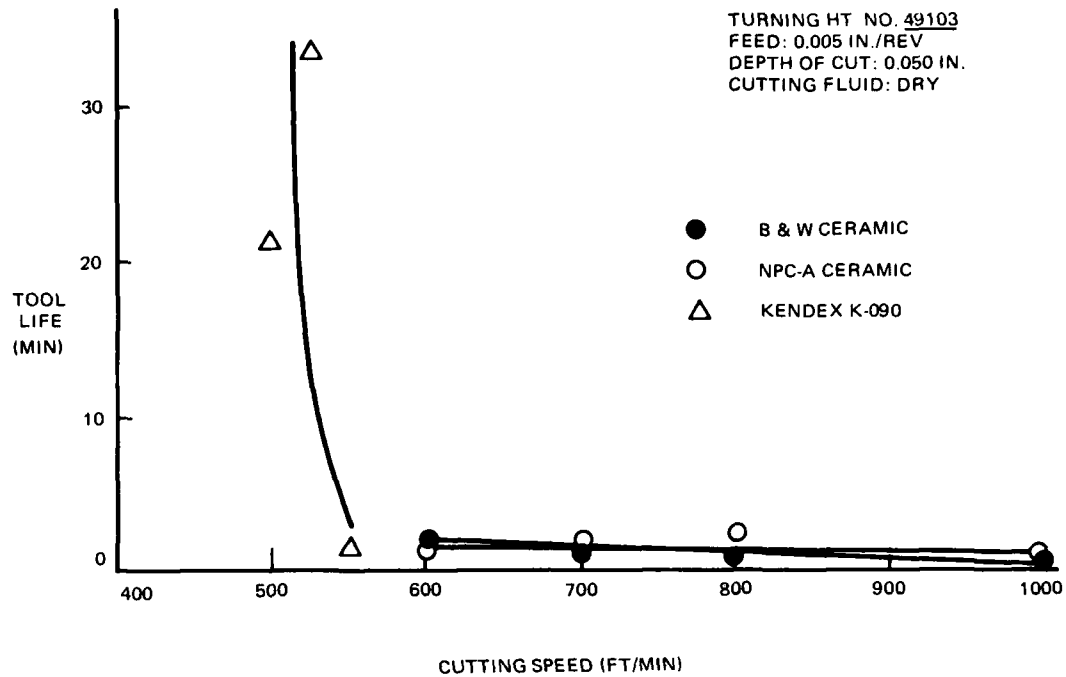


Figure 3. Effect of Cutting Speed and Tool Material (Ceramic Inserts)

tested due to its impracticality. The lower hardness of the residual heat material (Ht. 9087) seemed to make a great deal of difference regarding the life of the tool, in many cases doubling the tool life which was obtained when machining material from the other heat. A better picture of tool life variance due to insert types can be obtained by comparing the effects of turning material from heat No. 49103. Of the carbide inserts used for this heat, the Carboloy 545 and 350 grades seemed to perform the best. The 545 is an aluminum oxide coated, complex tungsten carbide insert used for finish machining. The 350 is an uncoated complex tungsten carbide insert used for light to medium roughing. Both have excellent resistance to high temperature crater and deformation. Ceramic inserts were expected to give better results, but chipping problems abruptly ended the tests after a few minutes. Speeds of 600 fpm and greater were used for these inserts. Another grade of ceramic, Kennametal Kendex K-090, was obtained in an attempt to eliminate chipping. Using lower cutting speeds, ~500 feet/minute, we were able to extend tool life up to approximately 30 minutes. The data obtained for the Kendex K-090 insert for Ht. 49103 is erratic. However, from the similarities of both heats involving the other ceramic inserts and the considerable improvements in tool life displayed by the K-090 in both heats, it is assumed that the curves are indicative of performance. The tool life end point was regarded as 0.015 inch wearland. This Kendex K-090 ceramic insert provided the best performance of all the tools tested.

Drilling was the next operation evaluated, using material from the new heat. The data obtained for drilling is presented in Table III. The study was limited to a single drilling diameter of 1/4 inch. Initially, various high speed steel and carbide drills were evaluated at various cutting speeds as low as 5 and 10 feet/minute and as high as 80 feet/minute. Using values of 0.001 ipr feed, 1/2 inch through depth of cut, with soluble and sulfurized oils, a determination of tool life was made. The results were very poor, with no more than 3 holes drilled per tool and a norm of 1 hole being drilled per tool. Attempts were made to obtain some T-15 drills, but a source could not be located. Chlorinated cutting fluid was obtained and appears to be of some benefit in drilling. The M-42 H.S.S. crankshaft point was used with the chlorinated oils to obtain additional data. Some of the effects of speeds and feeds using the M-42 drill is illustrated in Figure 4. Using very low cutting speeds of 5-15 feet/minute, and feeds of 0.0005-0.001 inches/revolution, drilling of multiple holes (~10/tool) was found to be possible. A tool life of 34 holes was obtained using a speed of 5 feet/minute and a feed of 0.0008 inches/revolution. As in turning, the tool life end point was regarded as 0.015 inch wear.

Face milling tests were conducted next, with an initial evaluation of various inserts. All of the information obtained is presented in Table IV. Figure 5 compares the various tools (including the Carmet CA310 which was

TABLE III. DRILLING

| Tools                             | Cutting Speed<br>(ft. /min. ) | Feed<br>(in. /rev. ) | Depth<br>of Cut<br>(in. ) | Cutting<br>Fluid   | Tool Life<br>No. of Holes |
|-----------------------------------|-------------------------------|----------------------|---------------------------|--------------------|---------------------------|
| High Speed<br>Steel               | 10                            | 0.001                | 1/2                       | Soluble Oil        | 0                         |
| High Speed<br>Steel<br>Crankshaft | 5                             | 0.001                | 1/2                       | Sulfurized<br>Oil  | 3                         |
| Carbide                           | 10                            | 0.001                | 1/2                       | Soluble Oil        | 1                         |
|                                   | 80                            | 0.0005               | 1/2                       | Sulfurized<br>Oil  | 1, 1, 1, 1                |
|                                   | 80                            | 0.001                | 1/2                       | Sulfurized<br>Oil  | 1                         |
| M-42                              | 25                            | 0.001                | 1/2                       | Soluble Oil        | 1                         |
| H. S. S.<br>Crankshaft            | 10                            | 0.001                | 1/2                       | Soluble Oil        | 3                         |
|                                   | 10                            | 0.001                | 1/2                       | Soluble Oil        | 1                         |
|                                   | 10                            | 0.0005               | 1/2                       | Soluble Oil        | 2                         |
|                                   | 5                             | 0.001                | 1/2                       | Soluble Oil        | 2                         |
| M-42                              | 5                             | 0.0008               | 1/2                       | Chlorinated<br>Oil | 34                        |
| H. S. S.<br>Crankshaft            | 5                             | 0.002                | 1/2                       | ↓                  | 10                        |
|                                   | 5                             | 0.005                | 1/2                       |                    | 2                         |
|                                   | 8                             | 0.0005               | 1/2                       |                    | 10                        |
|                                   | 10                            | 0.0008               | 1/2                       |                    | 7                         |
|                                   | 10                            | 0.001                | 1/2                       |                    | 11                        |
|                                   | 10                            | 0.002                | 1/2                       |                    | 1                         |
|                                   | 15                            | 0.0005               | 1/2                       |                    | 6                         |
|                                   | 15                            | 0.0008               | 1/2                       | Chlorinated<br>Oil | 3                         |

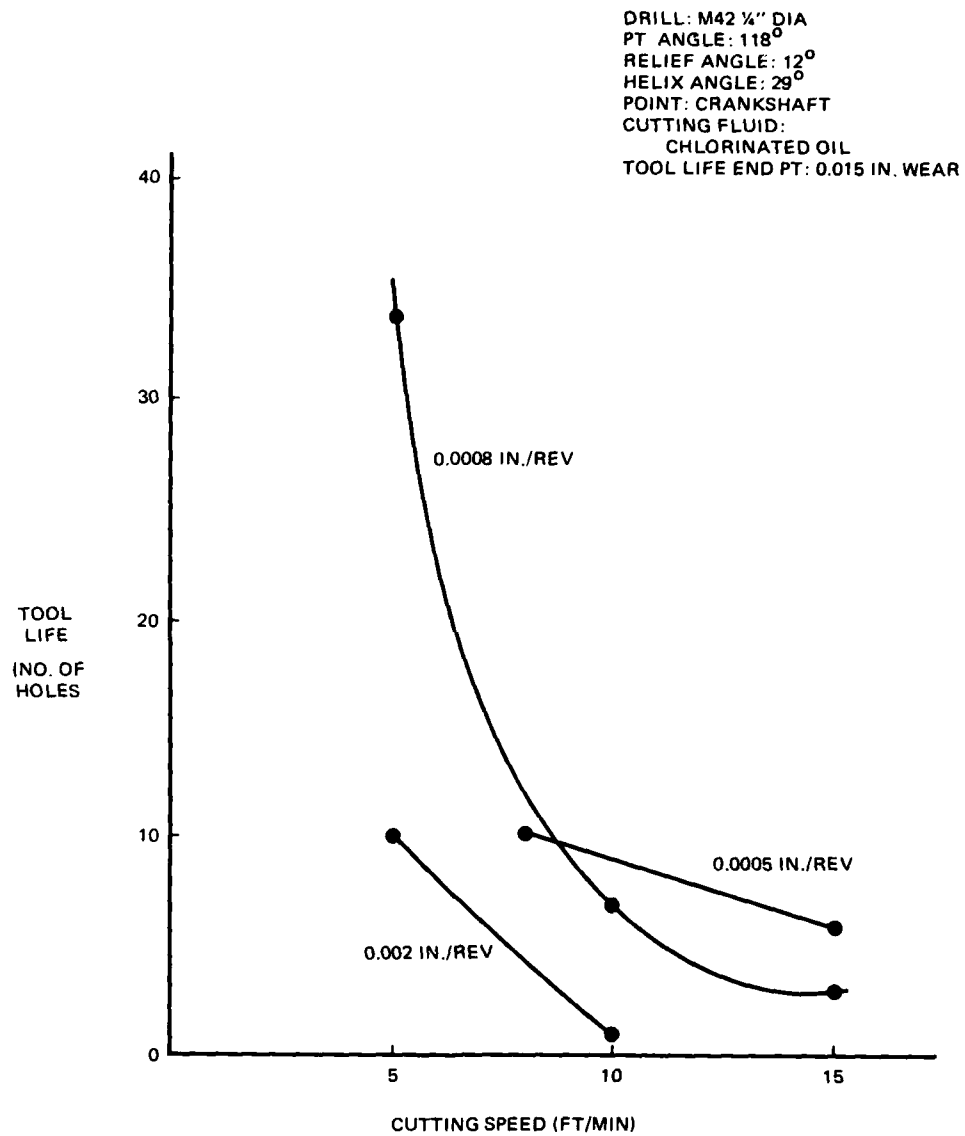


Figure 4. Effect of Cutting Speeds and Feeds in Drilling Using M42 H. S. S. Crankshaft Drill

TABLE IV. FACE MILLING DATA

Machining conditions constant for all tests below.

Depth of Cut = 0.060"

Width of Cut = 1 1/2"

Tool Life End Point: 0.015" wear

| Insert     | Cutting Speed<br>ft. /min | Feed<br>in. /tooth | Cutting<br>Fluid | Tool Life<br>Inches of Work<br>Traveled |
|------------|---------------------------|--------------------|------------------|-----------------------------------------|
|            | <u>Carbide</u>            |                    |                  |                                         |
| Sandvik    | 125                       | 0.005              | Dry              | 2 1/2"                                  |
| 315        | 150                       | 0.003              | Dry              | 4"                                      |
| Kennametal |                           |                    |                  |                                         |
| K-11       | 150                       | 0.003              | Dry              | 20"                                     |
| K7H        | 150                       | 0.003              | Dry              | 2"                                      |
| KC810      | 125                       | 0.005              | Dry              | 2 1/2"                                  |
| Carboloy   |                           |                    |                  |                                         |
| 210        | 150                       | 0.003              | Dry              | 1"                                      |
| 370        | 150                       | 0.003              | Dry              | 11"                                     |
| 545        | 125                       | 0.005              | Dry              | 1"                                      |
| 883        | 40                        | 0.005              | Dry              | 10"                                     |
|            | 60                        | 0.005              | Dry              | 12 1/2"                                 |
|            | 75                        | 0.005              | Dry              | 8", 12"                                 |
|            | 100                       | 0.003              | Dry              | 24"                                     |
|            | 125                       | 0.005              | Dry              | 12"                                     |
|            | 125                       | 0.0015             | Dry              | 19"                                     |
|            | 125                       | 0.003              | Dry              | 29"                                     |
|            | 150                       | 0.003              | Dry              | 36"                                     |
|            | 150 (0.030" depth)        | 0.003              | Dry              | 36"                                     |
|            | 150 (0.090" depth)        | 0.003              | Dry              | 28"                                     |
|            | 150                       | 0.003              | Soluble Oil      | 6 1/2"                                  |
|            | 200                       | 0.003              | Dry              | 15 1/2"                                 |
| 999        | 150                       | 0.003              | Dry              | 4"                                      |
| Carmet     | 75                        | 0.0085             | Dry              | 54"                                     |
| CA310      | 100                       | 0.0085             | Dry              | 60"                                     |
|            | 100                       | 0.003              | Dry              | 32"                                     |
|            | 100                       | 0.005              | Dry              | 41"                                     |
|            | 100                       | 0.007              | Dry              | 56"                                     |
|            | 100                       | 0.010              | Dry              | 48"                                     |
|            | 125                       | 0.0085             | Dry              | 24"                                     |
|            | 150                       | 0.003              | Dry              | 24"                                     |
|            | <u>Ceramic</u>            |                    |                  |                                         |
| Kennametal |                           |                    |                  |                                         |
| K060       | 125                       | 0.005              | Dry              | 1"                                      |
| K090       | 125                       | 0.005              | Dry              | 7", 9-3/4"                              |
|            | 150                       | 0.003              | Dry              | 5 1/2", 10 1/2"                         |
|            | 175                       | 0.003              | Dry              | 10 1/2"                                 |

FACE MILLING  
CUTTING SPEED: 125 FT/MIN  
FEED: 0.005 IN./TOOTH  
DEPTH: 0.060 IN.  
CUTTING FLUID: DRY

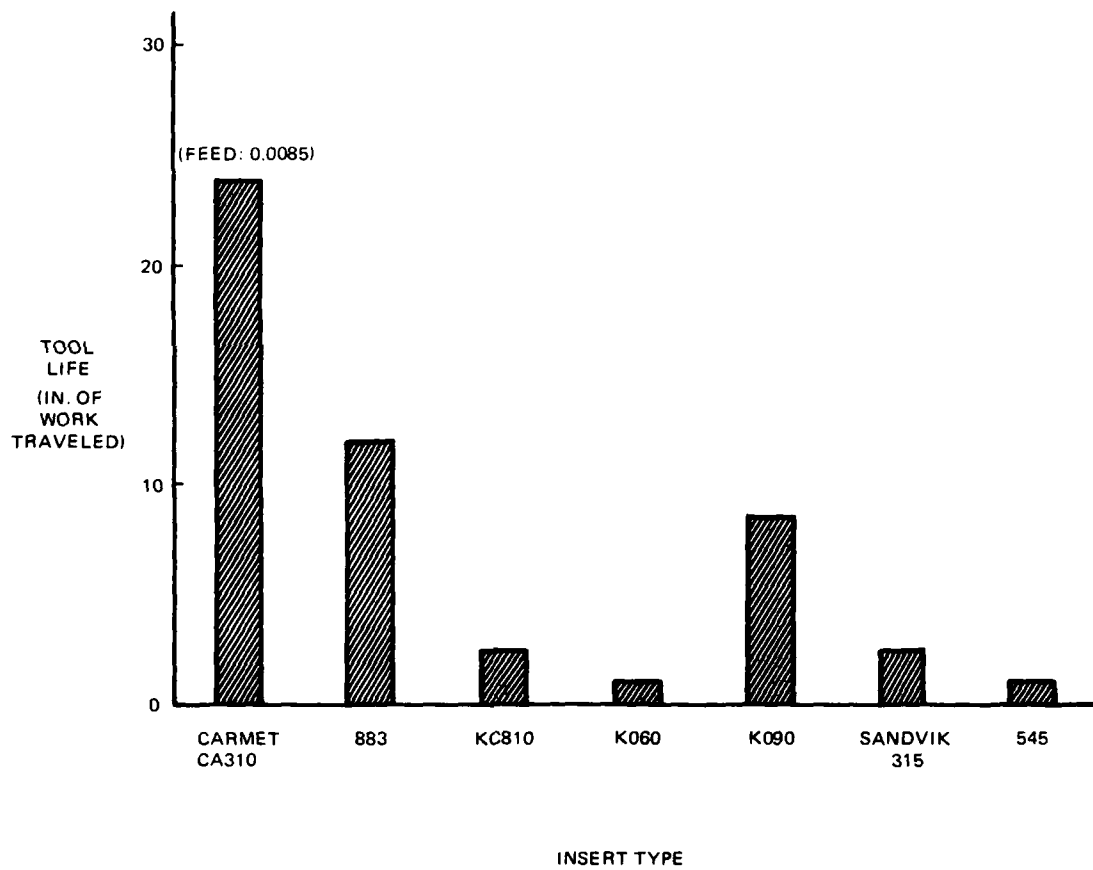


Figure 5. Comparison of Tools for Face Milling

obtained later) under like conditions. Of the tools initially evaluated, the Carboloy 883 insert appeared to perform the best. Effects of cutting speeds, feeds, and depths of cut were evaluated using this insert (Figure 6). It was determined that for this insert, a speed of 150 feet/minute and a feed of 0.003 inch/tooth was optimum. Also depths of cut higher than 0.060 inch seemed to result in a reduction of tool life, while lower depths of cut did not seem to produce much improvement. Another type of insert, a Carmet CA 310 was later obtained and tested. This micrograin carbide insert has the ability to withstand great impact and proved to be the best face milling tool tested. Figure 7 illustrates the effects of various parameters upon the performance of the CA 310 insert. Using greater feeds, but lesser speeds than the 883 carbide, tool lives of 40-60 inches of work traveled were obtainable with the Carmet insert. This is in comparison to the typical values of 10-30 inches obtained using the 883 insert. For the Carmet insert, a speed of 100 feet/minute and a feed of 0.0085 inch/tooth seemed to be optimum, using a 0.060 inch depth of cut. Some tests were attempted using cutting fluid but better results were obtained when the tests were run dry.

Peripheral end milling tests were run using various brazed on carbide end mills and insert type end mills. The data obtained with these tools is presented in Tables V and VI. A comparison of the tools tested is shown in Figure 8. Union, Rito and TRW end mills had brazed helical carbides while the 370 tool was brazed with a straight 370 carbide insert with no helix angle. These brazed end mills were all four-fluted. Ramet, 370 and 883 insert type end mills with equivalent geometries were tested. The insert types were all three fluted. The TRW was found to be the best of the brazed on type and the Ramet was found to be the best of the insert type. At a cutting speed of 100 feet/minute, a feed of 0.003 inch/tooth, a depth of cut of 0.060 inches, and a width of cut of 0.375 inches, both the Ramet and TRW tools had a tool life of 156 inches traveled. Though the tool life values for both of these tools were similar, the TRW tool had a higher removal rate due to the four-fluted nature of the tool. Again, better results were obtained without using a cutting fluid.

Finally, various grinding tests were conducted on the material. A study was made using low stress grinding techniques, and also using maximum and minimum values of two Hughes Helicopters process specifications, HP 18-12 and HP 15-51. The surface grinding conditions used are given in Table I of Appendix D. Figure 5 of Appendix D presents measured residual stress profiles from the surface to a depth of 0.0020 inches. Low level compressive stress, beneficial in fatigue, is present, along and just below the surface. Microhardness measurements taken at various distances from the surface illustrate the degree of surface degradation occurring for each condition.

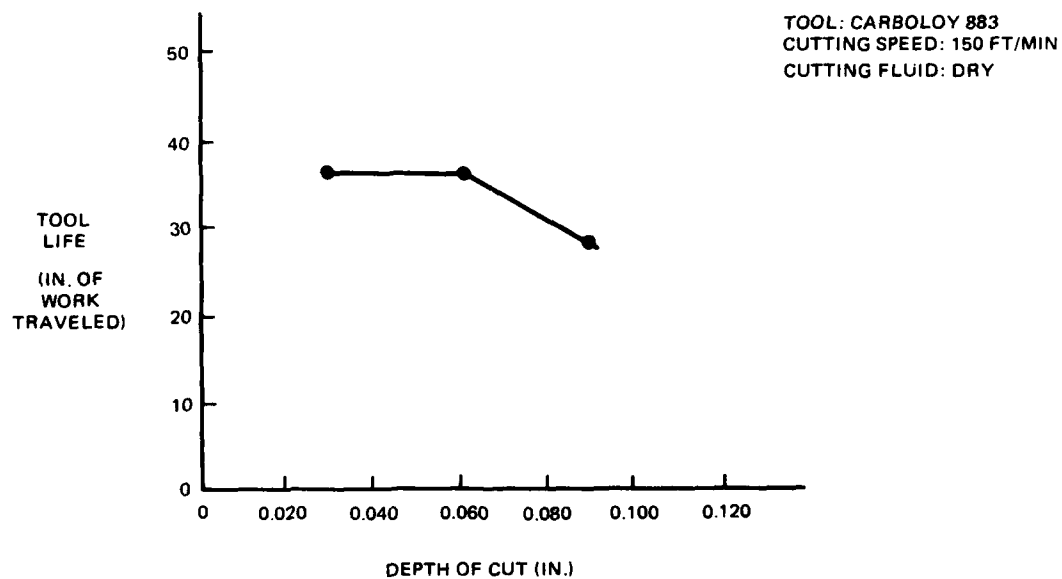
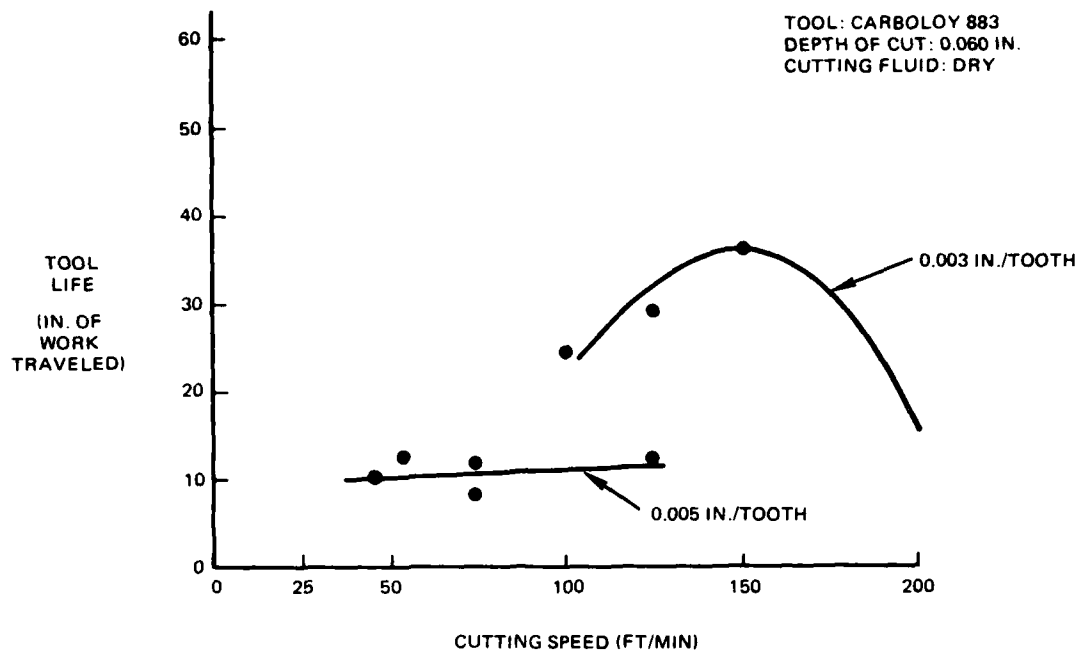


Figure 6. Effect of Parameter Variations in Face Milling with 883 Insert

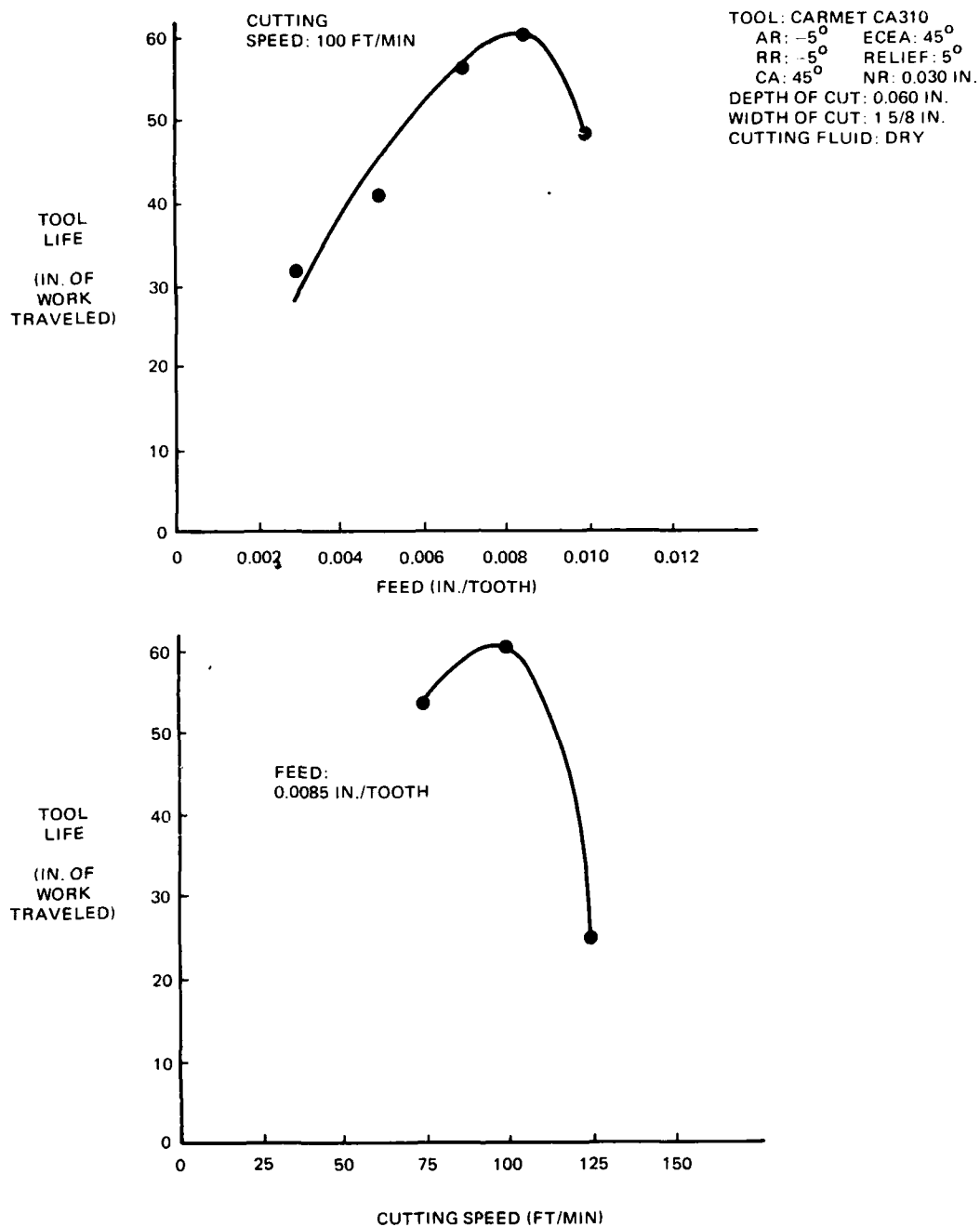


Figure 7. Effect of Parameter Variations in Face Milling with CA 310 Insert

TABLE V. PERIPHERAL END MILLING DATA

Brazed on carbide end mill geometry.

