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SURFACE INTEGRITY - A NEW REQUIREMENT FOR IMPROVING RELIABILITY OF AEROSPACE HARDWARE

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1. Introduction

The quality of a machined surface is becoming more and more important to satisfy the increasing demands of sophisticated hardware performance, longevity, and reliability. Aerospace structures are being subjected to more severe conditions of stress, temperature, and hostile environments. Section size is being reduced in response to the goal of reduced weight so that the surface condition of a component has an increasing influence on its performance. In response to the above needs, there has been a continued development and use of heat resistant, corrosion resistant, and high strength alloys in a wide variety of structural applications. These alloys include high strength steels heat treated to strength levels up to 300,000 psi, stainless steels, titanium alloys and nickel and cobalt base high temperature alloys.

Dynamic loading is a principle factor in the design of modern structures, and accordingly design capabilities are frequently limited by the fatigue characteristics of structural materials. Service histories and failure analyses of dynamic components indicate that fatigue failures almost always nucleate on or near the surface of the component. In considering stress corrosion resistance, it is also recognized that the surface of the component is a primary factor in determining susceptibility to attack and subsequent failure.

Modern production methods, both conventional and those which are electrically assisted, have been developed to process the highest strength and high temperature alloys which have evolved in recent years. These newer high performance materials have generally become inherently "more difficult" to machine. At the same time, advanced designs have necessitated the requirement for holding closer dimensional control of large surfaces as well as in areas of more intricate and complex geometry. Considering the nature of the advanced materials, the difficulty in machining these high strength materials and the sensitivity of component surfaces inherent in many processing operations in which these parts are subjected, the need for paying careful attention to the surfaces of finished hardware is brought critically into focus.

1. Introduction (continued)

When machining a component, it is necessary to satisfy the surface integrity requirements. Surface integrity has two important parts. The first is surface texture which is a measure of surface roughness or surface topography. The second is surface metallurgy which is a study of the nature of the surface layer produced in machining. Both aspects of surface integrity are important as they in many cases control the strength and performance of structural components.

Surface integrity is defined as the inherent or enhanced condition of a surface produced by machining or other generating operation. When a component is machined, the surface may contain metallurgical alterations. These alterations are generally quite shallow, usually .0002 in. to .006 in. in depth. It has been found that the alterations may have a decided effect on distortion of a component and its mechanical properties.

2. Types of Surface Alterations

The types of surface alterations associated with conventional and nonconventional metal removal practices include the following:

1. Plastic deformation as a result of hot or cold work.
2. Tears, laps, and crevice-like defects associated with the "built-up edge" produced in machining.
3. Recrystallization.
4. Change in hardness of the surface layer.
5. Phase transformations.
6. Intergranular attack and preferential solution of microconstituents.
7. Microcracking and macrocracking.
8. Residual stress distribution in the surface layer.
9. Embrittlement by chemical absorption of elements such as hydrogen or halogens.
10. Spattered