|                         | <u>Union</u> | <u>Rito</u> | <u>TRW</u> | <u>370</u> |
|-------------------------|--------------|-------------|------------|------------|
| Axial Rake:             | 20°          | 20°         | 7°         | 0°         |
| Radial Rake:            | 5°           | 5°          | 5°         | -5°        |
| Corner Angle:           | 45°          | 45°         | 45°        | 45°        |
| End Cutting Edge Angle: | 1°           | 1°          | 1°         | 1°         |
| Per. Cl.:               | 10°          | 10°         | 10°        | 10°        |
| End Cl.:                | 3°           | 3°          | 3°         | 3°         |

| <u>Cutting Tool</u> | <u>Cutting Speed<br/>ft. /min.</u> | <u>Feed<br/>in. /tooth</u> | <u>Depth of<br/>Cut in.</u> | <u>Width of<br/>Cut in.</u> | <u>Cutting<br/>Fluid</u> | <u>Tool Life<br/>in Work<br/>Traveled</u> |
|---------------------|------------------------------------|----------------------------|-----------------------------|-----------------------------|--------------------------|-------------------------------------------|
| <u>Brazed on</u>    |                                    |                            |                             |                             |                          |                                           |
| Union               | 100                                | 0.002                      | 0.060                       | 0.375                       | Dry                      | 84"                                       |
| Rito                | 100                                | 0.002                      | 0.060                       | 0.375                       | Dry                      | 60"                                       |
| Trw                 | 100                                | 0.002                      | 0.060                       | 0.375                       | Dry                      | 180"                                      |
|                     | 100                                | 0.003                      | 0.060                       | 0.375                       | Dry                      | 156"                                      |
| 370                 | 75                                 | 0.002                      | 0.060                       | 0.375                       | Dry                      | 48"                                       |
|                     | 100                                | 0.001                      | 0.060                       | 0.375                       | Dry                      | 108"                                      |
|                     | 100                                | 0.001                      | 0.060                       | 0.375                       | Sol. Oil                 | 48"                                       |
|                     | 100                                | 0.002                      | 0.060                       | 0.375                       | Dry                      | 132"                                      |
|                     | 100                                | 0.003                      | 0.060                       | 0.375                       | Dry                      | 108"                                      |
|                     | 125                                | 0.002                      | 0.060                       | 0.375                       | Dry                      | 120"                                      |

TABLE VI. PERIPHERAL END MILLING DATA

| Geometry of Insert End Mills. |                            |                    |                     |                     |                  |                                   |
|-------------------------------|----------------------------|--------------------|---------------------|---------------------|------------------|-----------------------------------|
| Axial Rake:                   |                            | 0°                 |                     |                     |                  |                                   |
| Radial Rake:                  |                            | 5°                 |                     |                     |                  |                                   |
| Corner Angle:                 |                            | 45°                |                     |                     |                  |                                   |
| End Cutting Edge Angle:       |                            | 45°                |                     |                     |                  |                                   |
| Per. Cl.:                     |                            | 5°                 |                     |                     |                  |                                   |
| End Cl.:                      |                            | 5°                 |                     |                     |                  |                                   |
| Insert                        | Cutting Speed<br>ft. /min. | Feed<br>in. /tooth | Depth of Cut<br>in. | Width of<br>Cut in. | Cutting<br>Fluid | Tool Life<br>In. Work<br>Traveled |
| Ramet                         | 100                        | 0.002              | 0.060               | 0.375               | Dry              | 132                               |
|                               | 100                        | 0.003              | 0.060               | 0.375               | Dry              | 156                               |
| 370                           | 100                        | 0.002              | 0.060               | 0.375               | Dry              | 72                                |
|                               | 100                        | 0.003              | 0.060               | 0.375               | Dry              | 48                                |
| 883                           | 100                        | 0.002              | 0.060               | 0.375               | Dry              | 82                                |
|                               | 100                        | 0.003              | 0.060               | 0.375               | Dry              | 72                                |

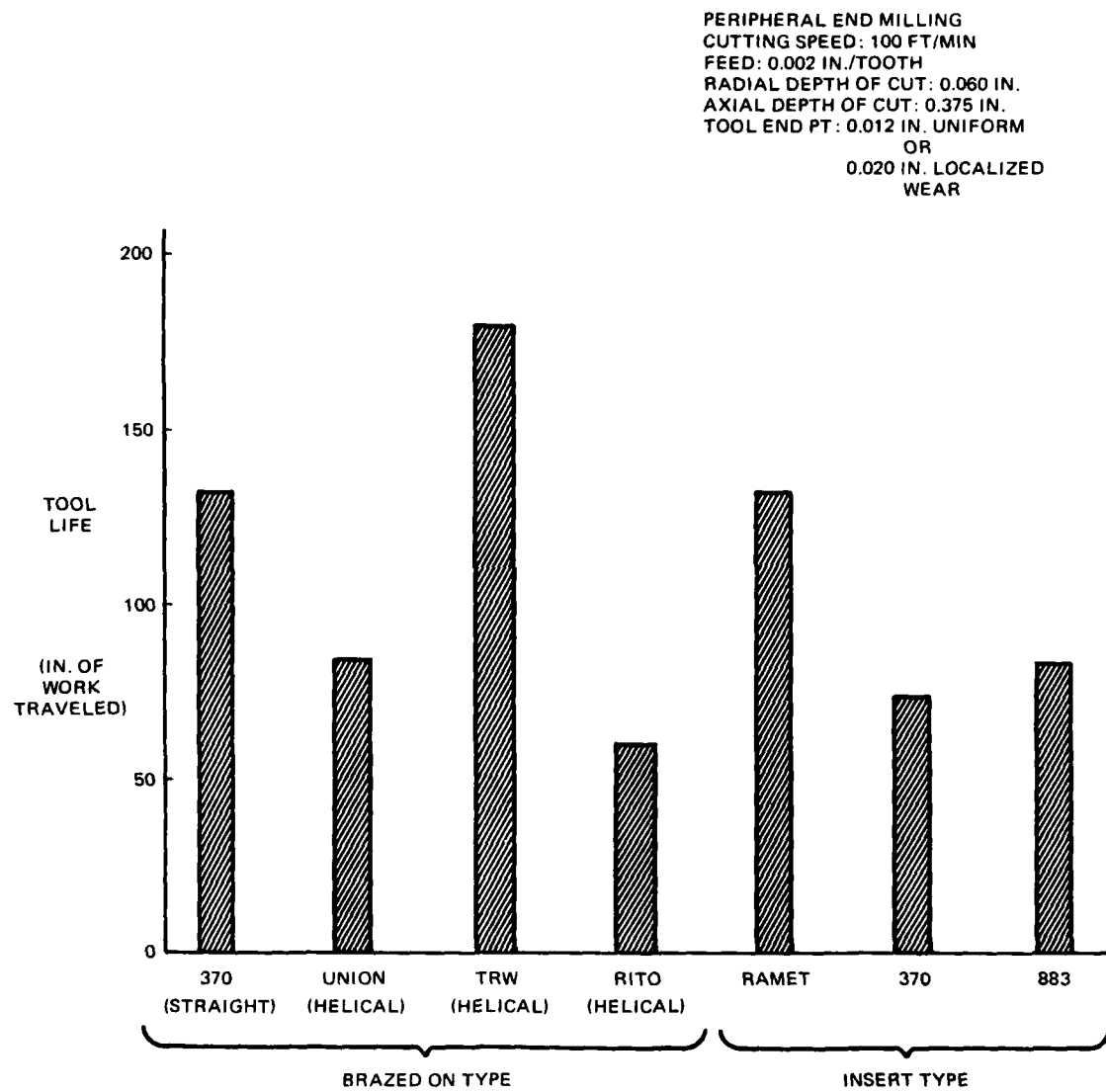


Figure 8. Comparison of Tools for Peripheral End Milling

This is illustrated in Figure 4 of Appendix D. Note that the greatest adverse effect takes place for HP 15-51 maximum. Detrimental surface tensile stresses occur for this condition and the photomicrograph (Figure 3 of Appendix D) indicates the extent of subsurface alterations. Photomicrographs (Figures 1, 2 and 3 of Appendix D) of the other conditions seem to show a generally smooth surface with a thin layer ( 0.0001 inch) of untempered martensite, and slight surface lapping and cracking.

The information obtained in this program, along with previously published data, indicate that certain modifications should be considered in the low stress grinding specification for ESR 4340 steel, HP 18-12 (Appendix E). The tests run by Metcut have verified the credibility of HP 18-12. However, certain variables such as crossfeeds and infeeds could be reduced to insure surface quality. Greater crossfeeds apply greater loads to the wheel, thereby increasing the probability of grinding burns. It is suggested that the crossfeed rate be reduced from 0.100 in./pass to 0.050 in./pass. The infeed rate is very important to surface integrity. It is suggested that a lower removal rate (0.0005 in./pass) be taken closer to the finish (0.002 in.) for rough grinding. Best finishing results are obtained at 0.0002 in./pass for such high strength steels.

Cutting fluids are also very important in low stress grinding. A sulfurized oil is best suited for this process. Oil based types include neutral fluids which do not give as much aid to the cutting process as a sulfurized oil. However, most machine shops have a certain cutting fluid generally used throughout the shop and changing this requirement in all shops would be difficult and impractical. It is suggested that sulfurized oil be mentioned in the specification as a recommended alternate to be used in low stress grinding procedures whenever possible.

From Metcut's past experiences, it was felt that an accurate definition of grinding wheel and dressing procedure was very important for achieving efficiency in grinding. A typical dressing procedure used for low stress grinding was to make 5 passes at 0.001 inch depth/pass with 2 sparkouts. The diamond traverse rate was 1 inch/7 seconds. It is suggested that this dress procedure be included as a part of the low stress grinding specification. A faster rate and greater depth of pass results in a rougher surface and increased diamond abuse. Slow rates with multiple shallow passes create maximum stress concentrations, although a smoother wheel is attained. The proper dressing procedure is one which utilizes the fastest rates while still maintaining an acceptable degree of surface roughness.

Under the scope of this program and with the amount of available material, an attempt was made to obtain the most comprehensive information possible regarding the conventional machining of ESR 4340 steel. All the machining operations were found to be extremely difficult and application towards production parts appears to be unfeasible. Reduced feeds and speeds still resulted in tool lives which were shorter than desired. Low stress grinding techniques do appear to be applicable to this material. Efforts are being made to incorporate the recommended changes to the low stress grinding specification. The extent of actual changes will be determined by the compromising effects of reduced production rates and increased quality. Table VII summarizes the results obtained, presenting the best tools and conditions for each of the machining operations investigated in this program. In view of the results, the program has been cancelled and studies regarding possible alternative methods for machining ESR 4340 steel are being considered for a new program.

TABLE VII. OPTIMUM CONDITIONS FOR MACHINING ESR 4340 STEEL

| Operation                                                                                            | Tool                                             | Cutting Speed | Feed             | Depth of Cut    | Width of Cut | Cutting Fluid   |
|------------------------------------------------------------------------------------------------------|--------------------------------------------------|---------------|------------------|-----------------|--------------|-----------------|
| Turning                                                                                              | Kendex K-090 Ceramic                             | 500 Ft/Min    | 0.050 In./Rev    | 0.005 In.       |              | Dry             |
| Tool Geom.: Back Rake: -5° SCEA: 15° Side Relief: 5°<br>Side Rake: -5° ECEA: 15° End Relief: 5°      |                                                  |               |                  |                 |              |                 |
| Drilling (1/4 In. Dia)                                                                               | M-42 H. S. S. Crankshaft Pt.                     | 5 Ft/Min      | 0.0008 In./Rev.  | 1/2 In. Through |              | Chlorinated Oil |
| Tool Geom.: Pt. Angle: 118° Helix Angle: 29°<br>Relief Angle: 112°                                   |                                                  |               |                  |                 |              |                 |
| Face Milling                                                                                         | Carmet CA 310                                    | 100 Ft/Min    | 0.0085 In./Tooth | 0.060 In.       | 1 5/8 In.    | Dry             |
| Tool Geom.: Axial Rake: -5° ECEA: 45° Corner angle: 45°<br>Radial Rake: -5° Relief: 5°               |                                                  |               |                  |                 |              |                 |
| Peripheral End Milling                                                                               | TRW Helical Brazed-On Carbide                    | 100 Ft/Min    | 0.002 In./Tooth  | 0.060 In.       | 0.375        | Dry             |
| Tool Geom.: Axial Rake: 7° ECEA: 10° Per. Cl.: 10°<br>Radial Rake: 5° Corner Angle: 45° End Cl.: 30° |                                                  |               |                  |                 |              |                 |
| Surface Grinding (Low Stress)                                                                        | Wheel Grade: A46 HV                              | 2000 Ft/Min   |                  |                 |              |                 |
|                                                                                                      | Wheel Speed: 40 Ft/Min                           |               |                  |                 |              |                 |
|                                                                                                      | Work Speed: 0.050 In./Pass                       |               |                  |                 |              |                 |
|                                                                                                      | Cross Feed: Sulfurized Oil                       |               |                  |                 |              |                 |
|                                                                                                      | Fluid: 0.0005 In./Pass to 0.002 In. of Finish    |               |                  |                 |              |                 |
|                                                                                                      | Downfeed: 0.0002 In./Pass Finish Grinding        |               |                  |                 |              |                 |
|                                                                                                      | Wheel Dress Procedure: 5 Passes @ 0.001 In./Pass |               |                  |                 |              |                 |
|                                                                                                      | 2 Sparkouts                                      |               |                  |                 |              |                 |
|                                                                                                      | Diamond Traverse Rate: 1 In./7 Sec               |               |                  |                 |              |                 |

### CONCLUSIONS AND RECOMMENDATIONS

This study regarding the machining of ESR 4340 has led to the following conclusions:

- Conventional machining methods are not applicable to this material. Tool lives remain short despite reductions in feeds and speeds. Material removal rates are lower than those which can be used for other high strength steels.
- In ranges above 50 Rc, slight hardness reductions create great improvements in machinability, occasionally allowing tool lives to double.
- Turning and milling operations generally gave the best results when machining was done without cutting fluid. Drilling was aided by the use of chlorinated cutting fluid, while grinding was best done with sulfurized oil.
- Low stress grinding techniques are applicable to this material, when proper dressing procedures and reduced rates are used. The results of this program indicate the need to revise the low stress grinding specification for ESR 4340 steel regarding dressing procedure, cutting fluids and cutting rates.

Based on the results of the program studies of alternative methods of machining ESR steel is recommended. Although not used during the course of this program, previous studies indicate that Borozon (cubic boron nitride) wheels should be considered for surface grinding operations. They are highly resistant to wear and allow higher grinding speeds for greater productivity. However, the wheels are extremely high priced, often more than ten times the cost of equivalent aluminum oxide wheels. The Borozon wheel is best suited for grinding situations which occur repeatedly.

APPENDIX A

A compilation of data obtained primarily through a literature survey conducted at the Machinability Data Center. The data consists of conditions used in attempts to machine various high hardness materials (50 Rc and above) which approach ESR 4340 steel. The information was used to help establish a starting point for tools and parameter values in our own machining investigations involving ESR 4340 steel.

## TURNING WITH CARBIDE AND HIGH SPEED STEEL TOOLS

| Material      | Hardness<br>F <sub>c</sub> | Condition | Depth<br>of Cut<br>(in) | Tool<br>Material | Speed<br>(fpm) | Feed<br>(inpr) | Back<br>Rake<br>(deg) | Side<br>Fank<br>(deg) | Relief<br>*FCEA | SCEA | N.R. | Cutting<br>Fluid<br>(min.) | Tool<br>Life,<br>Hearland<br>(hr.) |
|---------------|----------------------------|-----------|-------------------------|------------------|----------------|----------------|-----------------------|-----------------------|-----------------|------|------|----------------------------|------------------------------------|
| ---           | 63-65                      | -         | .008                    | S95              | 80             | .003           | -                     | -                     | -               | -    | -    | Dry                        | -                                  |
| ENH12N Steel  | 60-61                      | Q/T       | .020                    | T15K6            | 66             | .003           | -18                   | 0                     | 10              | 15   | 0    | Dry                        | -                                  |
| ENH12N Steel  | 60-61                      | Q/T       | .020                    | T15K6            | 55             | .005           | -18                   | 0                     | 10              | 15   | 0    | Dry                        | -                                  |
| ENH12N Steel  | 60-61                      | Q/T       | .020                    | T15K6            | 43             | .003           | -18                   | 0                     | 10              | 15   | 0    | Dry                        | -                                  |
| ENH12N Steel  | 60-61                      | Q/T       | .020                    | T15K6            | 36             | .012           | -18                   | 0                     | 10              | 15   | 0    | Dry                        | -                                  |
| ENH12N Steel  | 58-59                      | Q/T       | .019                    | T15K6            | 75.5           | .003           | -23                   | 0                     | 10              | 15   | 0    | Dry                        | -                                  |
| ENH12N Steel  | 58-59                      | Q/T       | .010                    | T15K6            | 66             | .005           | -23                   | 0                     | 10              | 15   | 0    | Dry                        | -                                  |
| ENH12N Steel  | 58-59                      | Q/T       | .010                    | T15K6            | 49             | .008           | -23                   | 0                     | 10              | 15   | 0    | Dry                        | -                                  |
| ENH12N Steel  | 58-59                      | Q/T       | .010                    | T15K6            | 36             | .012           | -23                   | 0                     | 10              | 15   | 0    | Dry                        | -                                  |
| 904c          | 51                         | -         | .000                    | C4               | 75             | .005           | -                     | -                     | -               | -    | -    | -                          | 15                                 |
| 440C          | 57                         | Q/T       | .062                    | C2               | 95             | .005           | -7                    | 0                     | 5               | 45   | .030 | Sol Oil 30<br>(1:20)       | .015                               |
| 440C          | 57                         | Q/T       | .062                    | C2               | 110            | .005           | -7                    | 0                     | 5               | 45   | .030 | Sol Oil 10<br>(1:20)       | .015                               |
| 440C          | 57                         | Q/T       | .062                    | C6               | 50             | .005           | -7                    | 0                     | 5               | 45   | .030 | Sol Oil 28<br>(1:20)       | .015                               |
| 440C          | 57                         | Q/T       | .062                    | C6               | 65             | .005           | -7                    | 0                     | 5               | 45   | .030 | Sol Oil 10<br>(1:20)       | .015                               |
| 300N (HSS)    | 56                         | Q/T       | .062                    | T15              | 10             | .005           | 0                     | 10                    | 5               | 5    | .030 | Sol Oil 60<br>(1:20)       | .060                               |
| 300N (HSS)    | 56                         | Q/T       | .062                    | T15              | 15             | .005           | 0                     | 10                    | 5               | 5    | .030 | Sol Oil 28<br>(1:20)       | .060                               |
| 300N (HSS)    | 56                         | Q/T       | .062                    | T15              | 20             | .005           | 0                     | 10                    | 5               | 5    | .030 | Sol Oil 10<br>(1:20)       | .060                               |
| 300N (HSS)    | 56                         | Q/T       | .062                    | M42              | 10             | .007           | 0                     | 10                    | 5               | 5    | .030 | Sol Oil 90<br>(1:20)       | .060                               |
| 300N (HSS)    | 56                         | Q/T       | .062                    | M42              | 15             | .007           | 0                     | 10                    | 5               | 5    | .030 | Sol Oil 30<br>(1:20)       | .060                               |
| 300N (HSS)    | 56                         | Q/T       | .062                    | M42              | 20             | .007           | 0                     | 10                    | 5               | 5    | .030 | Sol Oil 30<br>(1:20)       | .060                               |
| 300N Carbide  | 56                         | Q/T       | .062                    | C7(K7H)          | 125            | .005           | -5                    | -5                    | 5               | 15   | .030 | Dry                        | .015                               |
| 300N Carbide  | 56                         | Q/T       | .062                    | C7(K7H)          | 175            | .005           | -5                    | -5                    | 5               | 15   | .030 | Dry                        | .015                               |
| 300N Carbide  | 56                         | Q/T       | .062                    | C7(K7H)          | 200            | .005           | -8                    | -5                    | 5               | 45   | .030 | Dry                        | .015                               |
| 300N Carbide  | 56                         | Q/T       | .062                    | C7(K7H)          | 250            | .005           | -8                    | -5                    | 5               | 45   | .030 | Dry                        | .015                               |
| 300N Carbide  | 56                         | Q/T       | .062                    | C7(K7H)          | 300            | .005           | -8                    | -5                    | 5               | 45   | .030 | Dry                        | .015                               |
| 4340          | 54                         | -         | .120                    | C6               | 90             | .004           | -                     | -                     | -               | -    | -    | -                          | 19                                 |
| 1000 Jet 1000 | 54                         | -         | .050                    | C7(350)          | 100            | .0105          | -8                    | -1 1/2                | 6               | 20   | 1/8  | Dry                        | .015                               |
| 1000 Jet 1000 | 54                         | -         | .050                    | C7(350)          | 170            | .0105          | -8                    | -1 1/2                | 6               | 20   | 1/8  | Dry                        | .015                               |
| 4340 (HSS)    | 53                         | Q/T       | .050                    | 370              | 200            | .005           | -5                    | -5                    | 5               | 15   | .030 | Dry                        | .015                               |
| 4340 (HSS)    | 50-53                      | Q/T       | .040                    | HSS              | 24             | .007           | -                     | -                     | -               | -    | -    | Sol Oil<br>(1:20)          | -                                  |

## TURNING WITH CARBIDE AND HIGH SPEED STEEL TOOLS (cont.)

[illegible]

TURNING WITH CARBIDE AND HIGH SPEED STEEL TOOLS (cont)

| Material       | Hardness<br>Rc | Condition  | Depth<br>of Cut<br>(in) | Tool<br>Material              | Speed<br>(fpm) | Feed<br>(inpr) | Back<br>Rake<br>(deg) | Side<br>Rake<br>(deg) | Relief<br>% ECLA | SCEA | N.R. | Cutting<br>Fluid         | Tool<br>Life<br>(min) | Wear<br>(in) |
|----------------|----------------|------------|-------------------------|-------------------------------|----------------|----------------|-----------------------|-----------------------|------------------|------|------|--------------------------|-----------------------|--------------|
| HP 9-4-45(HSS) | 51             | Martemp    | .062                    | M42                           | 60             | .005           | 0                     | 10                    | 5                | 15   | 15   | Sol Oil 85<br>(1:20)     | 85                    | .015         |
| HP 9-4-45(HSS) | 51             | Martemp    | .062                    | M42                           | 65             | .005           | 0                     | 10                    | 5                | 15   | 15   | Sol Oil 17 1/2<br>(1:20) | 17 1/2                | .060         |
| HP 9-4-45(HSS) | 51             | Martemp    | .062                    | M2                            | 60             | .005           | 0                     | 10                    | 5                | 15   | 15   | Sol Oil 50<br>(1:20)     | 50                    | .060         |
| HP 9-4-45(HSS) | 51             | Martemp    | .062                    | M2                            | 65             | .005           | 0                     | 10                    | 5                | 15   | 15   | Sol Oil 20<br>(1:20)     | 20                    | .060         |
| HP 9-4-45(HSS) | 51             | Martemp    | .062                    | C8(K7H)                       | 300            | .007           | - 5                   | - 5                   | 5                | 15   | 15   | Sol Oil 24<br>(1:20)     | 24                    | .015         |
| HP 9-4-45(HSS) | 51             | Martemp    | .062                    | C8(K7H)                       | 355            | .007           | - 5                   | - 5                   | 5                | 15   | 15   | Sol Oil 10<br>(1:20)     | 10                    | .015         |
| HP 9-4-45(HSS) | 51             | Martemp    | .062                    | C8(K7H)                       | 375            | .007           | - 5                   | - 5                   | 5                | 15   | 15   | Sol Oil 5<br>(1:20)      | 5                     | .015         |
| HP 9-4-45(HSS) | 51             | Martemp    | .062                    | C6(370)                       | 200            | .007           | - 5                   | - 5                   | 5                | 15   | 15   | Sol Oil 20<br>(1:20)     | 20                    | .015         |
| HP 9-4-45(HSS) | 51             | Martemp    | .062                    | C6(370)                       | 250            | .007           | - 5                   | - 5                   | 5                | 15   | 15   | Sol Oil 7 1/2<br>(1:20)  | 7 1/2                 | .015         |
| HP 9-4-45(HSS) | 51             | Martemp    | .062                    | C8(K7H)                       | 300            | .010           | - 5                   | - 5                   | 5                | 15   | 15   | Sol Oil 9<br>(1:20)      | 9                     | .015         |
| H11            | 50             | -          | .050                    | 350 Carbal                    | 175            | .010           | 0                     | 0                     | 7                | 15   | 15   | .032 Dry                 | 100                   | .015         |
| H11            | 50             | -          | .050                    | 350 Carbal                    | 200            | .010           | 0                     | 0                     | 7                | 15   | 15   | .032 Dry                 | 38                    | .015         |
| H11            | 50             | -          | .050                    | 350 Carbal                    | 250            | .010           | 0                     | 0                     | 7                | 15   | 15   | .032 Dry                 | 10                    | .015         |
| H11            | 50             | -          | .050                    | 350 Carbal                    | 290            | .010           | 0                     | 0                     | 7                | 15   | 15   | .032 Dry                 | 5                     | .015         |
| 4340           | 50             | Q/T        | .062                    | C7(K7H)                       | 300            | .005           | - 5                   | - 5                   | 5                | 15   | 15   | .030 Dry                 | 37                    | .015         |
| 4340           | 50             | Q/T        | .062                    | C7(K7H)                       | 400            | .005           | - 5                   | - 5                   | 5                | 15   | 15   | .030 Dry                 | 12                    | .015         |
| 4340           | 50             | Q/T        | .062                    | C7(K7H)                       | 500            | .005           | - 5                   | - 5                   | 5                | 15   | 15   | .030 Dry                 | 7                     | .015         |
| 4340           | 50             | Q/T        | .062                    | 523                           | 275            | .005           | - 5                   | - 5                   | 5                | 15   | 15   | .030 Dry                 | 12                    | .015         |
| 4340           | 50             | Q/T        | .062                    | 523                           | 350            | .005           | - 5                   | - 5                   | 5                | 15   | 15   | .030 Dry                 | 10                    | .015         |
| 4340           | 50             | Q/T        | .062                    | C6(370)                       | 200            | .005           | - 5                   | - 5                   | 5                | 15   | 15   | .030 Dry                 | 27                    | .015         |
| 4340           | 50             | Q/T        | .062                    | C6(370)                       | 250            | .005           | - 5                   | - 5                   | 5                | 15   | 15   | .030 Dry                 | 15                    | .015         |
| 4340           | 50             | Q/T        | .062                    | XL-88                         | 275            | .005           | - 5                   | - 5                   | 5                | 15   | 15   | .030 Dry                 | 25                    | .015         |
| 4340           | 50             | Q/T        | .062                    | 516                           | 200            | .005           | - 5                   | - 5                   | 5                | 15   | 15   | .030 Dry                 | 60                    | .015         |
| 4340 OESR      | 28/35          | Normalized | .125                    | TNMG-432<br>Sandvik<br>GC1025 | 110            | .004           | -                     | -                     | -                | -    | -    | Trim Sol<br>(20:1)       | -                     | -            |
| 4340 OESR      | 28/35          | Normalized | .200                    | TNMG-432<br>Ceratip<br>50     | 150            | .004           | -                     | -                     | -                | -    | -    | Trim Sol<br>(20:1)       | -                     | -            |

## TURNING WITH CERAMIC TOOLS

| Material | Hardness<br>Kc | Condition   | Depth<br>of Cut<br>(in.) | Tool<br>Material  | Speed<br>(fpm) | Feed<br>(in/rev) | Back<br>Rake<br>(deg) | Side<br>Rake<br>(deg) | Relief<br>%SCEA | SCEA | N.R. | Cutting<br>Fluid | Tool<br>Life<br>(min.) | Workland<br>(in.) |
|----------|----------------|-------------|--------------------------|-------------------|----------------|------------------|-----------------------|-----------------------|-----------------|------|------|------------------|------------------------|-------------------|
| 50H      | 50             | Q/T         | .020                     | SNC432            | 600            | .002             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 30                     | .015              |
| 50H      | 50             | Q/T         | .030                     | SNC432            | 600            | .001             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 30                     | .015              |
| 50H      | 50             | Q/T         | .030                     | SNC432            | 600            | .001             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 60                     | .010              |
| 50H      | 50             | Q/T         | .010                     | SNC432            | 600            | .002             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 60                     | .012              |
| 53H      | 53             | 280-500 ksi | .013-.050                | Baxton DBA        | 235            | .009             | TNG-332               |                       |                 |      |      |                  |                        |                   |
| 43H      | 53.5           | -           | .050                     | 95% HfN<br>50ZrB2 | 300            | .005             | - 5                   | - 5                   | 5               | 15   | 1/16 | Dry              | 1/2                    | .015              |
| 43H      | 53             | Q/T         | .050                     | 0-30              | 340            | .005             | - 5                   | - 5                   | 5               | 15   | .045 | Dry              | 10                     | .015              |
| 43H      | 53             | Q/T         | .050                     | 0-30              | 315            | .035             | - 5                   | - 5                   | 5               | 15   | .045 | Dry              | 40                     | .015              |
| 43H      | 53             | Q/T         | .050                     | CCT-707           | 340            | .005             | - 5                   | - 5                   | 5               | 15   | .045 | Dry              | 10                     | .015              |
| 43H      | 53             | Q/T         | .050                     | CCT-707           | 400            | .005             | - 5                   | - 5                   | 5               | 15   | .045 | Dry              | 28                     | .015              |
| 43H      | 53             | Q/T         | .050                     | 60 TaN            | 770            | .005             | - 5                   | - 5                   | 5               | 15   | .045 | Dry              | 10                     | .015              |
| 43H      | 53             | Q/T         | .050                     | 40 ZrB2           | 600            | .005             | - 5                   | - 5                   | 5               | 15   | .045 | Dry              | 26                     | .015              |
| 43H      | 53             | Q/T         | .050                     | 60 TaN            | 325            | .005             | - 5                   | - 5                   | 5               | 15   | .045 | Dry              | 39                     | .015              |
| 43H      | 53             | Q/T         | .050                     | 0-30              | 335            | .005             | - 5                   | - 5                   | 5               | 15   | .045 | Dry              | 29                     | .015              |
| 43H      | 53             | Q/T         | .050                     | 0-30              | 350            | .005             | - 5                   | - 5                   | 5               | 15   | .045 | Dry              | 8 1/2                  | .015              |
| 43H      | 53             | Q/T         | .050                     | 60 TaN            | 700            | .005             | - 5                   | - 5                   | 5               | 15   | .045 | Dry              | 17                     | .015              |
| 43H      | 53             | Q/T         | .050                     | 40 ZrB2           | 800            | .005             | - 5                   | - 5                   | 5               | 15   | .045 | Dry              | 7                      | .015              |
| 43H      | 53             | Q/T         | .050                     | 50 TaN            | 800            | .005             | - 5                   | - 5                   | 5               | 15   | .045 | Dry              | 7                      | .015              |
| 43H      | 53             | Q/T         | .050                     | 40 ZrB2           | 464            | .0115            | TBT-124 P4            |                       |                 |      |      |                  | 23 1/2                 | -                 |
| 43H      | 52             | -           | 1/8-5/16                 | 0-30              | 544            | .0115            | TBT-123 P4            |                       |                 |      |      |                  | 15 1/2                 | -                 |
| 43H      | 52             | -           | .015                     | HF                | 550            | .005             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 35                     | .015              |
| 43H      | 52             | Q/T         | .050                     | 40 Ta-10Mo        | 600            | .005             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 19                     | .015              |
| 43H      | 52             | Q/T         | .050                     | Nitrided          | 700            | .005             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 15                     | .015              |
| 43H      | 52             | Q/T         | .050                     | HF-50Ta           | 600            | .005             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 50                     | .015              |
| 43H      | 52             | Q/T         | .050                     | SF-0113B          | 700            | .005             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 22                     | .015              |
| 43H      | 52             | Q/T         | .050                     | Nitrided          | 800            | .005             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 11                     | .015              |
| 43H      | 52             | Q/T         | .050                     | Nitrided          | 670            | .005             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 30                     | .015              |
| 50-51    | 50-51          | Q/T         | .010                     | 0-30              | 500            | .0075            | TATR; TB-125 P2       |                       |                 |      |      |                  | -                      | .010              |
| 43H      | 50             | Q/T         | .062                     | 0-30              | 700            | .005             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 31                     | .015              |
| 43H      | 50             | Q/T         | .062                     | 0-30              | 750            | .005             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 25                     | .015              |
| 43H      | 50             | Q/T         | .062                     | 0-30              | 800            | .005             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 12                     | .015              |
| 43H      | 50             | Q/T         | .062                     | Act 1             | 700            | .005             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 18                     | .015              |
| 43H      | 50             | Q/T         | .062                     | C06               | 600            | .005             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 40                     | .015              |
| 43H      | 50             | Q/T         | .062                     | ANA 68            | 600            | .005             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 23                     | .015              |
| 43H      | 50             | Q/T         | .062                     | DBA               | 600            | .005             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 15                     | .015              |
| 43H      | 50             | Q/T         | .062                     | 707               | 600            | .005             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 60                     | .015              |
| 43H      | 50             | Q/T         | .062                     | C06               | 600            | .005             | - 5                   | - 5                   | 5               | 15   | .030 | Dry              | 40                     | .015              |

## TURNING WITH CERAMIC TOOLS (cont.)

| Material      | Hardness<br>Rc | Condition | Depth<br>of Cut<br>(in.) | Tool<br>Material | Speed<br>(fpm) | Feed<br>(inpr) | Back<br>Rake<br>(deg) | Side<br>Rake<br>(deg) | Relief<br>Angle<br>(deg) | ICEA<br># | SCEA<br>N.R. | Cutting<br>Fluid  | Tool<br>Life<br>(min.) | Wearland<br>(in.) |
|---------------|----------------|-----------|--------------------------|------------------|----------------|----------------|-----------------------|-----------------------|--------------------------|-----------|--------------|-------------------|------------------------|-------------------|
| 52100 Rolls   | 68             | Hardened  | .045                     | LEN              | 275            | .022           | -5                    | -5                    | 5                        | -         | -            | Sol Oil<br>(1:20) | 120                    | -                 |
| Steel Forging | 65             | Hardened  | 1/32-1/8                 | Baxton<br>DBA    | 52-81          | .006           | RNG-43                |                       |                          |           |              |                   | 25                     | -                 |
| Steel Forging | 65             | Hardened  | 1/32-1/8                 | Baxton<br>DBA    | 150            | .010           | RNG-43                |                       |                          |           |              |                   | 15                     | -                 |
| 52100         | 65             | Q/T       | .100                     | VR-97            | 225            | .008           | -5                    | -5                    | -                        | -         | 30           | 1/16              | 5                      | .010              |
| 52100         | 65             | Q/T       | .100                     | VR-97            | 250            | .004           | -5                    | -5                    | -                        | -         | 30           | 1/16              | 5                      | .010              |
| 52100         | 65             | Q/T       | .100                     | VR-97            | 250            | .008           | -5                    | -5                    | -                        | -         | 30           | 1/16              | 5                      | .010              |
| 52100         | 65             | Q/T       | .100                     | VR-97            | 350            | .004           | -5                    | -5                    | -                        | -         | 30           | 1/16              | 5                      | .010              |
| 52100         | 65-60          | Q/T       | .015                     | 0-30             | 600            | .005           | 0                     | 0                     | 5                        | 15        | 60           | 11/32             | 15                     | -                 |
| 52100         | 65-60          | Q/T       | .015                     | 0-30             | 400            | .005           | 0                     | 0                     | 5                        | 15        | 60           | 11/32             | 65                     | -                 |
| 52100         | 62-65          | Q/T       | .010                     | 0-30             | 1050           | .0065          | -25                   | -25                   | -                        | -         | -            | 3/16              | -                      | -                 |
| 5000          | 60-62          | -         | -                        | SQT165 PO        | 600            | .005           | -25                   | -25                   | -                        | -         | -            | -                 | -                      | -                 |
| Mill Rolls    | 60-62          | -         | 1/32                     | VR-97            | 340            | .008           | HIGH LEAD ANGLE       |                       |                          |           |              | Dry               | 30+                    | .001              |
| Alloy Steel   | 60             | Carb.     | .015                     | 0-30             | 80             | .0105          | TDTL-85               |                       |                          |           |              |                   | 9                      | -                 |
| Alloy Steel   | 60             | Carb.     | .0025                    | 0-30             | 80             | .0105          | TDTL-85               |                       |                          |           |              |                   | 9                      | -                 |
| Alloy Steel   | 60             | Carb.     | .013/.018                | 0-30             | 115            | .0105          | TDTR-85               |                       |                          |           |              |                   | 6.5                    | -                 |
| Steel Forged  | 60             | -         | -                        | C06              | 280            | .0025          | -10                   | -                     | -                        | 20        | 20           | 1/16              | -                      | -                 |
| 440C          | 57             | Q/T       | .062                     | CCT-707          | 200            | .005           | -7                    | 0                     | 5                        | 45        | 45           | .045              | 26                     | .015              |
| 440C          | 57             | Q/T       | .062                     | CCT-707          | 225            | .005           | -7                    | 0                     | 5                        | 45        | 45           | .045              | 7 1/2                  | .015              |
| 640C          | 56             | Q/T       | .050                     | CCT-707          | 200            | .005           | -5                    | -5                    | 5                        | 15        | 15           | .045              | 10                     | .015              |
| 640C          | 56             | Q/T       | .050                     | CCT-707          | 110            | .005           | -5                    | -5                    | 5                        | 15        | 15           | .045              | 35                     | .015              |
| 640C          | 56             | Q/T       | .050                     | CCT-707          | 215            | .005           | -5                    | -5                    | 5                        | 15        | 45           | .045              | 10                     | .015              |
| 640C          | 56             | Q/T       | .050                     | CCT-707          | 150            | .005           | -5                    | -5                    | 5                        | 15        | 15           | .045              | 47                     | .015              |
| 640C          | 56             | Q/T       | .050                     | 0-30             | 280            | .005           | -5                    | -5                    | 5                        | 15        | 15           | .045              | 10                     | .015              |
| 640C          | 56             | Q/T       | .050                     | 0-30             | 200            | .005           | -5                    | -5                    | 5                        | 15        | 15           | .045              | 36                     | .015              |
| 640C          | 56             | Q/T       | .050                     | 60Tan-40ZrB2     | 580            | .005           | -7                    | 0                     | 5                        | 45        | 45           | .045              | 10                     | .015              |
| 640C          | 56             | Q/T       | .050                     | CCT-707          | 300            | .005           | -7                    | 0                     | 5                        | 45        | 45           | .045              | 28                     | .015              |
| 640C          | 56             | Q/T       | .050                     | CCT-707          | 150            | .005           | -7                    | 0                     | 5                        | 45        | 45           | .045              | 47                     | .015              |
| 640C          | 56             | Q/T       | .050                     | CCT-707          | 200            | .005           | -7                    | 0                     | 5                        | 45        | 45           | .045              | 19                     | .015              |
| 640C          | 56             | Q/T       | .050                     | CCT-707          | 250            | .005           | -7                    | 0                     | 5                        | 45        | 45           | .045              | 2-1/3                  | .015              |
| 640C          | 56             | Q/T       | .050                     | CCT-707          | 325            | .005           | -8                    | -5                    | 5                        | 45        | 45           | .030              | 35                     | .015              |
| 300M          | 56             | Q/T       | .062                     | Baxton DBA       | 375            | .005           | -8                    | -5                    | 5                        | 45        | 45           | .030              | 27                     | .015              |
| 300M          | 56             | Q/T       | .010                     | Act I            | 550            | .005           | -5                    | -5                    | 5                        | 15        | 15           | .030              | 27                     | .015              |
| 300M          | 56             | Q/T       | .010                     | Act I            | 650            | .003           | -5                    | -5                    | 5                        | 15        | 15           | .030              | 11                     | .015              |
| 300M          | 56             | Q/T       | .010                     | Act I            | 700            | .003           | -5                    | -5                    | 5                        | 15        | 15           | .030              | 9                      | .015              |
| 300M          | 56             | Q/T       | .010                     | C06              | 600            | .003           | -5                    | -5                    | 5                        | 15        | 15           | .030              | 30                     | .015              |
| 300M          | 56             | Q/T       | .010                     | VR-97            | 600            | .001           | -5                    | -5                    | 5                        | 15        | 15           | .030              | 30                     | .015              |

# DRILLING

| Material       | Hardness | Cond. | Drill Die. | Tool Matn. | Speed FPM | Feed R.P. | Point Ang. | Relief | Chisel Edge Ang. | Helix Ang. | Point Grind | Cutting Flute |
|----------------|----------|-------|------------|------------|-----------|-----------|------------|--------|------------------|------------|-------------|---------------|
| Thermolds      | 50       | Q/T   | .250       | M-33       | 20        | .0035     | 135        | -      | 100              | 12         | -           | Su-CL         |
| Vasco Jet 1000 | 50       | Q/T   | .250       | M-23       | 40        | .001      | 118        | 7      | -                | 29         | Crk.        | Su            |
| Vasco Jet 1000 | 50       | Q/T   | .250       | M-33       | 40        | .0015     | 118        | 7      | -                | 29         | Crk.        | Su            |
| Vasco Jet 1000 | 50       | Q/T   | .250       | M-33       | 40        | .0015     | 118        | 7      | -                | 29         | Crk.        | Su            |
| 4340           | 50       | Q/T   | .250       | T-15       | 30        | .001      | 118        | 7      | -                | 29         | Crk.        | Su            |
| 4340           | 52       | -     | .250       | T-15       | 20        | .0005     | 90         | 7      | -                | 29         | Std.        | Su-CL         |
| 4340           | 52       | -     | .250       | T-15       | 40        | .0005     | 90         | 7      | -                | 29         | Std.        | Su-CL         |
| 4340           | 52       | Q/T   | .257       | -          | 30        | .001      | 135        | 5      | -                | 12         | Notch       | CL            |
| 4340           | 52       | Q/T   | .257       | -          | 40        | .001      | 135        | 5      | -                | 12         | Notch       | CL            |
| 4340           | 52       | Q/T   | .257       | -          | 50        | .001      | 135        | 5      | -                | 12         | Notch       | CL            |
| 4340           | 52       | Q/T   | .250       | M-33       | 30        | .0006     | 135        | -      | 110              | 12         | Notch       | Su-CL         |
| 4340           | 52       | Q/T   | .250       | M-33       | 30        | .0006     | -          | -      | -                | 12         | -           | -             |
| 4340           | 52       | Q/T   | .250       | T-15       | 30        | .001      | 118        | 7      | -                | 29         | Crk.        | Su            |
| Vasco Jet 1000 | 52       | Q/T   | .250       | M-33       | 40        | .001      | 118        | 7      | -                | 29         | Crk.        | Su            |
| Vasco Jet 1000 | 52       | Q/T   | .250       | M-33       | 40        | .0015     | 118        | 7      | -                | 29         | Crk.        | Su            |
| 4340           | 52       | Q/T   | .250       | T-15       | 20        | .001      | 118        | 7      | -                | 29         | Crk.        | Su            |
| 4340           | 50/53    | -     | .250       | T-15       | 15        | .001      | 130        | -      | Chamfer          | -          | Std.        | Su-CL         |
| 4350/4140      | 52/53    | Q/T   | .250       | C-2        | 100       | .001      | 118-135    | 7      | 130              | 29         | Crk.        | Su-CL         |
| D6AC           | 54       | Q/T   | .250       | M-33       | 40        | .001      | 90         | 7      | -                | 29         | Crk.        | Su            |
| D6AC           | 54       | Q/T   | .250       | M-33       | 50        | .001      | 90         | 7      | -                | 29         | Crk.        | Su            |
| D6AC           | 54       | Q/T   | .250       | M-33       | 60        | .001      | 90         | 7      | -                | 29         | Crk.        | Su            |
| MX-2           | 54       | Q/T   | .250       | M-33       | 45        | .001      | 90         | 7      | -                | 29         | Crk.        | Su            |
| MX-2           | 54       | Q/T   | .250       | M-33       | 50        | .001      | 90         | 7      | -                | 29         | Crk.        | Su            |
| 4340           | 54       | Q/T   | .250       | C-2        | 27        | .0015     | -          | -      | -                | -          | -           | Sol. Oil      |
| 98BV40         | 54       | Q/T   | .250       | C-2        | 150       | .001      | 118        | 12     | -                | 20         | Std.        | CL            |
| 4340           | 55       | Q/T   | .250       | -          | 90        | .001      | 140        | -      | 110              | 0          | -           | Sol. Oil      |
| 4340           | 55       | Q/T   | .250       | T-15       | 30        | .001      | 118        | 7      | -                | 29         | Crk.        | Su            |
| 300M           | 55       | Q/T   | .250       | T-15       | 15-20     | .001      | 118        | 12     | -                | 29         | Std.        | CL            |
| 300M           | 55       | Q/T   | .250       | M-42       | 10        | .0005     | 118        | 12     | -                | 29         | Crk.        | CL-C          |
| 300M           | 55       | Q/T   | .250       | C-2        | 140       | .0005     | 118        | 12     | -                | 29         | Crk.        | CL-C          |
| 300M           | 55       | Q/T   | .250       | C-2        | 140       | .001      | 118        | 12     | -                | 29         | Crk.        | CL-O          |
| 4140/4150      | 54/56    | Q/T   | .250       | C-2        | 75        | .001      | 118-135    | 7      | 130              | 29         | Crk.        | Su-CL         |
| D6AC           | 56       | Q/T   | .250       | C-2        | 105       | .001      | -          | -      | -                | -          | -           | CL            |
| Thermal D J    | 57       | Q/T   | .250       | M-33       | 90        | .001      | 140        | -      | 110              | 12         | -           | Sol. Oil      |
| D6AC           | 57       | Q/T   | .250       | C-2        | 105       | .001      | -          | -      | -                | -          | -           | CL            |

# TAPPING

| Material       | Hardness | Condition | Tap<br>Dia. In. | Thds. | Flutes | Tap<br>Mat'l. | %<br>Thds. | Speed<br>FPM | Hook<br>Angle | Land<br>Width | Flute<br>Depth | Flute<br>Rad. | Cutting<br>Fluid |
|----------------|----------|-----------|-----------------|-------|--------|---------------|------------|--------------|---------------|---------------|----------------|---------------|------------------|
| 300M           | 55       | Q/T       | 5/16            | 24NF  | 3      | M42           | 75         | 5            | -             | -             | -              | -             | CL               |
| Diac           | 54       | Q/T       | 5/16            | 24NF  | 4      | M10           | 75         | 5            | 0             | .090          | .072           | .082          | CL               |
| 4340           | 52       | Q/T       | 5/16            | 24NF  | 4      | -             | 58         | 70           | -             | .099          | -              | -             | CL               |
| 4340           | 52       | Q/T       | 5/16            | 18NC  | 4      | 60            | 5          | -            | -             | -             | -              | -             | CL               |
| H-11           | 50       | Q/T       | 1/4             | 20NC  | -      | HSS           | 60         | 6            | 15            | -             | -              | -             | Sa               |
| Vasco Jet 1000 | 50       | Q/T       | 5/16            | 18NC  | 4      | M10           | 60         | 5            | -             | -             | -              | -             | CL               |
| Vasco Jet 1000 | 50       | Q/T       | 5/16            | 18NC  | 4      | M10           | 60         | 5            | -             | -             | -              | -             | -                |
| Vasco Jet 1000 | 50       | Q/T       | 5/16            | 18NC  | 4      | M10           | 60         | 5            | -             | -             | -              | -             | CL               |
| 4340           | 50       | Q/T       | 1/4             | 20NC  | -      | HSS           | 60         | 10           | 7             | -             | -              | -             | Sa               |
| 4340           | 50       | Q/T       | 5/16            | 18NC  | 4      | M10           | 60         | 5            | -             | -             | -              | -             | CL               |

# MILLING

| Material       | Hardness | Condition | Depth<br>Cm | Tool<br>Matl | Speed<br>FPM | Feed<br>IPT | Radial<br>Rate | Helix<br>Angle | Corner<br>Angle | Cutting<br>Fluid | Tool Wear<br>Life | Life<br>Min |
|----------------|----------|-----------|-------------|--------------|--------------|-------------|----------------|----------------|-----------------|------------------|-------------------|-------------|
| Gr-N-204NZA    | 50       | Hob       | .019        | VK6M         | 67           | .0016       | -15            | -              | -               | SJ               | 99                | .010        |
| Drac           | 56       | Face      | .040        | C2(883)      | 97           | .006        | -15            | -              | 45              | Dry              | -                 | .016        |
| Vasco Jet 1000 | 56       | Face      | .050        | C2           | 173          | .0057       | -8             | -              | 0               | Dry              | 40                | .015        |
| 304N           | 55       | End       | .060        | C6(370)      | 500          | .002        | 0              | 0              | 45              | Dry              | 1400              | .012        |
| 304M           | 55       | End       | .015        | C6(370)      | 70           | .002        | 0              | 0              | 45              | Dry              | -                 | .008        |
| 304N           | 55       | End       | .060        | C6(370)      | 550          | .002        | 0              | 0              | 0               | Dry              | 600               | .012        |
| 304M           | 55       | End       | .060        | C6(370)      | 600          | .002        | 0              | 0              | 45              | Dry              | 300               | .012        |
| 304M           | 55       | Face      | .025        | 2%Cr2C       | 2917         | 5           | 0              | -45            | -               | CO2              | 9                 | .008        |
| 304M           | 55       | Face      | .100        | 6%TiC        | 175          | 3.75        | 0              | 0              | -3              | CO2              | 4                 | .0035       |
| 304M           | 55       | Face      | .100        | 6%TiC        | 175          | 3.75        | 0              | 0              | -3              | Sol.Oil          | 217               | .008        |
| 304M           | 55       | Face      | .075        | 6%TiC        | 175          | 3.75        | 0              | 0              | -3              | CO2              | 135               | .008        |
| 304M           | 55       | Face      | .075        | 2%Cr2C       | 153          | 2.87        | 0              | 0              | -3              | CO2              | 142               | .010        |
| 304M           | 54       | Face      | .060        | C6           | 100          | .002        | -5             | -5             | 45              | Dry              | 160               | .015        |
| 304M           | 54       | End       | .125        | C6(370)      | 200          | .001        | -5             | -5             | 0               | Dry              | 215               | .012        |
| 304M           | 54       | End       | .125        | C6(370)      | 300          | .001        | -5             | -5             | 0               | Dry              | 125               | .012        |
| 304M           | 54       | End       | .025        | 6%TiC        | 1200         | 20          | -3             | -3             | 45              | CO2              | 175               | .002        |
| 304M           | 54       | End       | .025        | 6%TiC        | 1200         | 5           | -3             | -3             | 45              | CO2              | 113               | .003        |
| 304M           | 54       | End       | .025        | 6%TiC        | 1200         | 5           | -3             | -3             | 45              | CO2              | 210               | .002        |
| 304M           | 54       | Hob       | .020        | VK6          | 70           | .002        | 0              | 0              | -               | Dry              | 100               | .008        |
| 304M           | 54       | Face      | .050        | C-6          | 170          | .0046       | -              | -              | 0               | Dry              | 18                | .015        |
| 304M           | 53-50    | Hob       | -           | VK6M         | -            | -           | -              | -              | 10              | -                | 120-180           | .010        |
| 304M           | 52       | Face      | .100        | C-6          | 150          | .005        | 0              | -15            | 45              | Dry              | 60                | .015        |
| 304M           | 52       | Side      | .100        | C6(370)      | 150          | .0075       | -5             | -10            | 45              | Dry              | 60                | .015        |
| 304M           | 52       | Slot      | .250        | C-2          | 200          | .005        | -5             | -10            | 45              | Dry              | 35                | .015        |
| 304M           | 52       | End       | .250        | C-2(983)     | 50           | .0015       | 0              | 0              | 35              | Sol.Oil          | 78                | .015        |
| 304M           | 52       | End       | .062        | M-33         | 54           | .002        | -              | -              | -               | Sol.Oil          | 250               | .015        |
| 304M           | 52       | End       | .062        | M-33         | 127          | .002        | -              | -              | -               | Sol.Oil          | 160               | .015        |
| 304M           | 52       | End       | .062        | M-33         | 127          | .002        | -              | -              | -               | Sol.Oil          | 96                | .016        |
| 304M           | 52       | Face      | .100        | C6(370)      | 180          | .005        | -0             | -15            | 45              | Dry              | 90                | .015        |
| 304M           | 52       | Face      | .100        | C6(370)      | 188          | .005        | 0              | -15            | 45              | Dry              | 42                | .015        |
| 304M           | 52       | Face      | -           | C6(370)      | 180          | .005        | 0              | 0              | 15              | Dry              | 60                | .015        |
| 304M           | 52       | Face      | -           | C6(370)      | 425          | .005        | 0              | 0              | 15              | Dry              | 10                | .015        |
| 304M           | 52       | Face      | .100        | C-2          | 125          | .005        | 0              | -15            | 45              | Dry              | 80                | .015        |
| Vasco Jet 1000 | 52       | Face      | .100        | C-2          | 150          | .0075       | 0              | -15            | 45              | Dry              | 60                | .012        |
| Vasco Jet 1000 | 52       | Slot      | .250        | C-2          | 200          | .005        | -5             | -10            | 45              | Dry              | 50                | .012        |
| Vasco Jet 1000 | 52       | End       | .250        | C-2(883)     | 60           | .0015       | 0              | 0              | 45              | Sol.Oil          | 105               | .012        |

# GRINDING

## Surface Grinding

| Material       | Hardness | Wheel Speed<br>(FPM) | Table or<br>Work Speed | In Feed (in/pass) or |          | Gross Feed<br>(in/pass) | Wheel Grade | Cutting<br>Fluid | Grinding<br>Ratio | Grinding<br>Condition |
|----------------|----------|----------------------|------------------------|----------------------|----------|-------------------------|-------------|------------------|-------------------|-----------------------|
|                |          |                      |                        | Down Feed            | (in/rev) |                         |             |                  |                   |                       |
| Alloy Steel    | 62-48    | 3000-3400            | 100-250                | .0005 - .001         | -        | -                       | A46 H or G  | Su - O           | -                 | Rough                 |
| Alloy Steel    | 62-48    | 3000-3400            | 100-250                | .0005 - .001         | -        | -                       | A80 H or G  | Su - O           | -                 | Finish                |
| M-50           | 61       | 6000                 | 40                     | .001                 | .050     | .050                    | 32A46H8VBE  | Su - O           | 10.6              | Rough                 |
| M-50           | 61       | 4000                 | 40                     | .0005                | .050     | .050                    | 32A46H8VBE  | Su - O           | 7.4               | Finish                |
| Deac           | 57       | 6000                 | 40                     | .001                 | -        | -                       | A46H8V      | Su - O           | 75                | Conv.                 |
| Deac           | 56       | 6000                 | 40                     | .001                 | .050     | .050                    | 32A46H8VBE  | Sol. Oil         | -                 | Conv.                 |
| 1-1-45 Martemp | 51       | 6000                 | 40                     | .001                 | .050     | .050                    | 32A46K8VBE  | Sol              | 45                | Conv.                 |
| 4340           | 50       | 2000                 | -                      | LS                   | -        | -                       | A46HV       | Su               | -                 | L. S.                 |
| M-4            | -        | 12000                | 350                    | -                    | -        | -                       | A80P4V      | -                | 18                | -                     |

## Cylindrical Grinding

|                   |       |           |        |        |   |     |               |            |       |        |
|-------------------|-------|-----------|--------|--------|---|-----|---------------|------------|-------|--------|
| Alloy Steel       | 65-48 | 4500-6000 | 70-100 | .002   | - | W/4 | A60IV         | Su         | -     | Rough  |
| Alloy Steel       | 65-48 | 4500-6000 | 70-100 | .0004  | - | W/8 | A60IV         | Su         | -     | Finish |
| 52100             | 62-60 | 7200      | 24     | -      | - | -   | A220M14DIA XI | Su         | 96000 | -      |
| 52100             | 61    | 8500      | 226    | -      | - | -   | A80V9BC2ES    | Su         | Parts | -      |
| Ductile Iron      | 60-53 | 5500-6500 | 70-100 | .002   | - | W/4 | A60JV         | -          | -     | Rough  |
| Ductile Iron      | 60-53 | 5500-6500 | 70-100 | .0005  | - | W/8 | A60JV         | -          | -     | Finish |
| 4145              | 53    | 6782      | 130    | .00377 | - | -   | 23A36MVBE     | Int'l.     | 19    | Rough  |
|                   |       |           |        |        |   |     |               | 131(40:1)  |       |        |
| Internal Grinding |       |           |        |        |   |     |               |            |       |        |
| 52100             | 64    | -         | -      | -      | - | -   | B180N100V     | 3% Sol Oil | -     | -      |
| SAE 515           | 62-61 | 9396      | <156   | .0003  | - | -   | A46SM-1       | -          | 44    | -      |
| 52100             | 62-60 | 5715      | 975    | -      | - | -   | A80L6         | Cimcol     | -     | -      |
|                   |       |           |        |        |   |     |               | (50:1)     |       |        |
| 52100             | 60    | 9000      | 5      | -      | - | -   | 80LV          | -          | -     | -      |
| 52100             | 60    | 9000      | 2.5    | -      | - | -   | 80TB          | -          | -     | -      |
| 4140              | 55-50 | 7370      | 1186   | -      | - | -   | 60M6          | -          | -     | -      |

# GRINDING

## Plunge Grinding

| Material | Hardness | Wheel Speed<br>(FPM) | Table or<br>Work Speed | In Feed (in/pass)<br>or<br>Down Feed (in/rev) | Cross Feed<br>(in/pass) | Wheel Grade | Cutting<br>Fluid | Grinding<br>Ratio | Grinding<br>Condition |
|----------|----------|----------------------|------------------------|-----------------------------------------------|-------------------------|-------------|------------------|-------------------|-----------------------|
| 4140     | 55-53    | 6620                 | 1218                   | -                                             | -                       | 4A60M6VL    | Flowrex 100      | -                 | -                     |
| 4140     | 53-53    | 6620                 | 1218                   | -                                             | -                       | 32A70M6VBE  | Flowrex 100      | -                 | -                     |
| T-15     | 53-53    | 6620                 | 1218                   | -                                             | -                       | 4A60M6VL    | Flowrex 100      | -                 | -                     |

## Internal Plunge

|       |       |       |     |       |      |          |   |   |   |
|-------|-------|-------|-----|-------|------|----------|---|---|---|
| M-4   | 65    | 12000 | 250 | 0.004 | .001 | 460K4V   | - | - | - |
| M-4   | 63-63 | 12200 | 250 | -     | .001 | 12A80P4V | - | - | - |
| 52100 | 62-60 | 12000 | 250 | .004  | .001 | A70K8V   | - | - | - |
| 52100 | 62-60 | 7200  | 120 | .003  | -    | A60L5V   | - | - | - |
| 52100 | 62-60 | 7200  | 120 | .003  | -    | A90P6V   | - | - | - |

APPENDIX B

HMS 6-1121, Hughes material specification for electrosag refined 4340 steel forged billet.



| REVISIONS |                       |          |          |
|-----------|-----------------------|----------|----------|
| LTR       | DESCRIPTION           | DATE     | APPROVED |
| New       | Released on EO 126568 | 05/29/71 |          |
| A         | Released on EO 130696 | 08/15/75 |          |
| B         | Released on EO 130876 | 12/23/75 |          |
| C         | Released on EO 131222 | 08/12/76 |          |
| D         | Released on EO 131361 | 11/21/77 |          |
| E         | Released on EO 131962 | 03/24/78 |          |
| F         | Released on EO 132148 | 09/26/78 |          |

SCOPE: This specification covers electroslog refined (ESR 4340) steel forged billet intended for use at the 280- to 300-ksi strength level.

CHANGES: (1) Editorial change to format.

(2) Maximum carbon content in Table I changed from 0.43 to 0.41.

(3) 3.10.1 adds new microinclusions requirements.

Change bars indicate technical changes only.

|         |                          |  |  |                                                                                                                                                |                                                              |            |      |
|---------|--------------------------|--|--|------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------|------------|------|
| PREP    | J. C. Preston 8-24-78    |  |  |  <b>Hughes Helicopters</b><br>Division of Summa Corporation | Centinela and Teale Streets<br>Culver City, California 90230 |            |      |
| APPD    | J. C. Preston / W. H. H. |  |  |                                                                                                                                                | TITLE<br>ELECTROSLAG REFINED 4340 STEEL<br>FORGED BILLET     |            |      |
| 2-11-78 | J. C. Preston / W. H. H. |  |  |                                                                                                                                                |                                                              |            |      |
| 4-11-78 | J. C. Preston / W. H. H. |  |  |                                                                                                                                                |                                                              |            |      |
| 9-20-78 | J. C. Preston / W. H. H. |  |  |                                                                                                                                                |                                                              |            |      |
| 9-20-78 | J. C. Preston / W. H. H. |  |  |                                                                                                                                                |                                                              |            |      |
| 9-20-78 | J. C. Preston / W. H. H. |  |  | SIZE                                                                                                                                           | CODE IDENT NO.                                               | NO.        | REV. |
|         |                          |  |  | A                                                                                                                                              | 02731                                                        | HMS 6-1121 | F    |
|         |                          |  |  | SHEET 1 of 11                                                                                                                                  |                                                              |            |      |

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**Hughes Helicopters**  
Division of Sunbelt Corporation

Centennial and Teale Streets  
Culver City, California 90230

## MATERIAL SPECIFICATION

PREPARED \_\_\_\_\_

APPROVED \_\_\_\_\_

APPROVED \_\_\_\_\_

APPROVED \_\_\_\_\_

NUMBER HMS 6-1121

DATE ISSUED 5-9-74

DATE REVISED (F)

PAGE 3 OF 11

TITLE: **ELECTROSLAG REFINED 4340 STEEL FORGED BILLET**

### 1. SCOPE

1.1 This specification covers electros slag refined (ESR) 4340 forged billet intended for use at the 280- to 300-ksi strength level.

### 2. APPLICABLE DOCUMENTS

2.1 Government documents. The following documents of the exact issue in effect on date of the invitation for bids or request for proposal form a part of this specification to the extent specified herein. In case of conflict between these documents and this specification, the requirements of this specification shall prevail.

### SPECIFICATIONS

#### Military

MIL-I-8950

Inspection, Ultrasonic, Wrought  
Metals, Process for

### STANDARDS

#### Federal

FED-STD-151

Federal Test Method

2.1.1 Copies of specifications, standards, drawings, and publications required by suppliers in connection with specified procurement functions should be obtained from the procuring activity or as directed by the contracting officer.

## 2.2 Non-Government documents

### SPECIFICATIONS

#### Industry

##### Hughes Helicopters

|         |                                                                           |
|---------|---------------------------------------------------------------------------|
| HP 1-1  | Heat Treatment of Steels, Nickel-Base, and Cobalt-Base Alloys             |
| HP 6-5  | Magnetic Particle Inspection                                              |
| HP 6-19 | Hardness Testing of Metals                                                |
| HP 6-22 | Ultrasonic Inspection of Metals                                           |
| HP 6-25 | Procedure for Determining the Mechanical Properties of Metallic Materials |
| HP 8-5  | Identification of Detail Parts and Assemblies                             |

### OTHER PUBLICATIONS

#### Aeronautical Materials Specifications

|          |                                                                                            |
|----------|--------------------------------------------------------------------------------------------|
| AMS 2300 | Premium Aircraft Quality Steel<br>Cleanliness - Magnetic Particle<br>Inspection Procedures |
|----------|--------------------------------------------------------------------------------------------|

#### American Society for Testing and Materials

|            |                                                                                                                         |
|------------|-------------------------------------------------------------------------------------------------------------------------|
| ASTM E 45  | Determining the Inclusion Content<br>of Steel                                                                           |
| ASTM E 122 | Estimating the Average Grain Size<br>of Metals                                                                          |
| ASTM E 353 | Chemical Analysis of Stainless<br>Steel, Heat Resistant, Maraging,<br>and Other Similar Chromium-<br>Nickel-Iron Alloys |
| ASTM E 381 | Rating Macroetched Steel                                                                                                |



2.2.1 Technical society and technical association specifications and standards are generally available for reference from libraries. They are also distributed among technical groups and using Federal agencies.

### 3. REQUIREMENTS

#### 3.1 Definitions.

3.1.1 AOD. Argon-oxygen decarburized.

3.1.2 ESR. Electroslag refined.

3.1.3 Ingot. A quantity of 4340 AOD or ESR steel melted in a single mold of a known size and weight.

3.1.4 Lot. A quantity of 4340 steel melted by the ESR process into an ingot and hot worked as a single unit to different product sizes and forms.

3.1.5 Melt. A homogeneous batch of 4340 AOD steel melted and solidified into ingot(s).

3.1.6 RCS. Round corner square.

#### 3.2 Material quality.

3.2.1 The starting material shall be a single melt of 4340 argon-oxygen decarburized (AOD) ingot(s) or equivalent prior to remelting by the electroslag refining process.

3.2.2 The material shall be produced by the electroslag refining process using equipment specifically designed for electroslag refining of low-alloy, high-strength steels that has been approved for steel making by the Materials, Processes, and Standards Department of Hughes Helicopters.

3.2.3 The billet stock shall be hot worked in at least two longitudinal planes to ensure that minimum mechanical properties can be met in the transverse direction when heat treated and tempered to full strength level.

3.3 Forging temperature. The forging stock shall be heated to  $2100^{\circ} \pm 25^{\circ}\text{F}$  ( $1149^{\circ} \pm 13.9^{\circ}\text{C}$ ) for initial heating and shall receive a minimum reduction of 3:1 in cross section area. The finish forging temperature shall be within the range of  $1700^{\circ}$  to  $1800^{\circ}\text{F}$  ( $927^{\circ}$  to  $982^{\circ}\text{C}$ ).



3.4 Condition. Forged billet shall be supplied in the normalized and tempered condition in accordance with HP 1-1.

3.5 Composition. The lot shall conform to the percentages by weight shown in Table I.

TABLE I. COMPOSITION PERCENTAGES BY WEIGHT

| Element    | Minimum | Maximum |
|------------|---------|---------|
| Carbon     | 0.38    | 0.41    |
| Manganese  | 0.60    | 0.80    |
| Silicon    | 0.20    | 0.35    |
| Phosphorus | —       | 0.010   |
| Sulfur     | —       | 0.008   |
| Chromium   | 0.70    | 0.90    |
| Nickel     | 1.65    | 2.00    |
| Molybdenum | 0.20    | 0.30    |
| Copper     | —       | 0.35    |
| Aluminum   | —       | 0.030   |
| Iron       | —       | balance |

3.6 Macrostructure. Full cross-section macroslab wafer prepared in accordance with 4.2.3 shall be free of cracks, pipe, bursts, segregation, flakes, seams, and other deleterious effects which would adversely affect static mechanical properties after heat treat.

3.7 Mechanical properties. The material shall meet the minimum mechanical properties specified in Table II after heat treatment per HP 1-1 to the HT condition.

TABLE II. MINIMUM MECHANICAL PROPERTIES

| Direction    | F <sub>tu</sub><br>ksi (MPa) | F <sub>ty</sub><br>ksi (MPa) | El<br>Percent | R. A.<br>Percent |
|--------------|------------------------------|------------------------------|---------------|------------------|
| Longitudinal | 280 (2689)                   | 200 (2275)                   | 10            | 25               |
| Transverse   | 260 (1793)                   | 200 (1496)                   | 10            | 25               |



3.8 Hardness. Material hardness tested in accordance with HP 6-19 shall meet the hardness requirements after heat treatment to the HT condition as follows:

- a. Brinell Hardness, 535 to 578
- b. Rockwell Hardness, Rc 54 to 57

3.9 Cleanliness. The product shall be uniform in quality and condition, clean, sound and free from foreign materials when magnetic particle inspected per 4.2.6.

3.10 Microexamination.

3.10.1 Microinclusions. The size and frequency of microinclusions shall not exceed the Jernkontoret limits as shown in Table III when tested per 4.2.7.

TABLE III. MICROINCLUSION RATING

| Microinclusion Type | Dimensional Limitations Thickness or Diameter (inches) | Worst Field |
|---------------------|--------------------------------------------------------|-------------|
| Type A - thin       | 0.00016 max                                            | 1.5         |
| Type A - heavy      | 0.00040 max                                            | 1.0         |
| Type B - thin       | 0.0003 to 0.0005, excl                                 | 1.5         |
| Type B - heavy      | 0.0005 to 0.0010, incl                                 | 1.0         |
| Type C - thin       | 0.00020 max                                            | 1.5         |
| Type C - heavy      | 0.00035 max                                            | 1.0         |
| Type D - thin       | 0.0002 to 0.0004, excl                                 | 2.0         |
| Type D - heavy      | 0.0004 to 0.0010, incl                                 | 1.5         |

Note: For Types A, B and C thin combined, there shall be not more than three fields of No. 1.5A type, or No. 1.5B and No. 1.0C types, and not more than five other lower rateable A, B and C type-thin fields per specimen. For D type-thin, there shall be not more than three No. 1.5 fields, and no more than five other lower rateable D type-thin fields per specimen. There shall be not more than one field each of No. 1.0A, B and C type or No. 1.5D type-heavy per specimen. A rateable field is defined as one which has a Type A, B, C or D microinclusion rating of at least No. 1.0 thin or heavy in accordance with the dimensional limitations and the Jernkontoret Chart.



3.10.2 Microstructure. The microstructure shall be predominately tempered martensite after heat treatment to the HT condition.

3.10.3 Grain size. The austenitic grain size shall be 5 or finer.

3.11 Decarburization limits for forgings. Table IV defines acceptable limits for decarburization of as-forged products.

TABLE IV. DECARBURIZATION LIMITS FOR AS-FORGED PRODUCTS

| Nominal Diameter or Distance Between Opposite Faces in.<br>(mm)                                                                                                                                                                                                    | Maximum Depth of Decarburization*<br>in. (mm) |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------|
| — to 0.375 (9.53)                                                                                                                                                                                                                                                  | 0.010 (0.254)                                 |
| 0.376 to 0.500 (9.55 to 12.7)                                                                                                                                                                                                                                      | 0.012 (0.305)                                 |
| 0.501 to 0.625 (12.73 to 15.9)                                                                                                                                                                                                                                     | 0.014 (0.356)                                 |
| 0.626 to 1.000 (15.9 to 25.4)                                                                                                                                                                                                                                      | 0.017 (0.432)                                 |
| 1.010 to 1.500 (25.7 to 38.1)                                                                                                                                                                                                                                      | 0.020 (0.508)                                 |
| 1.510 to 2.000 (38.4 to 50.8)                                                                                                                                                                                                                                      | 0.025 (0.635)                                 |
| 2.010 to 2.500 (51.1 to 63.5)                                                                                                                                                                                                                                      | 0.030 (0.762)                                 |
| 2.510 to 3.000 (63.8 to 76.2)                                                                                                                                                                                                                                      | 0.035 (0.889)                                 |
| Over 3.000 (76.2)                                                                                                                                                                                                                                                  | 0.045 (1.143)                                 |
| *The value specified as the maximum depth of decarburization is the sum of the complete, plus the partial decarburization.                                                                                                                                         |                                               |
| Note: When determining the depth of decarburization, it is permissible to disregard local areas provided the decarburization of such areas does not exceed the limits of Table III by more than 0.005 inch (0.127mm) and the width is 0.065 inch (1.65mm) or less. |                                               |

#### 4. QUALITY ASSURANCE PROVISIONS

##### 4.1 Responsibility for testing.

4.1.1 Supplier responsibility. The supplier is responsible for the performance of all testing requirements as specified herein. The supplier may utilize his own facilities or any commercial testing laboratory acceptable to Materials, Processes, and Standards Department of Hughes Helicopters.



4.1.2 Hughes Helicopters. All incoming material shall be inspected upon receipt at Hughes Helicopters for compliance to the requirements specified herein. Each lot shall be tested. When more than one size of material is represented by a single lot, a sample from each of the following product sizes shall be tested.

2.5 to 3.5 RCS or dia, in.

4.5 to 5.5 RCS or dia, in.

8.0 to 10 RCS or dia, in.

Substitution or deviation from the above sizes shall be approved by HH Materials, Processes and Standards Department.

4.1.3 Process control documentation. Written procedures controlling fabrication, inspection, and testing of material shall be maintained by the supplier and shall be available for review by Hughes Helicopters.

4.2 Testing requirements.

4.2.1 Chemical analysis. Chemical composition shall be determined by wet chemical methods in accordance with ASTM E 353, by spectrographic methods in accordance with FED-STD-151, Method 112, or by other approved analytical methods.

4.2.2 Ultrasonic. Each forged billet shall exhibit an ultrasonic quality per MIL-I-8950, Class A, or HP 6-22, Class B, as applicable.

4.2.3 Macroexamination. A serialized full cross-section macroslab wafer approximately 1 inch thick shall be taken from the top and bottom of the largest forged billet. The wafer shall be ground to an RHR 63 finish, or better, and etched in a hydrochloric-sulfuric acid mixture per ASTM E 381.

4.2.4 Mechanical properties. The material shall meet the minimum mechanical properties specified in Table II after heat treatment to the HT condition per HP 1-1, and testing per HP 6-25. Longitudinal and transverse specimens shall be tested.

4.2.5 Hardness. Material shall be hardness tested per HP 6-19 and meet hardness requirements after heat treatment to the HT condition.



4.2.6 Magnetic particle inspection. Each lot shall be magnetic particle inspected in accordance with AMS 2300 or HP 6-5 using a stepped down test bar and shall meet the cleanliness requirements of 3.9.

4.2.7 Microexamination. A section of material taken in the longitudinal and transverse direction shall be examined for conformance to 3.10. Austenitic grain size shall be measured per ASTM E 122. The size and frequency of microinclusions shall be determined on a longitudinal section in accordance with ASTM E 45.

#### 4.3 Reports.

4.3.1 The supplier shall furnish with each shipment three copies of a test report for each lot to determine conformance to the requirements of Section 3 of this specification.

4.3.2 Records. Copies of these test reports shall be filed for a minimum of 3 years after completion of the contract and shall be made available to Hughes Helicopters personnel upon demand.

#### 4.4 Identification.

4.4.1 Unless otherwise specified, each forged billet shall be marked in accordance with the requirements of HP 8-5, Type I, Class 3 with HMS 6-1121, lot number, manufacturer's identification, ingot number, and nominal size in inches. The characters shall not be less than 3/8 inch (9.6 mm) in height.

#### 4.5 Rejection and retests.

4.5.1 If any of the tests specified herein fails, the lot represented by the failed specimen shall be rejected and shall be submitted to Hughes Helicopters Material Review Board for disposition.

Where stock sizes are furnished that have been qualified by first article testing at HH the supplier will be required to requalify the material in the event that reforging operations have been performed.

### 5. PREPARATION FOR DELIVERY

5.1 Packaging. All material shall be properly separated by size, shape, and condition, and packaged in a manner acceptable to common carrier for safe transportation.



5.1.1 Shipping containers, crates, boxes, or bundles shall be marked to give the following information:

- a. Material - ESR 4340 steel forged billet
- b. Hughes Helicopters Material Specification (HMS) 6-1121
- c. Condition - normalized and tempered
- d. Size
- e. Quality in this container
- f. Purchase order number
- g. Manufacturer's name or trademark
- h. Lot number

## 6. NOTES

6.1 Intended use. The process covers an electroslag refined steel forged billet at a 280- to 300-ksi strength level used in the manufacture of helicopters and their ordnance.

## 7. APPROVED VENDORS

7.1 Vendors whose products are acceptable under this specification are listed in Hughes Helicopters' Approved Vendors List (AVL) 1121.



APPENDIX C

Excerpt from HP1-1, Hughes Helicopter's heat treatment specification for steel. The excerpt describes the heat treat process established for ESR 4340.



Hughes Helicopters  
Division of Sundt Corporation

Center 1440 Teaneck Street  
Culver City, California 90230

## PROCESS SPECIFICATION

Table X. Heat Treatment of Special Steels

### 4340 Electroslog Refined Steel (ESR) (See HMS 6-1121)

Equipment - Normalize, temper (1175°F/635°C) and austenitize shall be performed in a vacuum furnace capable of meeting all of the requirements specified herein.

Condition NT - Normalize at 1650°F ±25°F (899° ±13.9° C) for 3 hours minimum at temperature per inch (2.54 cm) of thickness, and cool in inert atmosphere. Temper at 1175° ±25° F (635° ±13.9° C) for 3 hours per inch (2.54 cm) of thickness; air or furnace cool.

Condition HT - (Material must be in condition NT prior to heat treating to condition HT). Austenitize at 1525°F ±25°F (829° ±13.9° C) for 3 hours minimum at temperature per inch (2.54 cm) of thickness.

Oil quench (bath temperature after quenching not to exceed 140°F (60°C)).

Temper at 340°F ±10°F (171° ±5.6° C) for 4 hours.

Hardness - Material shall meet the hardness requirements as follows:

Condition NT - Brinell Hardness 277-321 (R<sub>C</sub>28-35)

HT - Brinell Hardness 535-578 (R<sub>C</sub>54-57)

Decarburization - Parts designated as "ballistic critical" shall be free of decarburization (total and partial). For fully hardened material intended for final use in non-ballistic applications, the depth of partial decarburization (complete decarburization not permitted) after all heat treat operations shall not exceed 0.003 inch (0.008 cm) on any surface.

After any grinding operation in the hardened condition, stress relief- 275° ±10°F (135° ±5.6° C) for two hours minimum.

|           |                |                                                                    |                         |
|-----------|----------------|--------------------------------------------------------------------|-------------------------|
| HP<br>1-1 | REV.<br>K      | HEAT TREATMENT OF STEELS<br>NICKEL-BASE, AND<br>COBALT-BASE ALLOYS | CODE IDENT NO.<br>02731 |
|           | SHEET 18 of 26 |                                                                    |                         |



**Hughes Helicopters**  
Division of Summa Corporation

Centinela and Teale Streets  
Culver City, California 90230

## PROCESS SPECIFICATION

Table X. Heat Treatment of Special Steels (Cont)

Process Control - Each batch of parts shall include three tensile bars for each heat of material in the batch. The tensile bars shall be transverse, full sized (R1) per HS 101, and shall be of the same heat as the parts they represent. In the event that size and/or configuration of available material will not permit making full sized transverse tensile bars, the largest obtainable sub-sized transverse tensile bars, per HS 101, may be used. The tensile bars shall accompany the parts they represent through all cleaning and heat treating processes. The tensile bars shall be tested at a Hughes Helicopters approved testing facility and mechanical properties thus obtained shall conform to the requirements of HMS 6-1121.

|                         |                                                                    |                |           |
|-------------------------|--------------------------------------------------------------------|----------------|-----------|
| CODE IDENT NO.<br>02731 | HEAT TREATMENT OF STEELS<br>NICKEL-BASE, AND<br>COBALT-BASE ALLOYS | HP 1-1         | REV.<br>K |
|                         |                                                                    | SHEET 19 of 26 |           |

APPENDIX D

Metcut report regarding surface grinding of ESR 4340 steel. An evaluation was made using low stress grinding techniques and also using maximum and minimum conditions of two Hughes Helicopters specifications. Studies of photomicrographs, hardnesses, and residual stress concentrations were conducted to determine the effects of the various conditions.

SURFACE GRINDING OF 4340 ESR STEEL

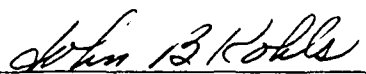
Metcut Report 1752-26887-2

for

Hughes Helicopter  
Division Summa Corporation  
Attn: Mr. Kenneth Niji  
Building 305  
Culver City, CA 90230

Purchase Order HH112976-737

March 13, 1980

  
\_\_\_\_\_  
John B. Kohls, Supervisor  
Machinability Department

Metcut Research Associates Inc.  
3980 Rosslyn Drive  
Cincinnati, OH 45209

513/271-5100

At the request of Mr. Ken Niji of Hughes Helicopter, Metcut Research Associates performed various surface grinding test cuts on 4340 ESR steel. These test cuts were then compared using various metallographic techniques. The comparisons included 100X to 1000X visual examination, micro-hardness travers and residual stress profiles.

Metcut has performed extensive studies in the area of Surface Integrity. Surface integrity is a study of the surface quality of the workpiece after machining. This work includes both surface and subsurface alterations. As a result of this work, Metcut has developed grinding procedures that will produce a low level compressive stress that is beneficial in fatigue applications.

One of the five (5) conditions evaluated in this program is the technique mentioned above and is identified as "LSG". The remaining four (4) conditions were taken from Hughes Process Specifications supplied by Mr. Niji. The specifications supplied were HP 18-12 and HP 15-51.

The five (5) conditions evaluated are listed in Table I. For each condition, the various grinding parameters are listed in the table.

After machining, metallographic sections were removed from the samples in such a manner as to minimize heat induced by cut-off.

Sections were taken both longitudinal and transverse to the grinding lays.

After metallographic mounting, the sections were ground back approximately 0.060 inches using a low speed wheel and silicon carbide paper which was flushed continuously with water.

Samples were prepared using metallographic techniques that assure optimum edge retention.

Examination of the samples was performed at magnifications from 100X to 1000X with micro-sections in the etched and unetched condition.

Photomicrographs and microhardness values were obtained on samples prepared in the direction transverse to the grinding lay axis.

Figures 1, 2, and 3, are typical photomicrographs of the five test conditions. All surfaces are relatively smooth. The only surface showing excessive subsurface alteration is HP 15-51 Max. in Figure 3.

The microhardness traverse profiles are shown in Figure 4. Each condition shows some surface softening as a result of the grinding conditions. Condition HP 15-51 Max. again shows the most alteration from the core hardness values.

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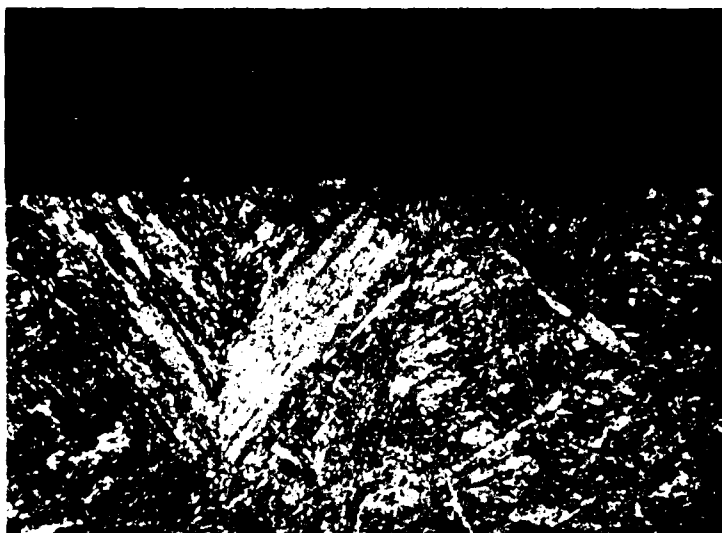
Figure 5 is a graph of the residual stress profiles for each test surface. The only surface showing the detrimental tensile stresses is the HP 15-51 Max. A writeup on the residual stress technique and calculation is given immediately after Figure 5.

From this investigation, it seems that specifying the specification HP 18-12 can yield a fairly good level of surface quality. However specifying the specification HP 15-51 would not produce a similar effect. HP 15-51 depending on parameters selected, could yield either compressive or tensile stress. This wide variation in residual stress is not recommended for a high stressed critical part.

TABLE I

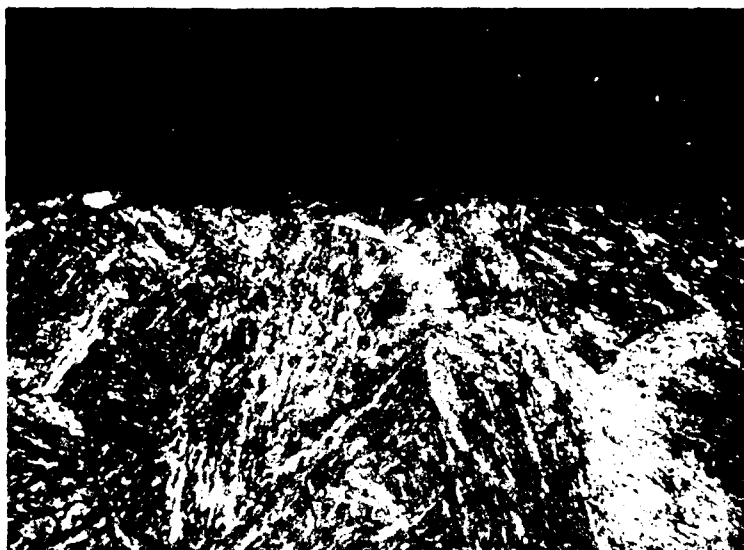
## SURFACE GRINDING CONDITIONS 4340 ESR STEEL

| Parameter                  | LSG         | HP 18-12     |               | HP 15-51     |               |
|----------------------------|-------------|--------------|---------------|--------------|---------------|
|                            |             | Min.         | Max.          | Min.         | Max.          |
| Wheel Speed, fpm           | 2000        | 2000         | 3500          | 2000         | 6000          |
| Wheel Grade                | A46HV       | A60I         | A60J          | A46HV        | A60J          |
| Work Speed, fpm            | 40          | 40           | 80            | 30           | 60            |
| Cross Feed, in./pass       | .050        | .050         | .100          | .100         | .400          |
| Fluid                      | Sulf Oil    | Sulf Oil     | Straight Oil  | Polar Chip   | Polar Chip    |
| Depth of Grind, in.        | .010        | .010         | .010          | .010         | .010          |
| Down Feed                  | 16 @ .0005  | 7 @ .0007    | 7 @ .0007     | 6 @ .001     | 6 @ .001      |
| No. of Passes @ Depth/Pass | 2 @ .0004   | 17 @ .0003   | 17 @ .0003    | 8 @ .0005    | 8 @ .0005     |
|                            | 6 @ .0002   |              |               |              |               |
| Dress Procedure            |             |              |               |              |               |
| No. of Passes @ Depth/Pass | 5 @ .001    | 5 @ .001     | 5 @ .001      | 5 @ .001     | 5 @ .001      |
|                            | 2 Sparkouts | 2 Sparkouts  | 2 @ .0005     | 2 Sparkouts  | 2 @ .0005     |
|                            |             |              | 5 @ .0002     |              | 5 @ .0002     |
|                            |             |              | 4 Sparkouts   |              | 4 Sparkouts   |
| Diamond Traverse Rate      |             | 1 in./7 sec. | 1 in./21 sec. | 1 in./7 sec. | 1 in./21 sec. |



Mount No. 24257

1000X



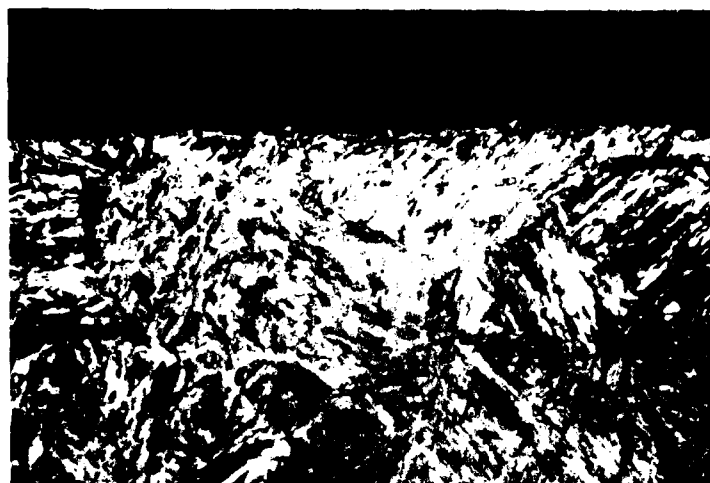
Mount No. 24257

1000X

Generally Smooth Surface With Isolated Light Etching  
Scallops. No Evidence of Laps or Cracks.

PHOTOMICROGRAPHS OF 4340SR STEEL SURFACE GROUND BY METCUT  
"LOW STRESS" GRIND TECHNIQUES

Figure 1



Mount No. 24179 1000X  
HP 18-12 Min.

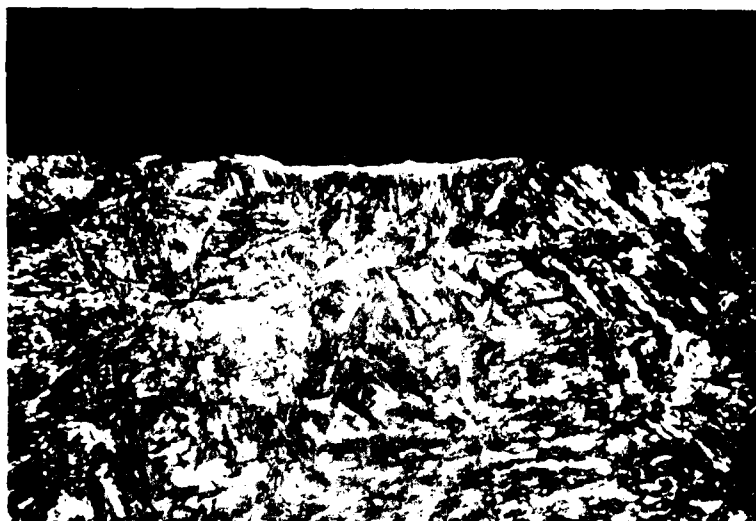
Generally Smooth Surface with Very Thin Light Etching  
Surface Layer (less than 0.0001 ins.). Isolated Instances of Surface Laps.



Mount No. 24175 1000X  
HP 18-12 Max.

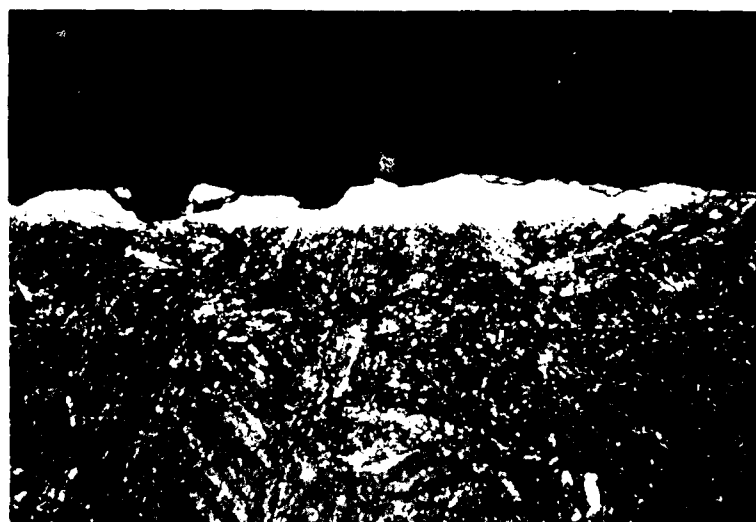
Generally Smooth Surface With Layer More Frequent Light Etching Scallop  
Than Low Stress Believed to be Untempered Martensite. Some  
Instances of Laps and Micro-cracks

PHOTOMICROGRAPHS OF 4340 FSR STEEL SURFACE GROUND  
BY TECHNIQUES PERMITTED IN HP 18-12



Mount No. 24183 1000X  
HP 15-51 Min.

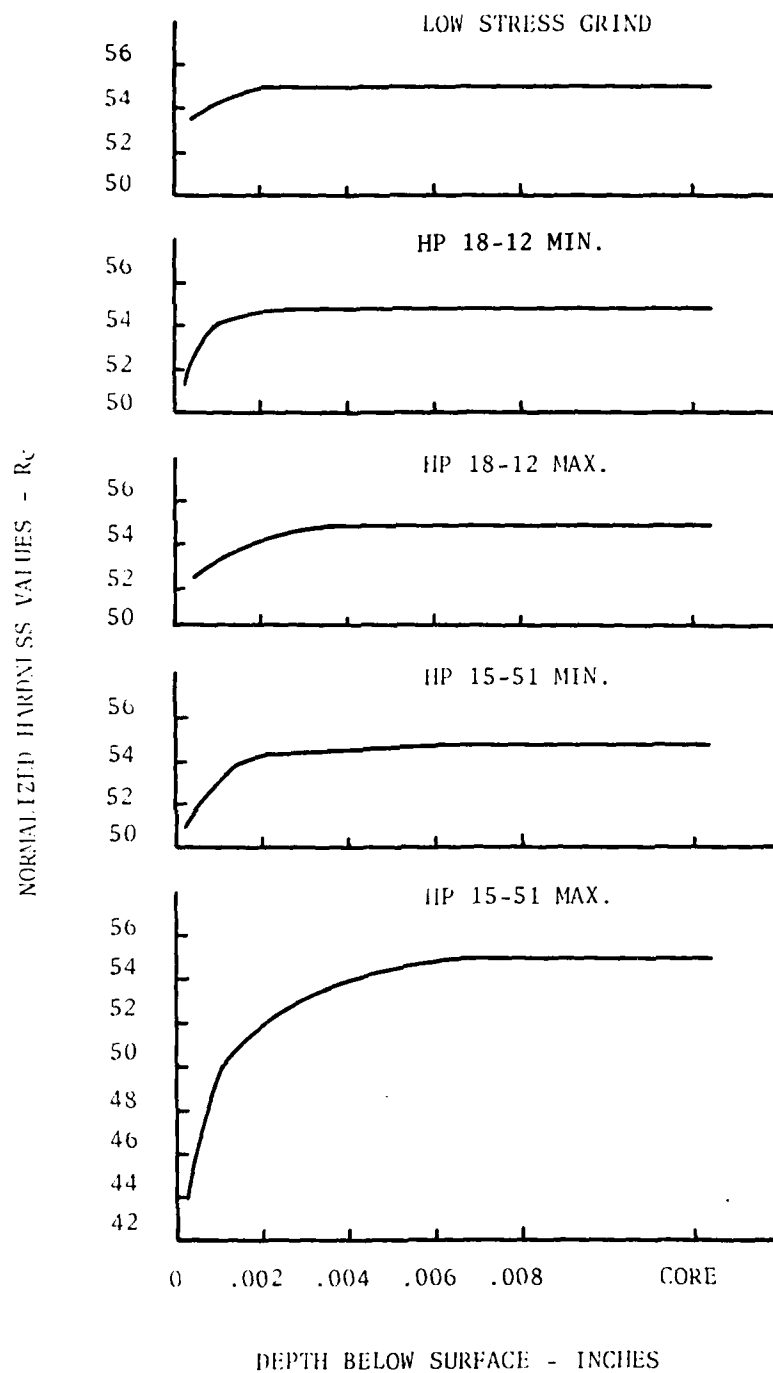
Generally Smooth Surface with Isolated Instances of  
Scallops (UTM), Tracks and Laps



Mount No. 24181 1000X  
HP 15-51 Max.

Larger and More Frequent Instances of Untempered Martensite,  
Laps and Cracks

PHOTOMICROGRAPHS OF 4340 FSR STEEL SURFACE GROUND BY  
TECHNIQUES PERMITTED IN HP 15-51



MICROHARDNESS TRAVERSE PROFILES OF SURFACE  
GROUND 4340 ESR STEEL

Figure 4

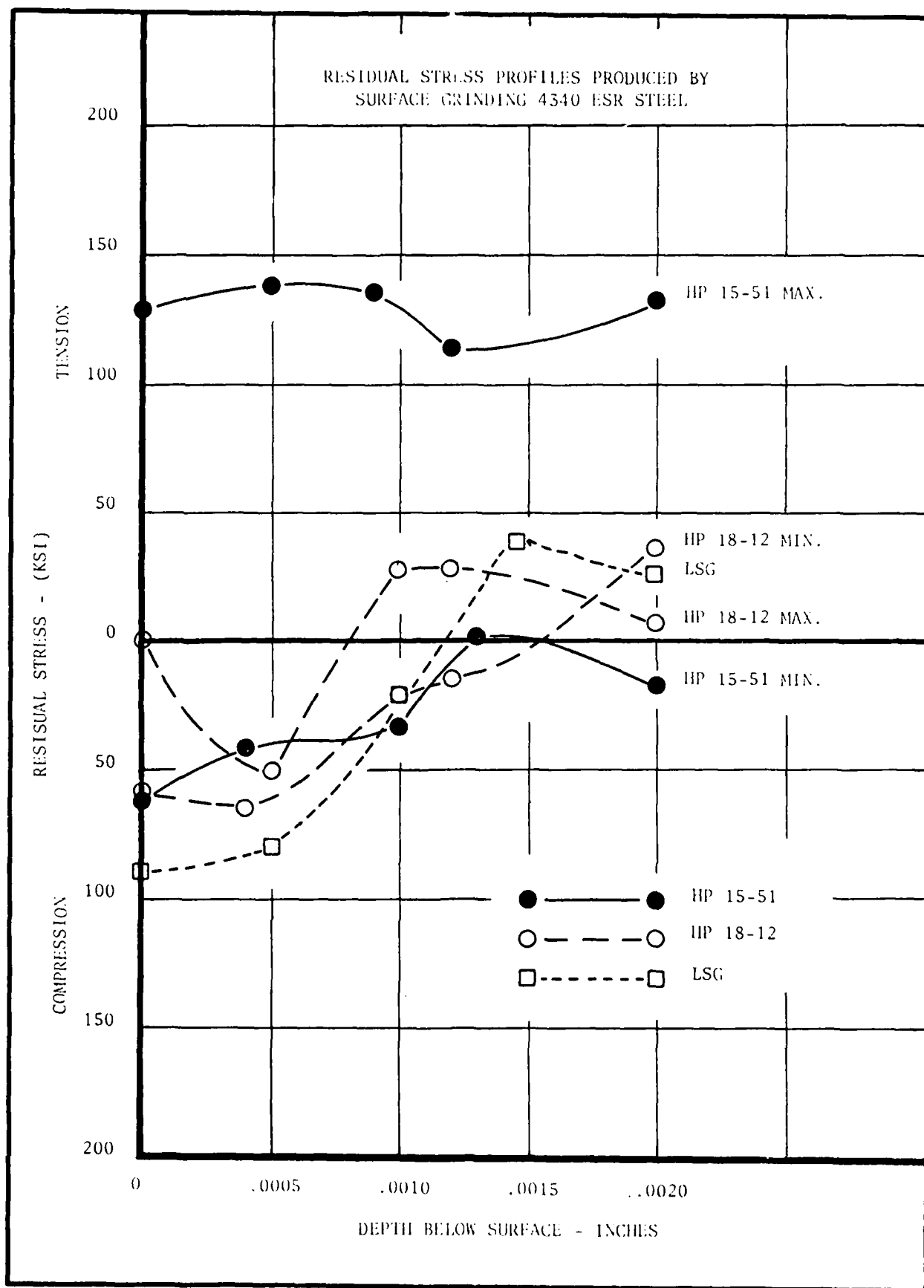


Figure 5

## LABORATORY REPORT

The logo for METCUT Research Associates Inc. features the word "METCUT" in a bold, sans-serif font, with the letters "M", "E", and "T" each enclosed within a separate rectangular box.

**METCUT RESEARCH ASSOCIATES INC.**

3980 Rosslyn Drive, Cincinnati, Ohio 45209 / Teletype: 810-461-2840 / Telephone: (513) 271-5100

Number: 1752-26887-2

Residual stress measurements were made using the technique recommended by the Society of Automotive Engineers. The specific technique employed differed from the more common SAE technique in two respects. First, the diffraction peak used for stress measurement was located using a five-point parabolic regression procedure rather than the three-point algebraic procedure more commonly used. Second, the intensities measured at each of the five points were corrected for the background intensity. These modifications improve the repeatability of stress measurements. Except for these modifications, the technique is identical to that described in the Society of Automotive Engineers Publication "Residual Stress Measurement by X-Ray Diffraction," SAW J784a. Details of the technique and diffractometer fixturing are outlined below:

Diffraction Peak: (211)  
Radiation: CrK $\alpha$   
Incident Beam Divergence: 3°  
Detection Slit: 0.7°  
 $E/(1 + \nu)$ :  $24.5 \times 10^6$  psi

The value of the elastic property  $E/(1 + \nu)$  in the direction normal to the (211) crystallographic planes was taken to be the same as previously determined for hardened 4340 steel, 50 R $_c$ . The determination of crystal elastic constants for the steel used to manufacture the ESR4340 Steel in question was not included in the scope of this program.

## LABORATORY REPORT



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## Results

Surface residual stresses measured in each test surface were as follows:

| <u>Specimen</u> | <u>Depth Below Surface<br/>(in.)</u> | <u>Residual Stress *</u><br>(ksi) |
|-----------------|--------------------------------------|-----------------------------------|
| LSG             | 0.0000                               | -88.3                             |
|                 | 0.0005                               | -79.8                             |
|                 | 0.0010                               | -20.1                             |
|                 | 0.0012                               | 43.7                              |
|                 | 0.0020                               | 28.9                              |
| HP 18-12 MIN.   | 0.0000                               | -58.1                             |
|                 | 0.0004                               | -64.2                             |
|                 | 0.0010                               | -21.4                             |
|                 | 0.0012                               | -14.5                             |
|                 | 0.0020                               | 31.7                              |
| HP 18-12 MAX.   | 0.0000                               | 0.9                               |
|                 | 0.0005                               | -50.7                             |
|                 | 0.0010                               | 27.8                              |
|                 | 0.0012                               | 29.3                              |
|                 | 0.0020                               | 8.5                               |
| HP 15-51 MIN.   | 0.0000                               | -61.5                             |
|                 | 0.0004                               | -41.5                             |
|                 | 0.0010                               | -33.0                             |
|                 | 0.0013                               | 4.5                               |
|                 | 0.0020                               | -18.5                             |
| HP 15-51 MAX.   | 0.0000                               | 127.8                             |
|                 | 0.0005                               | 138.0                             |
|                 | 0.0009                               | 136.4                             |
|                 | 0.0012                               | 114.5                             |
|                 | 0.0020                               | 133.0                             |

\* Negative value denotes compressive stress.

Details of the data analysis are shown in the attached computer printouts. The error shown for the stress values are  $\pm$  one standard deviation resulting from random error in the calibration constant and uncertainty in the diffraction peak position. An additional systematic error of  $\pm$  3 ksi arises from instrument misalignment and sample positioning errors.

METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

RESIDUAL STRESS DEPTH CORRECTION ANALYSIS

1752-26887 1-LSG

LONG., @ 2.0 MILS., GRN DIR.

$E/(1+\nu) = 24500. \pm 441. \text{ (KSI)}$   $\mu = 2196. \text{ (1/IN)}$

| DATA POINT | DEPTH<br>(IN.) | *****           | RESIDUAL STRESS (KSI) |                  | ***** |
|------------|----------------|-----------------|-----------------------|------------------|-------|
|            |                | MEASURED        | GRAD. CORRECTED       | RELAX. CORRECTED |       |
| 1          | 0.0000         | -88.3 $\pm$ 2.4 | -82.8                 | -82.8            |       |
| 2          | 0.0005         | -79.8 $\pm$ 2.6 | -93.4                 | -93.2            |       |
| 3          | 0.0010         | -20.1 $\pm$ 1.7 | -68.5                 | -68.1            |       |
| 4          | 0.0012         | 43.7 $\pm$ 1.6  | -2.6                  | -2.2             |       |
| 5          | 0.0020         | 28.9 $\pm$ 1.6  | 80.0                  | 80.1             |       |

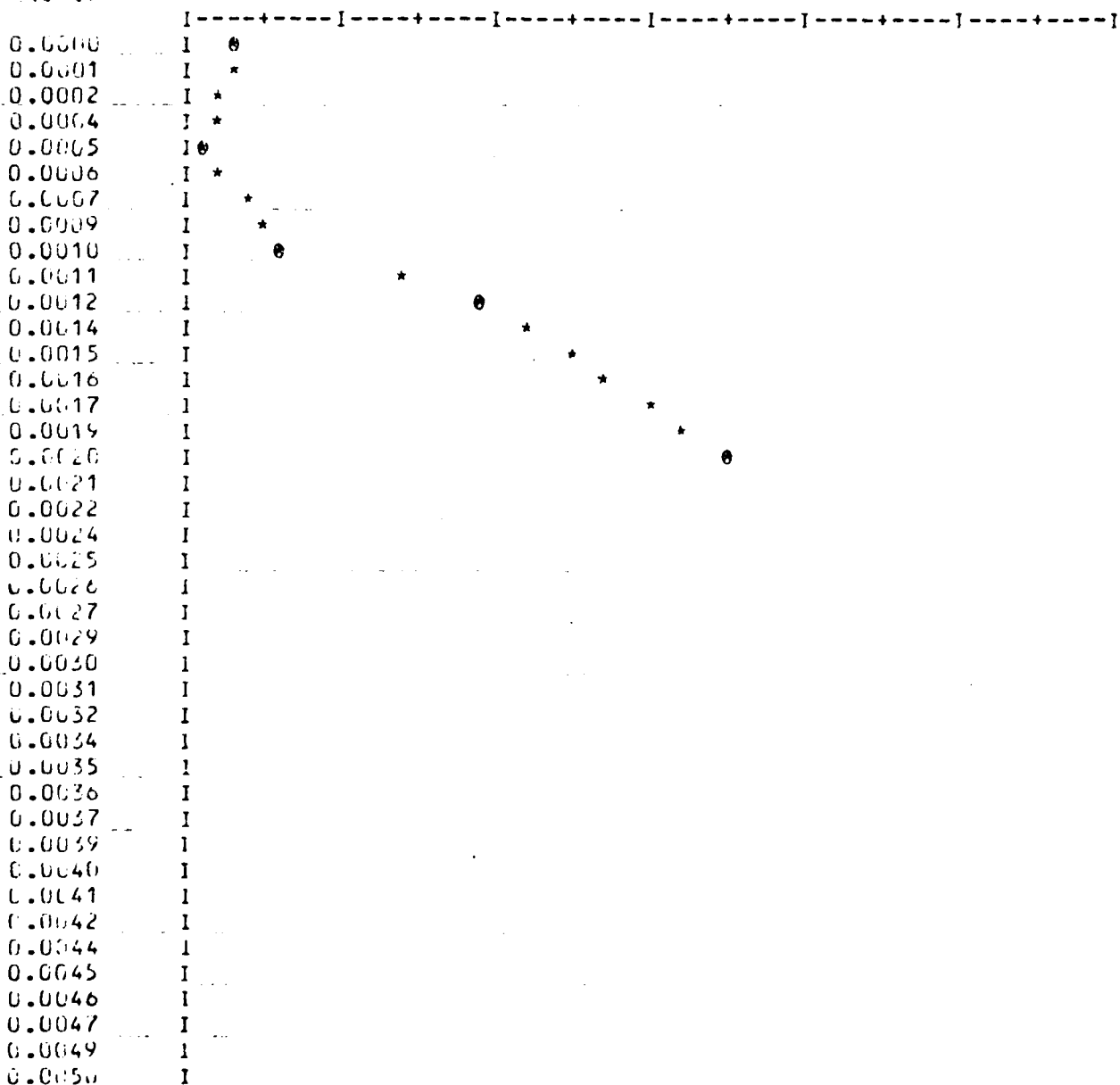
METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI OHIO

X-RAY DIFFRACTION RESIDUAL STRESS ANALYSIS

1752-26887 1-LSG

LONG, 2.0 MILS., GRN DIR.

DEPTH -100.0 -50.0 0.0 50.0 100.0 150.0 200.0  
(IN.)



FITTED POINTS = \* MEASURED DATA = O

METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 1-LSG

LONG, SURFACE, GRN DIR.

| PSI    | 2 THETA | TIME   | COR. TIME | D (A)   | VERTEX +- ST.DEV. |
|--------|---------|--------|-----------|---------|-------------------|
| 0.000  | 154.000 | 33.040 | 308.448   |         |                   |
|        | 154.500 | 32.220 | 275.249   |         |                   |
|        | 155.000 | 31.740 | 258.769   |         |                   |
|        | 155.700 | 32.220 | 277.681   |         |                   |
|        | 156.200 | 33.030 | 313.329   | 1.17310 | 155.0736 +-0.0052 |
| 45.000 | 155.000 | 20.510 | 335.693   |         |                   |
|        | 155.540 | 19.850 | 263.829   |         |                   |
|        | 156.200 | 19.480 | 244.958   |         |                   |
|        | 156.600 | 19.600 | 272.733   |         |                   |
|        | 157.000 | 19.830 | 325.481   | 1.17099 | 156.0277 +-0.0031 |

E/(1+V) = 24500. +- 441. (KSI)

STRESS = -88.3 +- 2.4 (KSI)

DELTA D = -0.00211 (A)

STRAIN = -0.001902 (IN./IN.)

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 1-LSG

LONG., @ 0.5 MILS., GRN DIR.

| PSI    | 2 THETA | TIME   | COR. TIME | D (A)   | VERTEX +- ST.DEV. |
|--------|---------|--------|-----------|---------|-------------------|
| 0.000  | 154.000 | 33.630 | 339.222   |         |                   |
|        | 154.500 | 32.690 | 295.517   |         |                   |
|        | 155.000 | 32.110 | 273.214   |         |                   |
|        | 155.500 | 32.220 | 278.452   |         |                   |
|        | 156.000 | 32.800 | 303.769   | 1.17285 | 155.1859 +-0.0053 |
| 45.000 | 155.000 | 23.700 | 137.001   |         |                   |
|        | 155.500 | 23.090 | 126.990   |         |                   |
|        | 156.200 | 22.600 | 121.162   |         |                   |
|        | 156.600 | 22.820 | 127.663   |         |                   |
|        | 157.000 | 23.010 | 134.060   | 1.17094 | 156.0506 +-0.0075 |

E/(1+V) = 24500. +- 441. (KSI)

STRESS = -79.8 +- 2.6 (KSI)

DELTA D = -0.00191 (A)

STRAIN = -0.001629 (IN./IN.)

METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-24287 1-LSG-1

LONG, SURFACE, REPOSITIONED, GRN DIR

| PSI   | 2 THETA | TIME   | COR. TIME | D (A)   | VERTEX +/- ST. DEV. |
|-------|---------|--------|-----------|---------|---------------------|
| 0.000 | 154.000 | 33.490 | 323.715   |         |                     |
|       | 154.500 | 32.470 | 280.234   |         |                     |
|       | 155.000 | 31.960 | 262.298   |         |                     |
|       | 155.500 | 32.220 | 272.697   |         |                     |
|       | 156.000 | 32.770 | 295.659   | 1.17296 | 155.1322 +/- 0.0057 |

|        |         |        |         |         |                     |
|--------|---------|--------|---------|---------|---------------------|
| 45.000 | 155.000 | 23.220 | 205.513 |         |                     |
|        | 155.500 | 22.290 | 171.071 |         |                     |
|        | 156.200 | 21.780 | 158.636 |         |                     |
|        | 156.600 | 21.930 | 168.343 |         |                     |
|        | 157.000 | 22.180 | 183.506 | 1.17076 | 156.1342 +/- 0.0043 |

E/(1+V) = 24500 +/- 441. (KSI)

STRESS = -91.9 +/- 2.5 (KSI)

DELTA D = -0.00220 (A)

STRAIN = -0.001875 (IN./IN.)

METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 1-LSG

LONG., @ 1.0 MILS., GRN. DIR.

| PSI                             | 2 THETA | TIME   | COR. TIME                    | D (A)   | VERTEX +/- ST.DEV.  |
|---------------------------------|---------|--------|------------------------------|---------|---------------------|
| 0.000                           | 154.500 | 34.190 | 335.737                      |         |                     |
|                                 | 155.000 | 33.410 | 300.845                      |         |                     |
|                                 | 155.500 | 33.080 | 288.386                      |         |                     |
|                                 | 156.000 | 33.390 | 302.240                      |         |                     |
|                                 | 156.500 | 33.810 | 322.295                      | 1.17200 | 155.5655 +/- 0.0064 |
| 45.000                          | 155.000 | 23.680 | 190.233                      |         |                     |
|                                 | 155.500 | 23.310 | 180.911                      |         |                     |
|                                 | 156.000 | 23.100 | 178.342                      |         |                     |
|                                 | 156.500 | 23.220 | 189.370                      |         |                     |
|                                 | 157.000 | 23.440 | 206.631                      | 1.17152 | 155.7837 +/- 0.0072 |
| E/(1+V) = 24500. +/- 441. (KSI) |         |        | STRESS = -20.1 +/- 1.7 (PSI) |         |                     |
| DELTA D = -0.00048 (A)          |         |        | STRAIN = -0.000410 (IN./IN.) |         |                     |

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 1-LSG

LONG., @ 1.2 MILS., GRN. DIR.

| PSI                             | 2 THETA | TIME   | COR. TIME                   | D (A)   | VERTEX +/- ST.DEV.  |
|---------------------------------|---------|--------|-----------------------------|---------|---------------------|
| 0.000                           | 155.000 | 42.670 | 856.428                     |         |                     |
|                                 | 155.500 | 42.400 | 807.631                     |         |                     |
|                                 | 156.000 | 42.170 | 770.548                     |         |                     |
|                                 | 156.500 | 42.470 | 831.251                     |         |                     |
|                                 | 157.000 | 42.770 | 901.068                     | 1.17131 | 155.8821 +/- 0.0064 |
| 45.000                          | 154.500 | 29.180 | 545.353                     |         |                     |
|                                 | 155.000 | 29.020 | 546.182                     |         |                     |
|                                 | 155.500 | 28.470 | 466.190                     |         |                     |
|                                 | 156.000 | 28.630 | 531.248                     |         |                     |
|                                 | 156.700 | 28.740 | 620.532                     | 1.17235 | 155.4086 +/- 0.0042 |
| E/(1+V) = 24500. +/- 441. (KSI) |         |        | STRESS = 43.7 +/- 1.0 (PSI) |         |                     |
| DELTA D = 0.00104 (A)           |         |        | STRAIN = 0.000892 (IN./IN.) |         |                     |

METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 1-LSG

LONG., @ 2.0 MILS., GRN DIR.

| PSI                             | 2 THETA | TIME   | COR. TIME | D (A)                       | VERTEX +/- ST.DEV.  |
|---------------------------------|---------|--------|-----------|-----------------------------|---------------------|
| 0.000                           | 155.000 | 43.750 | 1531.169  |                             |                     |
|                                 | 155.500 | 43.370 | 936.834   |                             |                     |
|                                 | 156.000 | 43.170 | 896.035   |                             |                     |
|                                 | 156.500 | 43.490 | 980.265   |                             |                     |
|                                 | 157.000 | 43.770 | 1067.564  | 1.17123                     | 155.9167 +/- 0.1054 |
| 45.000                          | 155.000 | 30.470 | 333.588   |                             |                     |
|                                 | 155.500 | 30.300 | 332.759   |                             |                     |
|                                 | 156.200 | 30.020 | 328.188   |                             |                     |
|                                 | 156.600 | 30.370 | 370.049   |                             |                     |
|                                 | 157.000 | 30.660 | 415.211   | 1.17192                     | 155.6022 +/- 0.1064 |
| E/(1+V) = 24500. +/- 441. (KSI) |         |        |           |                             |                     |
| STRESS =                        |         |        |           | 28.9 +/- 1.6 (KSI)          |                     |
| DELTA D = 0.00067 (A)           |         |        |           | STRAIN = 0.000596 (IN./IN.) |                     |

METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

RESIDUAL STRESS DEPTH CORRECTION ANALYSIS

1752-26847 3-12-12-MIN LONG., @ 2.0 MILS., GRN DIR.

$E/(1+V) =$  24500.  $\pm$  441. (KSI)  $\mu =$  2196. (1/IN)

| DATA POINT | DEPTH<br>(IN.) | *****<br>MEASURED | RESIDUAL STRESS (KSI)<br>GRAD. CORRECTED | *****<br>RELAX. CORRECTED |
|------------|----------------|-------------------|------------------------------------------|---------------------------|
| 1          | 0.0000         | -58.1 $\pm$ 2.5   | -41.8                                    | -41.8                     |
| 2          | 0.0004         | -64.2 $\pm$ 1.0   | -66.2                                    | -66.1                     |
| 3          | 0.0010         | -21.4 $\pm$ 1.5   | -31.5                                    | -31.5                     |
| 4          | 0.0012         | -14.5 $\pm$ 1.5   | -23.4                                    | -23.                      |
| 5          | 0.0020         | 31.7 $\pm$ 1.6    | 17.0                                     | 17.2                      |

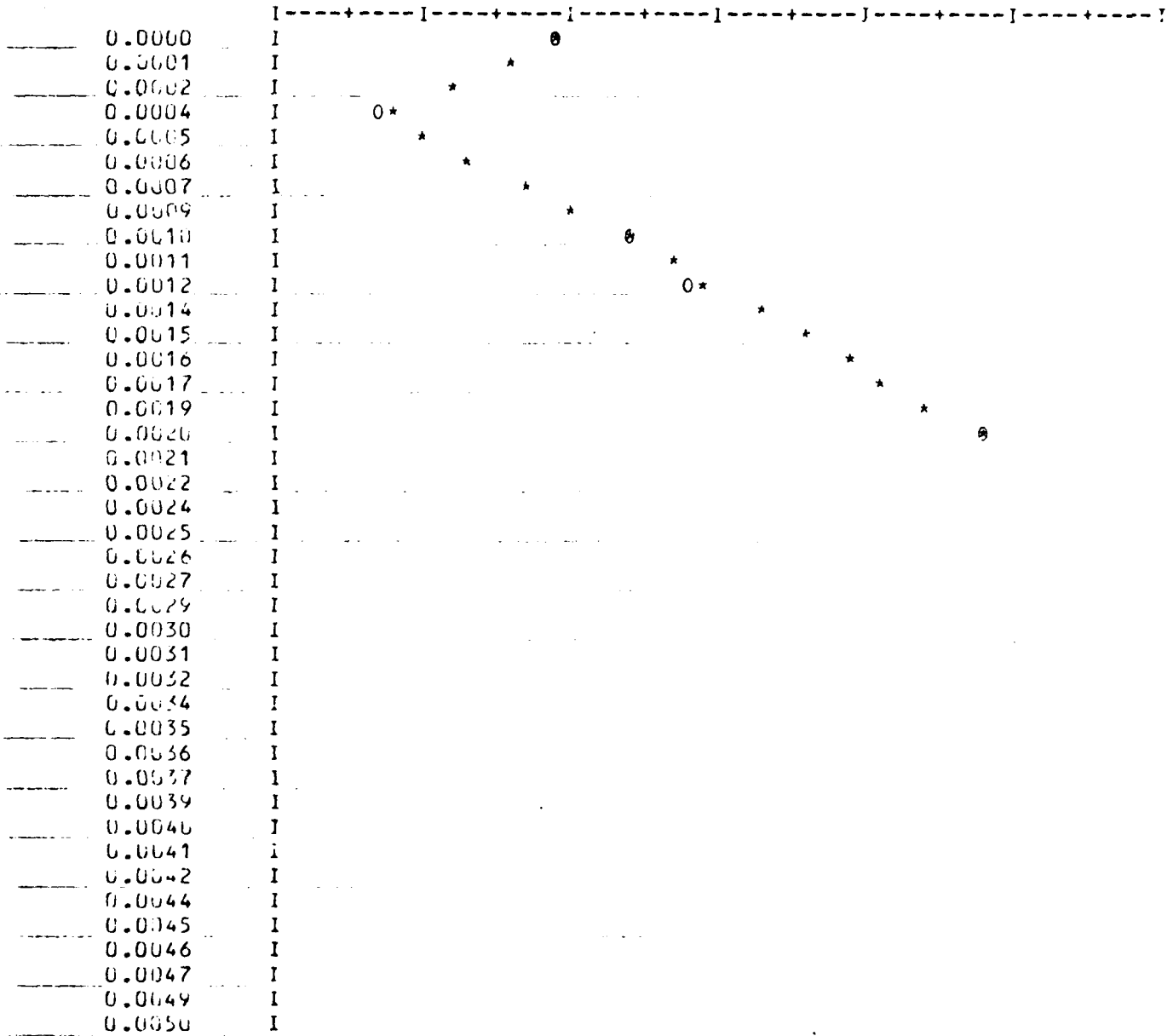
METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI OHIO

X-RAY DIFFRACTION RESIDUAL STRESS ANALYSIS

1752-26887 3-18-12-MIN

LONG., 2.0 MILS., GRN DIR.

DEPTH (IN.)      -80.0      -60.0      -40.0      -20.0      0.0      20.0      40.0  
RESIDUAL STRESS (KSI)



FITTED POINTS = \*      MEASURED DATA = 0

METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 3-18-12-MIN

LONG SURFACE, GRN DIF.

| PSI   | 2 THETA | TIME   | COR. TIME | D (A)   | VERTEX +- ST.DEV. |
|-------|---------|--------|-----------|---------|-------------------|
| 0.000 | 154.500 | 33.250 | 313.035   |         |                   |
|       | 154.700 | 33.800 | 340.875   |         |                   |
|       | 155.000 | 32.590 | 285.555   |         |                   |
|       | 155.500 | 32.930 | 300.778   |         |                   |
|       | 156.000 | 33.260 | 316.833   | 1.17253 | 155.5268 +- 0.064 |

|        |         |        |         |         |                   |
|--------|---------|--------|---------|---------|-------------------|
| 45.000 | 155.000 | 23.070 | 109.128 |         |                   |
|        | 155.500 | 22.390 | 101.418 |         |                   |
|        | 156.000 | 22.150 | 100.061 |         |                   |
|        | 156.700 | 22.360 | 105.777 |         |                   |
|        | 157.000 | 22.570 | 110.227 | 1.17114 | 155.9571 +- 0.090 |

E/(1+V) = 24500. +- 441. (KSI)

STRESS = -58.1 +- 2.5 (KSI)

DELTA D = -0.00139 (A)

STRAIN = -0.001186 (IN./IN.)

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 3-18-12-MIN

LONG., 0.4 MILS, GRN DIF

| PSI   | 2 THETA | TIME   | COR. TIME | D (A)   | VERTEX +- ST.DEV. |
|-------|---------|--------|-----------|---------|-------------------|
| 0.000 | 154.000 | 41.010 | 751.168   |         |                   |
|       | 154.500 | 40.470 | 669.028   |         |                   |
|       | 155.000 | 39.860 | 593.391   |         |                   |
|       | 155.500 | 40.170 | 634.341   |         |                   |
|       | 156.000 | 40.890 | 746.036   | 1.17320 | 155.0312 +- 0.038 |

|        |         |        |          |         |                   |
|--------|---------|--------|----------|---------|-------------------|
| 45.000 | 155.000 | 27.620 | 1408.052 |         |                   |
|        | 155.500 | 27.170 | 1055.646 |         |                   |
|        | 156.000 | 26.940 | 1010.428 |         |                   |
|        | 156.500 | 27.000 | 1301.208 |         |                   |
|        | 157.000 | 27.340 | 3314.546 | 1.17166 | 155.7197 +- 0.014 |

E/(1+V) = 24500. +- 441. (KSI)

STRESS = -64.2 +- 1.6 (KSI)

DELTA D = -0.00154 (A)

STRAIN = -0.001310 (IN./IN.)

METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 3-18-12-MIN LONG., @ 1.0 MILS., GRN DIR.

| PSI   | 2 THETA | TIME   | COR. TIME | D (A)   | VERTEX +- ST.DEV. |
|-------|---------|--------|-----------|---------|-------------------|
| 0.000 | 154.500 | 33.920 | 325.090   |         |                   |
|       | 155.000 | 33.350 | 300.406   |         |                   |
|       | 155.500 | 33.010 | 287.447   |         |                   |
|       | 156.000 | 33.340 | 302.015   |         |                   |
|       | 156.600 | 34.030 | 335.422   | 1.17219 | 155.4819 +-0.0064 |

|        |         |        |         |         |                   |
|--------|---------|--------|---------|---------|-------------------|
| 45.000 | 155.000 | 23.330 | 170.294 |         |                   |
|        | 155.500 | 22.890 | 160.539 |         |                   |
|        | 155.900 | 22.710 | 158.686 |         |                   |
|        | 156.500 | 22.920 | 172.404 |         |                   |
|        | 157.000 | 23.450 | 201.488 | 1.17168 | 155.7137 +-0.0054 |

E/(1+V) = 24500. +- 441. (KSI)

STRESS = -21.4 +- 1.5 (KSI)

DELTA D = -0.00051 (A)

STRAIN = -0.000487 (IN./IN.)

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 3-18-12-MIN LONG., @ 1.2 MILS., GRN DIR.

| PSI   | 2 THETA | TIME   | COR. TIME | D (A)   | VERTEX +- ST.DEV. |
|-------|---------|--------|-----------|---------|-------------------|
| 0.000 | 154.500 | 34.170 | 339.171   |         |                   |
|       | 155.000 | 33.810 | 322.506   |         |                   |
|       | 155.800 | 33.390 | 305.110   |         |                   |
|       | 156.300 | 33.770 | 323.932   |         |                   |
|       | 156.800 | 34.330 | 353.482   | 1.17199 | 155.5708 +-0.0070 |

|        |         |        |         |         |                   |
|--------|---------|--------|---------|---------|-------------------|
| 45.000 | 155.000 | 23.750 | 196.653 |         |                   |
|        | 155.500 | 23.340 | 185.596 |         |                   |
|        | 156.000 | 23.100 | 182.171 |         |                   |
|        | 156.500 | 23.340 | 199.920 |         |                   |
|        | 157.100 | 23.710 | 228.623 | 1.17164 | 155.7280 +-0.0055 |

E/(1+V) = 24500. +- 441. (KSI)

STRESS = -14.5 +- 1.5 (KSI)

DELTA D = -0.00035 (A)

STRAIN = -0.000296 (IN./IN.)

METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 3-18-12-MIN LONG., @ 2.0 MILS., GRN DIR.

| PSI                            | 2 THETA | TIME   | COR. TIME                   | d (A)   | VERTEX +- ST.DEV. |
|--------------------------------|---------|--------|-----------------------------|---------|-------------------|
| 0.000                          | 155.000 | 44.270 | 924.298                     |         |                   |
|                                | 155.500 | 43.730 | 818.613                     |         |                   |
|                                | 156.000 | 43.570 | 794.200                     |         |                   |
|                                | 156.700 | 44.100 | 903.470                     |         |                   |
|                                | 157.300 | 44.520 | 1011.533                    | 1.17116 | 155.9479 +-0.0051 |
| 45.000                         | 155.300 | 29.740 | 584.684                     |         |                   |
|                                | 155.700 | 29.540 | 570.317                     |         |                   |
|                                | 156.300 | 29.470 | 608.557                     |         |                   |
|                                | 156.800 | 29.610 | 713.033                     |         |                   |
|                                | 157.300 | 29.680 | 822.211                     | 1.17192 | 155.6026 +-0.0059 |
| E/(1+V) = 24500. +- 441. (KSI) |         |        |                             |         |                   |
|                                |         |        | STRESS = 31.7 +- 1.6 (KSI)  |         |                   |
| DELTA d = 0.00076 (A)          |         |        | STRAIN = 0.000647 (IN./IN.) |         |                   |

METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

RESIDUAL STRESS DEPTH CORRECTION ANALYSIS

1752-26887 2-18-12-MAX LONG., @ 2.0 MILS., GRN DIR.

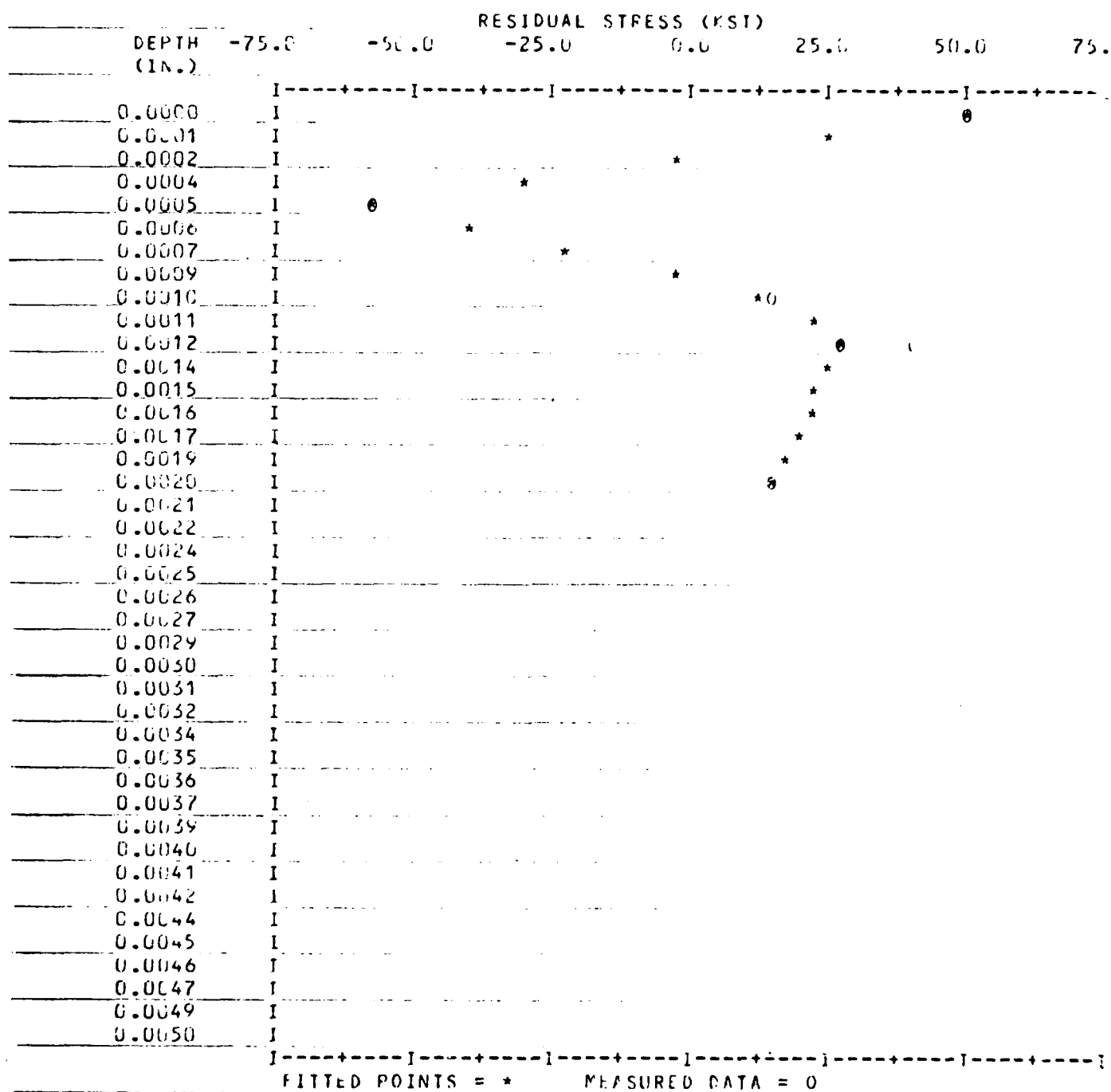
$E/(1+V) = 24500. \pm 441. \text{ (KSI)}$   $MU = 2196. \text{ (1/IN)}$

| DATA POINT | DEPTH<br>(IN.) | *****<br>MEASURED | RESIDUAL STRESS (KSI)<br>GRAD. CORRECTED | *****<br>RELAX. CORRECTED |
|------------|----------------|-------------------|------------------------------------------|---------------------------|
| 1          | 0.0000         | 0.9 $\pm$ 0.5     | 52.0                                     | 52.0                      |
| 2          | 0.0005         | -50.7 $\pm$ 1.1   | -58.6                                    | -58.6                     |
| 3          | 0.0010         | 27.8 $\pm$ 1.6    | 17.5                                     | 17.6                      |
| 4          | 0.0012         | 29.3 $\pm$ 1.8    | 30.5                                     | 30.5                      |
| 5          | 0.0020         | 8.5 $\pm$ 0.3     | 17.8                                     | 17.7                      |

MEICUT RESEARCH ASSOCIATES INC.  
CINCINNATI OHIO

X-RAY DIFFRACTION RESIDUAL STRESS ANALYSIS

1752-26887 2-10-12-MAX LONG. 2.0 MILS. GRN DIP.



MEICUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 2-18-12-MAX

LONG, SURFACE, GRN DIR.

| PSI                            | 2 THETA | TIME   | COR. TIME                   | D (A)   | VERTEX +- ST.DEV.  |
|--------------------------------|---------|--------|-----------------------------|---------|--------------------|
| 0.000                          | 154.500 | 32.570 | 291.325                     |         |                    |
|                                | 155.000 | 31.820 | 263.193                     |         |                    |
|                                | 155.500 | 31.500 | 252.912                     |         |                    |
|                                | 156.000 | 31.700 | 260.620                     |         |                    |
|                                | 156.400 | 32.480 | 291.317                     | 1.17222 | 155.4675 +- 0.0057 |
| 45.000                         | 154.500 | 23.340 | 306.998                     |         |                    |
|                                | 155.000 | 22.620 | 252.316                     |         |                    |
|                                | 155.500 | 22.210 | 233.076                     |         |                    |
|                                | 156.000 | 22.310 | 254.074                     |         |                    |
|                                | 156.400 | 22.700 | 307.378                     | 1.17224 | 155.4576 +- 0.0031 |
| E/(1+V) = 24500. +- 441. (KSI) |         |        | STRESS = 0.9 +- 0.2 (KSI)   |         |                    |
| DELTA D = 0.00002 (A)          |         |        | STRAIN = 0.000014 (IN./IN.) |         |                    |

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 2-18-12-MAX

LONG, & 0.5 MILS., GRN DIR.

| PSI                            | 2 THETA | TIME   | COR. TIME                    | D (A)   | VERTEX +- ST.DEV.  |
|--------------------------------|---------|--------|------------------------------|---------|--------------------|
| 0.000                          | 154.500 | 33.610 | 299.900                      |         |                    |
|                                | 155.000 | 32.500 | 259.407                      |         |                    |
|                                | 155.600 | 31.790 | 238.132                      |         |                    |
|                                | 156.300 | 31.910 | 242.704                      |         |                    |
|                                | 156.600 | 0.030  | 0.058                        | 1.17333 | 154.9737 +- 0.0014 |
| 45.000                         | 154.500 | 23.430 | 265.417                      |         |                    |
|                                | 155.000 | 22.590 | 216.042                      |         |                    |
|                                | 155.700 | 22.140 | 202.891                      |         |                    |
|                                | 156.400 | 22.520 | 242.511                      |         |                    |
|                                | 156.700 | 23.010 | 296.182                      | 1.17212 | 155.5144 +- 0.0031 |
| E/(1+V) = 24500. +- 441. (KSI) |         |        | STRESS = -50.7 +- 1.1 (KSI)  |         |                    |
| DELTA D = -0.00121 (A)         |         |        | STRAIN = -0.001035 (IN./IN.) |         |                    |

METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 2-18-12-MAX-1 LONG, SURFACE, REPOSITIONED, GRA DIP

| PSI   | 2 THETA | TIME   | COR. TIME | D (A)   | VERTEX +/- ST. DEV. |
|-------|---------|--------|-----------|---------|---------------------|
| 0.000 | 154.500 | 33.210 | 293.558   |         |                     |
|       | 155.000 | 32.420 | 264.624   |         |                     |
|       | 155.500 | 32.150 | 256.263   |         |                     |
|       | 156.000 | 32.630 | 273.883   |         |                     |
|       | 156.500 | 33.470 | 308.700   | 1.17235 | 155.4099 +/- 0.0057 |

|        |         |        |         |         |                     |
|--------|---------|--------|---------|---------|---------------------|
| 45.000 | 154.500 | 23.550 | 253.624 |         |                     |
|        | 155.000 | 22.730 | 209.642 |         |                     |
|        | 155.700 | 22.420 | 204.871 |         |                     |
|        | 156.100 | 22.500 | 217.075 |         |                     |
|        | 156.500 | 22.950 | 258.708 | 1.17219 | 155.4741 +/- 0.0039 |

$E/(1+\nu) = 24500. \pm 441. \text{ (KSI)}$  STRESS =  $-6.4 \pm 1.0 \text{ (KSI)}$

DELTA D =  $-0.00015 \text{ (A)}$  STRAIN =  $-0.000131 \text{ (IN./IN.)}$

METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 2-16-12-MAX

LONG., @ 1.0 MILS., GRN DIR.

| PSI   | 2 THETA | TIME   | COR. TIME | D (A)   | VERTEX +- ST.DEV. |
|-------|---------|--------|-----------|---------|-------------------|
| 0.000 | 155.000 | 33.570 | 301.842   |         |                   |
|       | 155.500 | 33.070 | 282.716   |         |                   |
|       | 156.000 | 32.800 | 273.561   |         |                   |
|       | 156.500 | 32.990 | 281.490   |         |                   |
|       | 157.000 | 33.500 | 302.903   | 1.17106 |                   |

155.9968 +-0.0084

|        |         |        |         |         |  |
|--------|---------|--------|---------|---------|--|
| 45.000 | 155.000 | 23.430 | 300.795 |         |  |
|        | 155.500 | 22.970 | 271.156 |         |  |
|        | 156.000 | 22.820 | 272.721 |         |  |
|        | 156.500 | 23.020 | 312.024 |         |  |
|        | 157.000 | 23.430 | 400.073 | 1.17172 |  |

155.6752 +-0.036

E/(1+V) = 24500. +- 441. (KSI)

STRESS = 27.6 +- 1.6 (PSI)

DELTA D = 0.00066 (A)

STRAIN = 0.000567 (IN./IN.)

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 2-18-12-MAX

LONG., @ 1.2 MILS., GRN DIR.

| PSI   | 2 THETA | TIME   | COR. TIME | D (A)   | VERTEX +- ST.DEV. |
|-------|---------|--------|-----------|---------|-------------------|
| 0.000 | 155.000 | 42.570 | 808.861   |         |                   |
|       | 155.500 | 42.220 | 751.045   |         |                   |
|       | 156.000 | 41.940 | 710.599   |         |                   |
|       | 156.700 | 42.350 | 782.657   |         |                   |
|       | 157.300 | 42.880 | 894.175   | 1.17114 |                   |

155.9580 +-0.055

|        |         |        |         |         |  |
|--------|---------|--------|---------|---------|--|
| 45.000 | 155.000 | 29.000 | 208.799 |         |  |
|        | 155.500 | 28.660 | 209.673 |         |  |
|        | 156.000 | 28.440 | 210.929 |         |  |
|        | 156.500 | 28.740 | 217.261 |         |  |
|        | 157.300 | 29.100 | 242.966 | 1.17184 |  |

155.6388 +-0.0062

E/(1+V) = 24500. +- 441. (KSI)

STRESS = 29.3 +- 1.8 (PSI)

DELTA D = 0.00070 (A)

STRAIN = 0.000597 (IN./IN.)

METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 2-18-12-MAX

LONG., @ 2.0 MILS., GRN DIR.

| PSI    | 2 THETA | TIME   | COR. TIME | D (A)   | VERTEX +/- ST.DEV. |
|--------|---------|--------|-----------|---------|--------------------|
| 0.000  | 155.000 | 44.190 | 925.783   |         |                    |
|        | 155.500 | 43.720 | 880.658   |         |                    |
|        | 156.000 | 43.570 | 854.400   |         |                    |
|        | 156.500 | 43.870 | 923.785   |         |                    |
|        | 157.000 | 44.880 | 1234.810  | 1.17150 | 155.7959 +/- .0034 |
| 45.000 | 155.000 | 33.370 | -2422.256 |         |                    |
|        | 155.500 | 33.070 | -2877.042 |         |                    |
|        | 156.000 | 32.880 | -2865.226 |         |                    |
|        | 156.700 | 32.920 | -1859.002 |         |                    |
|        | 157.000 | 33.030 | -1483.159 | 1.17170 | 155.7038 +/- .0010 |

E/(1+V) = 24500. +/- 441. (KSI)

STRESS = 8.5 +/- 0.4 (KSI)

DELTA D = 0.00020 (A)

STRAIN = 0.000173 (IN./IN.)

METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

RESIDUAL STRESS DEPTH CORRECTION ANALYSIS

1752-26887 5-15-51-MIN LONG., @ 2.0 MILS., GRN DIR.

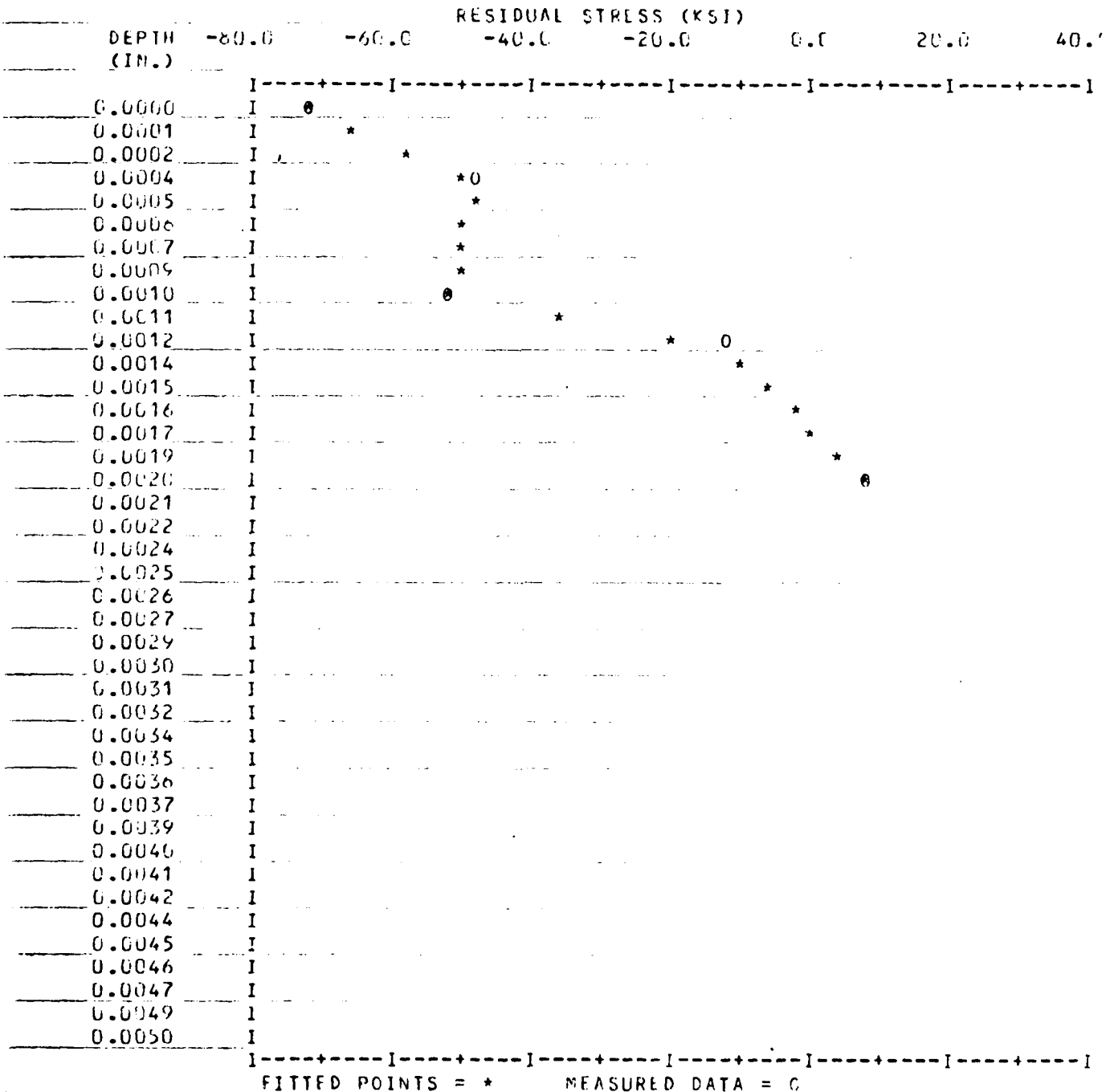
$E/(1+V) =$  24500.  $\pm$  441. (KSI)  $\mu =$  2196. (1/IN)

| DATA POINT | DEPTH<br>(IN.) | *****<br>MEASURED | RESIDUAL STRESS (KSI)<br>GRAD. CORRECTED | *****<br>RELAX. CORRECTED |
|------------|----------------|-------------------|------------------------------------------|---------------------------|
| 1          | 0.0000         | -61.5 $\pm$ 1.8   | -72.0                                    | -72.0                     |
| 2          | 0.0004         | -41.5 $\pm$ 1.5   | -48.1                                    | -48.0                     |
| 3          | 0.0010         | -33.0 $\pm$ 1.4   | -51.2                                    | -51.0                     |
| 4          | 0.0013         | 4.5 $\pm$ 1.0     | -11.3                                    | -11.0                     |
| 5          | 0.0020         | -18.5 $\pm$ 0.9   | 10.0                                     | 10.2                      |

METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI OHIO

X-RAY DIFFRACTION RESIDUAL STRESS ANALYSIS

1752-26887 5-15-51-MIN LONG. 2.0 MILS. GRN DIR.



METCUT RESEARCH ASSOCIATES I.N.C.  
CINCINNATI, OHIO

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 5-15-51-MIN

LONG, SURFACE, GRN DIR.

| PSI   | 2 THETA | TIME   | COR. TIME | D (A)   | VERTEX +- ST.DEV. |
|-------|---------|--------|-----------|---------|-------------------|
| 0.000 | 154.200 | 33.830 | 324.907   |         |                   |
|       | 154.700 | 32.760 | 279.958   |         |                   |
|       | 155.300 | 32.430 | 268.853   |         |                   |
|       | 155.800 | 32.760 | 282.096   |         |                   |
|       | 156.200 | 33.570 | 317.326   | 1.17274 |                   |
|       |         |        |           |         | 155.2340 +-0.0049 |

|        |         |        |         |         |                   |
|--------|---------|--------|---------|---------|-------------------|
| 45.000 | 155.000 | 23.370 | 381.148 |         |                   |
|        | 155.500 | 22.790 | 320.367 |         |                   |
|        | 156.000 | 22.370 | 291.299 |         |                   |
|        | 156.700 | 22.500 | 341.271 |         |                   |
|        | 157.000 | 22.980 | 458.229 | 1.17127 |                   |
|        |         |        |         |         | 155.8986 +-0.0026 |

E/(1+V) = 24500. +- 441. (KSI)

STRESS = -61.5 +- 1.8 (KSI)

DELTA D = -0.00147 (A)

STRAIN = -0.001255 (IN./IN.)

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 5-15-51-MIN

LONG., @ 0.4 MILS., FRN DIR.

| PSI   | 2 THETA | TIME   | COR. TIME | D (A)   | VERTEX +- ST. EV. |
|-------|---------|--------|-----------|---------|-------------------|
| 0.000 | 154.000 | 41.320 | 779.048   |         |                   |
|       | 154.500 | 40.760 | 689.449   |         |                   |
|       | 155.000 | 40.230 | 620.412   |         |                   |
|       | 155.500 | 40.300 | 632.392   |         |                   |
|       | 156.000 | 40.540 | 668.089   | 1.17261 |                   |
|       |         |        |           |         | 155.2944 +-0.0055 |

|        |         |        |          |         |                   |
|--------|---------|--------|----------|---------|-------------------|
| 45.000 | 155.000 | 27.780 | 1009.900 |         |                   |
|        | 155.500 | 27.420 | 882.245  |         |                   |
|        | 156.000 | 27.110 | 809.418  |         |                   |
|        | 156.500 | 27.160 | 985.448  |         |                   |
|        | 157.000 | 27.400 | 1590.387 | 1.17161 |                   |
|        |         |        |          |         | 155.7419 +-0.0071 |

E/(1+V) = 24500. +- 441. (KSI)

STRESS = -41.5 +- 1.5 (KSI)

DELTA D = -0.00099 (A)

STRAIN = -0.000847 (IN./IN.)

MECHT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 5-15-51-MIN

LONG., @ 1.0 MILS., GRN DIR.

| PSI   | 2 THETA | TIME   | COR. TIME | D (A)   | VERTEX +- ST.DEV. |
|-------|---------|--------|-----------|---------|-------------------|
| 0.000 | 154.500 | 35.470 | 415.147   |         |                   |
|       | 154.500 | 33.870 | 322.941   |         |                   |
|       | 155.000 | 33.210 | 294.806   |         |                   |
|       | 155.500 | 32.780 | 278.828   |         |                   |
|       | 156.000 | 33.190 | 296.059   | 1.17231 | 155.4277 +-0.0046 |

|        |         |        |         |         |                   |
|--------|---------|--------|---------|---------|-------------------|
| 45.000 | 155.000 | 23.640 | 329.376 |         |                   |
|        | 155.500 | 23.060 | 283.626 |         |                   |
|        | 156.000 | 22.940 | 289.796 |         |                   |
|        | 156.500 | 23.020 | 320.005 |         |                   |
|        | 157.000 | 23.290 | 388.944 | 1.17152 | 155.7852 +-0.0041 |

E/(1+V) = 24500. +- 441. (KSI)

STRESS = -33.0 +- 1.4 (KSI)

DELTA D = -0.00079 (A)

STRAIN = -0.000674 (IN./IN.)

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 5-15-51-MIN

LONG., @ 1.3 MILS., GRN DIR.

| PSI   | 2 THETA | TIME   | COR. TIME | D (A)   | VERTEX +- ST.DEV. |
|-------|---------|--------|-----------|---------|-------------------|
| 0.000 | 154.500 | 42.010 | 791.733   |         |                   |
|       | 155.000 | 41.550 | 717.504   |         |                   |
|       | 155.500 | 41.080 | 653.533   |         |                   |
|       | 156.000 | 41.280 | 684.453   |         |                   |
|       | 156.500 | 41.450 | 713.348   | 1.17166 | 155.7206 +-0.0060 |

|        |         |        |         |         |                   |
|--------|---------|--------|---------|---------|-------------------|
| 45.000 | 155.000 | 28.450 | 724.354 |         |                   |
|        | 155.500 | 25.210 | 236.221 |         |                   |
|        | 156.000 | 27.870 | 648.483 |         |                   |
|        | 156.500 | 27.960 | 762.304 |         |                   |
|        | 157.000 | 28.050 | 940.744 | 1.17177 | 155.6717 +-0.0036 |

E/(1+V) = 24500. +- 441. (KSI)

STRESS = 4.5 +- 1.0 (KSI)

DELTA D = 0.00011 (A)

STRAIN = 0.000092 (IN./IN.)

METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 5-15-51-MIN

LONG., @ 2.0 MILS., GRN DIP.

| PSI   | 2 THETA | TIME   | COR. TIME | D (A)   | VERTEX +- ST.DEV. |
|-------|---------|--------|-----------|---------|-------------------|
| 0.000 | 154.500 | 44.120 | 943.508   |         |                   |
|       | 155.000 | 43.840 | 885.667   |         |                   |
|       | 155.500 | 43.520 | 826.386   |         |                   |
|       | 156.000 | 43.750 | 876.914   |         |                   |
|       | 156.500 | 43.910 | 917.072   | 1.17199 | 155.5705 +-0.0071 |

|        |         |        |           |         |                   |
|--------|---------|--------|-----------|---------|-------------------|
| 45.000 | 155.000 | 29.960 | -2652.369 |         |                   |
|        | 155.500 | 29.480 | -5862.312 |         |                   |
|        | 155.953 | 29.320 | -5240.021 |         |                   |
|        | 156.500 | 29.520 | -1929.152 |         |                   |
|        | 157.000 | 29.660 | -1280.087 | 1.17155 | 155.7716 +-0.0005 |

E/(1+V) = 24500. +- 441. (KSI)

STRESS = -18.5 +- 0.9 (KSI)

DELTA\_D = -0.00044 (A)

STRAIN = -0.000378 (IN./IN.)

AD-A088 451

HUGHES HELICOPTERS CULVER CITY CALIF  
CONVENTIONAL MACHINING OF ESR 4340 STEEL.(U)  
JUL 80 K K NIJI  
HH-80-125

F/G 13/8

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USAAVRADCOM-TR-80-F-14

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2 of 2  
AD  
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NETCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

RESIDUAL STRESS DEPTH CORRECTION ANALYSIS

1752-26887 4-15-51-MAX LONG., @ 2.0 MILS., GRN DIR.

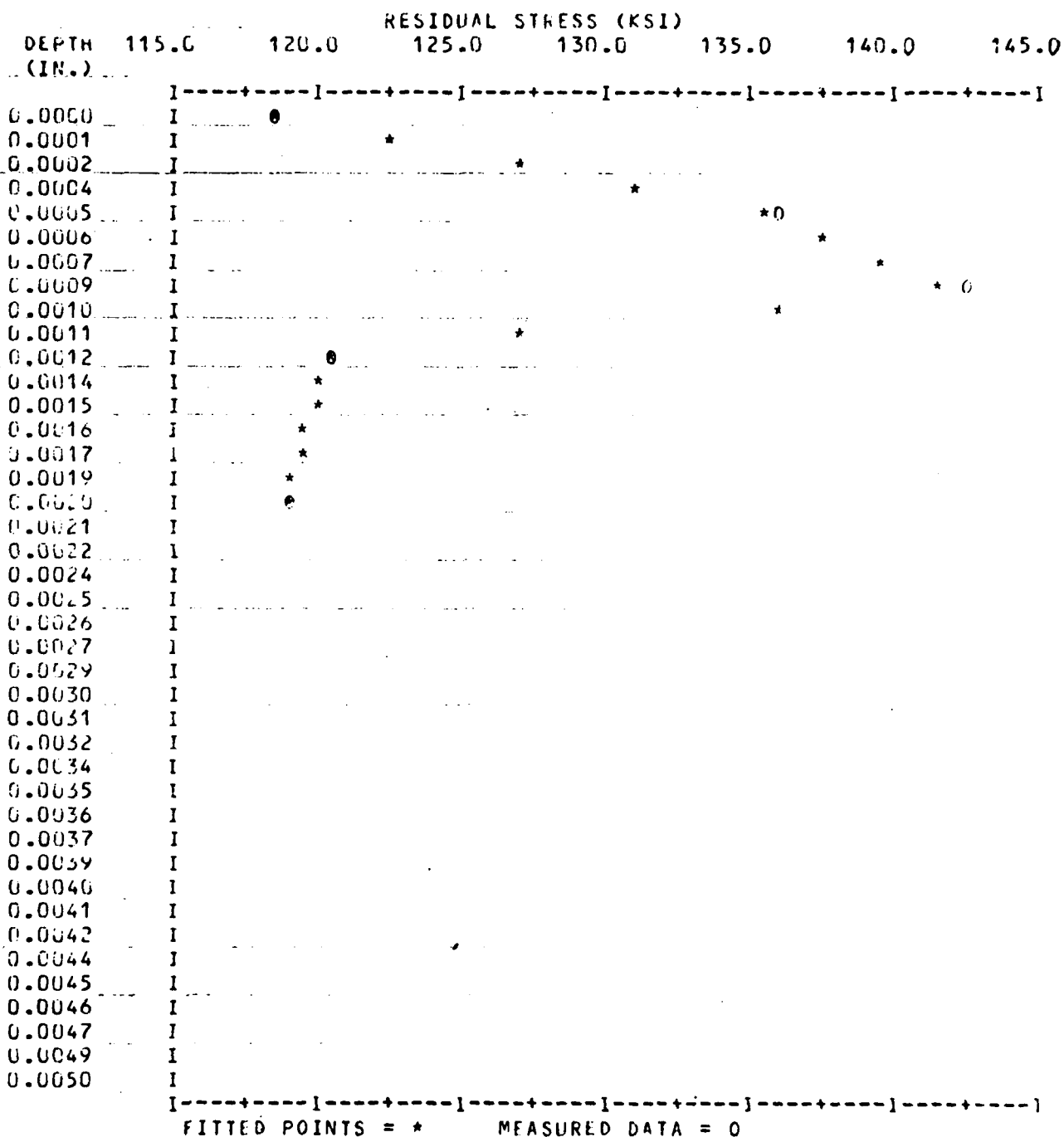
$E/(1+V) = 24500. \pm 441. \text{ (KSI)}$   $\mu = 2196. \text{ (1/IN)}$

| DATA POINT | DEPTH<br>(IN.) | ***** RESIDUAL STRESS (KSI) ***** |                 |                  |
|------------|----------------|-----------------------------------|-----------------|------------------|
|            |                | MEASURED                          | GRAD. CORRECTED | RELAX. CORRECTED |
| 1          | 0.0000         | 127.8 $\pm$ 3.0                   | 119.4           | 119.4            |
| 2          | 0.0005         | 138.0 $\pm$ 3.1                   | 136.8           | 136.5            |
| 3          | 0.0009         | 136.4 $\pm$ 3.0                   | 143.5           | 143.1            |
| 4          | 0.0012         | 114.5 $\pm$ 2.7                   | 122.0           | 121.3            |
| 5          | 0.0020         | 133.0 $\pm$ 2.7                   | 120.6           | 119.6            |

METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI OHIO

X-RAY DIFFRACTION RESIDUAL STRESS ANALYSIS

1752-26887 4-15-51-MAX LONG. 2.0 MILS., GRN DIR.



METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 4-15-51-MAX.

LONG, SURFACE, BURNED AREA, GRN DIR.

| PSI                            | 2 THETA | TIME   | COR. TIME                   | D (A)   | VERTEX +- ST.DEV. |
|--------------------------------|---------|--------|-----------------------------|---------|-------------------|
| 0.000                          | 156.300 | 32.420 | 291.593                     |         |                   |
|                                | 156.600 | 31.340 | 251.874                     |         |                   |
|                                | 157.300 | 31.140 | 246.075                     |         |                   |
|                                | 157.700 | 31.620 | 263.112                     |         |                   |
|                                | 158.000 | 32.050 | 279.848                     | 1.16852 | 157.1951 +-0.0048 |
| 45.000                         | 155.000 | 21.750 | 229.704                     |         |                   |
|                                | 155.500 | 21.120 | 199.203                     |         |                   |
|                                | 156.000 | 20.900 | 196.275                     |         |                   |
|                                | 156.500 | 21.160 | 224.667                     |         |                   |
|                                | 157.000 | 21.760 | 298.835                     | 1.17157 | 155.7619 +-0.0031 |
| E/(1+V) = 24500. +- 441. (KSI) |         |        | STRESS = 127.8 +- 3.0 (KSI) |         |                   |
| DELTA D = 0.00305 (A)          |         |        | STRAIN = 0.002607 (IN./IN.) |         |                   |

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 4-15-51-MAX

LONG., & 0.5 MILS, GRN DIR.

| PSI                            | 2 THETA | TIME   | COR. TIME                   | D (A)   | VERTEX +- ST.DEV. |
|--------------------------------|---------|--------|-----------------------------|---------|-------------------|
| 0.000                          | 156.500 | 29.790 | 207.165                     |         |                   |
|                                | 156.900 | 28.890 | 186.590                     |         |                   |
|                                | 157.300 | 28.540 | 179.607                     |         |                   |
|                                | 157.700 | 28.660 | 182.503                     |         |                   |
|                                | 158.100 | 29.600 | 204.358                     | 1.16825 | 157.3287 +-0.0050 |
| 45.000                         | 155.000 | 21.230 | 184.444                     |         |                   |
|                                | 155.500 | 20.270 | 150.180                     |         |                   |
|                                | 156.000 | 20.030 | 147.322                     |         |                   |
|                                | 156.500 | 20.500 | 173.290                     |         |                   |
|                                | 157.000 | 21.620 | 258.872                     | 1.17154 | 155.7759 +-0.0024 |
| E/(1+V) = 24500. +- 441. (KSI) |         |        | STRESS = 138.0 +- 3.1 (KSI) |         |                   |
| DELTA D = 0.00329 (A)          |         |        | STRAIN = 0.002816 (IN./IN.) |         |                   |

METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 4-15-51-MAX

LONG., @ 0.9 MILS., GRN DIP.

| PSI   | 2 THETA | TIME   | COR. TIME | D (A)   | VERTEX +- ST.DEV. |
|-------|---------|--------|-----------|---------|-------------------|
| 0.000 | 156.000 | 32.540 | 271.962   |         |                   |
|       | 156.500 | 30.770 | 218.096   |         |                   |
|       | 157.000 | 29.570 | 190.220   |         |                   |
|       | 157.500 | 29.650 | 192.488   |         |                   |
|       | 158.000 | 30.600 | 215.597   | 1.16838 | 157.2630 +-0.0036 |

|        |         |        |         |         |                   |
|--------|---------|--------|---------|---------|-------------------|
| 45.000 | 155.000 | 22.720 | 189.044 |         |                   |
|        | 155.500 | 22.020 | 166.584 |         |                   |
|        | 156.000 | 21.870 | 167.154 |         |                   |
|        | 156.500 | 22.110 | 184.209 |         |                   |
|        | 157.000 | 23.270 | 267.895 | 1.17164 | 155.7318 +-0.0029 |

E/(1+V) = 24500. +- 441. (KSI)

STRESS = 136.4 +- 3.0 (KSI)

DELTA D = 0.00325 (A)

STRAIN = 0.002784 (IN./IN.)

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 4-15-51-MAX

LONG., @ 1.2 MILS., GRN DIR.

| PSI   | 2 THETA | TIME   | COR. TIME | D (A)   | VERTEX +- ST.DEV. |
|-------|---------|--------|-----------|---------|-------------------|
| 0.000 | 156.300 | 31.350 | 227.624   |         |                   |
|       | 156.700 | 30.370 | 203.328   |         |                   |
|       | 157.300 | 29.850 | 192.335   |         |                   |
|       | 157.600 | 30.320 | 203.200   |         |                   |
|       | 157.900 | 30.460 | 206.850   | 1.16841 | 157.2511 +-0.0055 |

|        |         |        |         |         |                   |
|--------|---------|--------|---------|---------|-------------------|
| 45.000 | 155.000 | 22.020 | 186.349 |         |                   |
|        | 155.500 | 23.320 | 290.463 |         |                   |
|        | 156.000 | 20.000 | 126.003 |         |                   |
|        | 156.500 | 21.300 | 176.223 |         |                   |
|        | 157.000 | 22.380 | 252.775 | 1.17114 | 155.9592 +-0.0019 |

E/(1+V) = 24500. +- 441. (KSI)

STRESS = 114.5 +- 2.7 (KSI)

DELTA D = 0.00273 (A)

STRAIN = 0.002337 (IN./IN.)

METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO

FIVE POINT PARABOLIC DIFFRACTION PEAK STRESS ANALYSIS

1752-26887 4-15-51-MAX

LONG., @ 2.0 MILS., GRA DIP.

| PSI                            | 2 THETA | TIME   | COR. TIME                   | D (A)   | VERTEX +- ST.DEV. |
|--------------------------------|---------|--------|-----------------------------|---------|-------------------|
| 0.000                          | 156.000 | 43.910 | 1004.309                    |         |                   |
|                                | 156.500 | 43.030 | 811.831                     |         |                   |
|                                | 157.300 | 42.220 | 688.466                     |         |                   |
|                                | 157.600 | 42.530 | 736.001                     |         |                   |
|                                | 158.000 | 43.390 | 899.518                     | 1.16207 | 157.1221 +-0.0029 |
| 45.000                         | 155.000 | 29.360 | 1543.133                    |         |                   |
|                                | 155.500 | 28.930 | 1205.224                    |         |                   |
|                                | 156.000 | 28.820 | 1318.065                    |         |                   |
|                                | 156.500 | 28.970 | 2075.323                    |         |                   |
|                                | 157.000 | 29.250 | 9213.071                    | 1.17185 | 155.6362 +-0.0010 |
| E/(1+V) = 24500. +- 441. (KSI) |         |        |                             |         |                   |
|                                |         |        | STRESS = 133.0 +- 2.7 (KSI) |         |                   |
| DELTA D = 0.00317 (A)          |         |        | STRAIN = 0.002715 (IN./IN.) |         |                   |

APPENDIX E

HP 18-12, Hughes Helicopters specification for low stress grinding of high strength steel. This specification was released during the course of this program. It is included here as it was originally written. Based on the efforts of this program, some changes are recommended as discussed in the content of the report.

Hughes Helicopters  
division of su  
corporation

# ENGINEERING O' ER

E.O. NO. 32596

|            |  |                                                              |  |                                                                                                           |  |                                                              |  |
|------------|--|--------------------------------------------------------------|--|-----------------------------------------------------------------------------------------------------------|--|--------------------------------------------------------------|--|
| MODEL      |  | EFFECTIVE ON                                                 |  | E.O. TYPE                                                                                                 |  | AUTHORITY                                                    |  |
| All        |  | Record                                                       |  | Process Specification                                                                                     |  | MJO 0136                                                     |  |
|            |  | PARTS MAY BE REWORKED                                        |  | RECORD                                                                                                    |  | X                                                            |  |
|            |  | MADE OK TO USE                                               |  | NOTED                                                                                                     |  |                                                              |  |
| AFF. GROUP |  | SPECIFICATION AFFECTED                                       |  | ATP AFFECTED                                                                                              |  | INTERCHANGEABILITY AFFECTED                                  |  |
| NO.        |  | YES NO                                                       |  | YES NO                                                                                                    |  | YES NO                                                       |  |
|            |  | <input type="checkbox"/> <input checked="" type="checkbox"/> |  | <input type="checkbox"/> <input checked="" type="checkbox"/>                                              |  | <input type="checkbox"/> <input checked="" type="checkbox"/> |  |
| DOCUMENT   |  | REV.                                                         |  | SIGNIFICANT CHANGE                                                                                        |  | YES NO                                                       |  |
| HP 18-12   |  | New                                                          |  |                                                                                                           |  | <input type="checkbox"/> <input type="checkbox"/>            |  |
|            |  |                                                              |  | Low Stress Grinding of High Strength Steel (ESR 4340, 300M VAR 4340) at Strength Levels of 260 to 300 ksi |  |                                                              |  |
|            |  |                                                              |  | GROUP                                                                                                     |  | E.O. BY                                                      |  |
|            |  |                                                              |  | 18-10                                                                                                     |  | L. Soffa                                                     |  |
|            |  |                                                              |  | DATE                                                                                                      |  | 8-23-79                                                      |  |
|            |  |                                                              |  | NEXT ASSY.                                                                                                |  |                                                              |  |
|            |  |                                                              |  | APPROVED BY                                                                                               |  | DATE                                                         |  |
|            |  |                                                              |  | M. J. Soffa                                                                                               |  | 8/23/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/22/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8-23-79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/21/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/23/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8-23-79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/21/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/23/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8-23-79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/21/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/23/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8-23-79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/21/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/23/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8-23-79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/21/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/23/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8-23-79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/21/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/23/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8-23-79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/21/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/23/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8-23-79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/21/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/23/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8-23-79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/21/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/23/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8-23-79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/21/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/23/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8-23-79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/21/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/23/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8-23-79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/21/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/23/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8-23-79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/21/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/23/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8-23-79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/21/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/23/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8-23-79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/21/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/23/79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8-23-79                                                      |  |
|            |  |                                                              |  | P. J. Soffa                                                                                               |  | 8/21/79                                                      |  |
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| REVISIONS |                       |          |          |
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| LTR       | DESCRIPTION           | DATE     | APPROVED |
| New       | Released on EO 132596 | 08/23/79 |          |

SCOPE: This process specification establishes the requirements and procedures for grinding hardened steel and chrome-plated steel parts by surface, cylindrical, and centerless grinding methods using bonded abrasive wheels. This process is specifically intended for grinding of ESR 4340, 300M, and VAR 4340 steels at strength levels of 260 to 300 ksi.

|         |                       |                                                                                                                                                |                |                                                              |      |
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| PREP    | <i>J. Solera</i>      |  <b>Hughes Helicopters</b><br>Division of Summa Corporation |                | Centinela and Teale Streets<br>Culver City, California 90230 |      |
| APPD    | <i>J.C. [unclear]</i> |                                                                                                                                                |                |                                                              |      |
| 8/21/79 | <i>E.J. Salati</i>    | <b>TITLE LOW STRESS GRINDING OF HIGH STRENGTH STEEL (ESR 4340, 300M AND VAR 4340) AT STRENGTH LEVELS OF 260 TO 300 KSI</b>                     |                |                                                              |      |
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**Hughes Helicopters**  
Division of Summa Corporation

Centinela and Teale Streets  
Culver City California 90230

## PROCESS SPECIFICATION

### 1. SCOPE

1.1 This process specification establishes the requirements and procedures for grinding hardened steel and chrome-plated steel parts by surface, cylindrical, and centerless grinding methods using bonded abrasive wheels. This process is specifically intended for grinding of ESR 4340, 300M, and VAR 4340 steels at strength levels of 260 to 300 ksi.

1.2 Classification. The steels covered by the requirements of this specification are listed by AISI and HH designations and by heat-treat ranges.

| <u>AISI<br/>Designation</u> | <u>HH<br/>Designation</u> | <u>Heat Treat Range</u>                        |
|-----------------------------|---------------------------|------------------------------------------------|
| 4340                        |                           | 260 to 280 ksi<br>(1793 to 1931 MPa)           |
| 300M                        |                           | 280 to 300 ksi<br>(1931 to 2069 MPa)           |
|                             | 4340 ESR                  | R <sub>c</sub> 54 (280 ksi, min)<br>(1931 MPa) |

### 2. APPLICABLE DOCUMENTS

2.1 Government documents. The following documents, of the issue in effect on date of the invitation for bids or request for proposal, form a part of this specification to the extent specified herein. In case of conflict between these documents and this specification, the requirements of this specification shall prevail.

#### SPECIFICATIONS

##### Military

MIL-H-6875

Heat Treatment of Steels (Aerospace Practice, Process for

MIL-S-8844

Steel Bars, Reforging Stock and Mechanical Tubing, Low Alloy, Premium Quality

|                         |                                                                                                                  |               |             |
|-------------------------|------------------------------------------------------------------------------------------------------------------|---------------|-------------|
| CODE IDENT NO.<br>02731 | LOW STRESS GRINDING OF HIGH STRENGTH<br>STEEL (ESR 4340, 300M, VAR 4340) AT<br>STRENGTH LEVELS OF 260 TO 300 KSI | HP 18-12      | REV.<br>New |
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**Hughes Helicopters**  
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Culver City, California 90230

## PROCESS SPECIFICATION

2.1.1 Copies of specifications, standards, drawings, and publications required by suppliers in connection with specified procurement functions should be obtained from the procuring activity or as directed by the contracting officer.

2.2 Non-Government documents. The following documents form a part of this specification to the extent specified herein. Unless otherwise indicated, the issue in effect on date of invitation for bids or request for proposal shall apply. In case of conflict between these documents and this specification, the requirements of this specification shall prevail.

### SPECIFICATIONS

#### Industry

##### Hughes Helicopters

|            |                                                             |
|------------|-------------------------------------------------------------|
| HP 1-1     | Heat Treatment of Steels Nickel Base and Cobalt-Base Alloys |
| HP 1-9     | Hydrogen Embrittlement Relief                               |
| HP 4-1     | Corrosion and Handling Protection                           |
| HP 6-5     | Magnetic Particle Inspection                                |
| HP 6-19    | Hardness Testing of Metals                                  |
| HP 9-25    | Vapor Degreasing                                            |
| HP 30-4    | Etching for Detection of Grinding Burns                     |
| HMS 6-1121 | 4340 ESR Steel                                              |

### OTHER PUBLICATIONS

#### American Society for Metals

Metals Handbook  
(8th Edition - Volume 3)

Machining

|           |               |             |                                                                                                                  |                |
|-----------|---------------|-------------|------------------------------------------------------------------------------------------------------------------|----------------|
| <b>HP</b> | 18-12         | REV.<br>New | LOW STRESS GRINDING OF HIGH STRENGTH<br>STEEL (ESR 4340, 300M, VAR 4340) AT<br>STRENGTH LEVELS OF 260 TO 300 KSI | CODE IDENT NO. |
|           | SHEET 4 of 10 |             |                                                                                                                  | 02731          |



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## PROCESS SPECIFICATION

### Machining Data Center

MDC 78-103

Low Stress Grinding  
for Quality Production

### 3. REQUIREMENTS

#### 3.1 Equipment

3.1.1 Machines. Grinding machines used shall be equipped with:

a. Positive controls to maintain feed and speed limitations during processing.

b. A system providing continuous filtered coolant flow at the part/grinding wheel interface.

c. Tooling capable of holding parts in a completely rigid position during processing.

3.1.2 Grinding wheels. Wheels used shall be vitrified-bonded, aluminum oxide, or equivalent, as described in the ASM Handbook on machining and in MDC 78-103, and shall have an appropriate grit size to produce the desired finish.

#### 3.2 Procedures

3.2.1 Cleaning. Parts shall be cleaned in accordance with the requirements of HP 9-25 (do not anodic clean) prior to grinding.

3.2.2 Dressing. Grinding wheels shall be dressed, as necessary, but always prior to rough and finish grinding.

3.2.3 Grinding. All grinding shall be performed on the periphery surface of the grinding wheel only. Grinding on the flat side of the wheel shall be forbidden.

3.2.4 Coolant. Coolant shall be supplied continuously across the width of the grinding wheel and directly into the part/wheel interface. The direction of coolant flow shall coincide with wheel rotation.

|                             |                                                                                                                  |               |      |
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FORM 1642B



**Hughes Helicopters**  
Division of Summa Corporation

Centinela and Teale Streets  
Culver City, California 90230

## PROCESS SPECIFICATION

3.2.5 High spots. Prior to starting the grinding operation, high spots on the part shall be located to avoid accidental excessive infeed during grinding.

### 3.3 Grinding requirements

3.3.1 Surface and cylindrical grinding. All surface and cylindrical grinding shall be accomplished in accordance with 3.3.1.1 and 3.3.1.2 herein.

3.3.1.1 Limitations. Surface and cylindrical grinding limitations shall be as specified in Table I.

3.3.1.2 Technique data cards. Surface and cylindrical grinding shall meet the requirements of a technique data card established for each part and shall be maintained at the vendor facility for HH review.

3.3.1.2.1 The technique specified on the data card shall have been demonstrated to produce ground surfaces in conformance to the requirements of the engineering drawing.

3.3.1.2.2 A record of all changes in technique data cards showing effectivity (date or serial number) shall be maintained. The technique data card shall include the following information and other pertinent data as required:

- a. Part number.
- b. Outline of surfaces to be ground.
- c. Grinding machines authorized for use.
- d. Required tooling.
- e. Wheel speed.
- f. Workpiece (part) speed.
- g. Infeed rates.
- h. Cross feed.
- i. Wheel dressing practice, including number of passes between redressing for both rough and finish grinding.
- j. Coolant-type, supply rate, and nozzle location.

|                 |               |                                                                                                                  |                |
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## PROCESS SPECIFICATION

### NOTE

Tolerances shall be noted for feeds and speeds.

**TABLE I SURFACE AND CYLINDRICAL GRINDING  
LIMITATIONS FOR HARDENED STEEL AND  
CHROME PLATE ON HARDENED STEEL**

| Parameter                                      | Chrome Plate                                 | ESR 4340 and 300M                            |                                      | 4340 at 260-280 ksi                          |          |
|------------------------------------------------|----------------------------------------------|----------------------------------------------|--------------------------------------|----------------------------------------------|----------|
| Wheel Grade                                    | I or softer                                  | I or softer                                  |                                      | J or softer                                  |          |
| Wheel Speed<br>SFPM, Max                       | Internal cylindrical - 6000<br>Other - 4000  | Low-under 3500                               |                                      | Low-under 3500                               |          |
| Work Speed<br>SFPM, Max                        | 150                                          | 80                                           |                                      | 80                                           |          |
| Gross Feed -<br>Surface, Inch per<br>Pass, Max | 0.100                                        | 0.100                                        |                                      | 0.100                                        |          |
| Cylindrical, Exter-<br>nal and Internal        | 1/4 wheel width per part<br>revolution, max. | 1/4 wheel width per part<br>revolution, max. |                                      | 1/4 wheel width per part<br>revolution, max. |          |
| Infeed (Downfeed)<br>Inch per Pass, Max.       | 0.0002                                       | Surface and External<br>Cylindrical          | Internal                             | Surface and External<br>Cylindrical          | Internal |
| Rough                                          |                                              | 0.0007 to within<br>0.005 inch of finish     | 0.0005 to<br>0.005 inch<br>of finish | 0.0008                                       | 0.0004   |
| Finish                                         |                                              | 0.0003                                       | 0.0002                               | 0.0008                                       | 0.0004   |
| Grinding Fluid                                 | Oil base types shall be used.                |                                              |                                      |                                              |          |

### CAUTION

Centerless grinding will produce multi-lobe conditions on parts. Caution must be exercised to determine actual lobing condition as this will effect actual diameter of the part.

**3.3.2 Centerless grinding.** All centerless grinding shall be accomplished in accordance with 3.3.2.1 and 3.3.2.2 herein.

**3.3.2.1 Limitations.** Centerless grinding limitations shall be as specified in Table II.

|                         |                                                                                                                  |               |             |
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FORM 1642B



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## PROCESS SPECIFICATION

TABLE II. CENTERLESS GRINDING LIMITATIONS FOR  
HARDENED STEEL AND CHROME PLATE ON  
HARDENED STEEL

| Parameter                                                                             | Chrome Plate                  | Hardened Steel |
|---------------------------------------------------------------------------------------|-------------------------------|----------------|
| Wheel Grade                                                                           | I or softer                   | I or softer    |
| Wheel Speed<br>SFPM, Max.                                                             | 4000                          | Low-under 3500 |
| Diametric metal<br>removal rate per<br>pass, inch per<br>inch of wheel<br>width, max. |                               |                |
| Rough (to within<br>0.002 inch of<br>finish)                                          | 0.0003                        | 0.0005         |
| Finish                                                                                | 0.0008                        | 0.0008         |
| Grinding Fluid                                                                        | Oil base types shall be used. |                |

3.3.2.2 Technique data cards. Centerless grinding shall meet the requirements of a technique data card established for each part.

3.3.2.2.1 The technique specified on the data card shall have been demonstrated to produce ground surfaces in conformance to the requirements of the engineering drawing.

3.3.2.2.2 A record of all changes in technique data cards showing effectivity (date or serial number) shall be maintained. The technique data card shall include the following information and other pertinent data as required:

- Part number.
- Outline of surfaces to be ground.
- Grinding machines authorized for use.
- Required tooling.

|                 |               |                                                                                                                  |                |
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## PROCESS SPECIFICATION

- e. Wheel speed.
- f. Part through feed speed.
- g. Regulating wheel angle.
- h. Vertical position and rake angle of work-rest blade.
- i. Metal removal rate per pass.
- j. Wheel dressing practice, including number of passes between redressing for both rough and finish grinding.
- k. Coolant - type, supply rate, and nozzle location.

### NOTE

Tolerances for operating variables shall be noted.

#### 4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for inspection. Unless otherwise specified in the contract or order, the supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified, the supplier may utilize his own facilities or any commercial laboratory acceptable to Hughes Helicopters. Hughes Helicopters reserves the right to perform any of the inspections set forth in the specification where such inspections are deemed necessary to assure that suppliers and services conform to prescribed requirements.

4.2 Test methods. Tests and inspections shall be performed to assure conformance to the requirements of Section 3.

#### 4.3 Acceptance inspection.

4.3.1 Etching of hardened steel. The following inspections shall be performed after grinding of unplated steel.

a. Surfaces of parts ground after hardening shall be etched in accordance with HP 30-4 and inspected for surface effects. Etching shall be performed prior to any operation altering the ground surface, including but not limited to polishing, honing, lapping, shot peening and heating.

|                             |                                                                                                                  |          |             |
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## PROCESS SPECIFICATION

b. Parts shall be embrittlement relieved in accordance with HP 1-9 prior to honing, lapping, shot peening, and plating when etching is performed in accordance with HP 30-4.

c. Parts and stock etched in accordance with HP 30-4 shall be examined visually in good light by qualified personnel. Surfaces of parts and stock shall be uniform in color and free of the following indications:

- (1) Dark areas - Indicative of overtempering.
- (2) Light area within dark area - Indicative of the presence of a rehardened zone from heat generated during grinding surrounded by a transition zone of annealed and overtempered metal.
- (3) Cracks - Indicative of presence of high stresses induced during grinding.

Parts and stock showing any of the above indications shall be rejected.

4.3.2 Magnetic particle inspection. Parts shall be magnetic particle inspected in accordance with HP 6-5 after grinding.

4.4 Records. Records shall be retained for 3 years after completion of the contract.

4.5 Reports. Unless otherwise specified, the vendor of the product shall furnish with each shipment three copies of a report of the results of all tests performed for determining conformance to the technical requirements of this specification. This report shall include the purchase order number material specification number with revision date, and size and quantity from each heat. When forgings are supplied, the lot number and part number, shall be included in the report.

### 5. PREPARATION FOR DELIVERY

5.1 All parts shall be processed in accordance with HP 4-1 prior to delivery or storage.

### 6. NOTES

### 7. APPROVED VENDORS

7.1 Only vendors listed on Hughes Helicopters Approved Vendors List (AVL) 18-12 shall perform this process.

|    |       |             |                                                                                                                  |                             |
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Cutting rates  
Cutting fluids  
Turning

This program involved the study of conventional machining of heat treated ESR 4340 steel (Rc 54-57). Initial effort involved a survey of available data regarding the machining of high strength steels with hardnesses of Rc 50 and above. A machining program was conducted, determining optimum tools and conditions for turning, drilling, face milling, and grinding operations. Effects of various parameters including cutting speeds, feeds, depths of cut, and cutting fluids on tool life was determined. All the operations were found to be extremely difficult and application of conventional procedures is not feasible. Tool lives remained short despite reductions in speeds and feeds. Conventional grinding methods induced detrimental residual tensile stresses along the surface, resulting in cracking, lapping, and untempered martensitic structures. Low stress grinding techniques were found to be applicable to this material when proper dressing procedures and reduced rates were used.

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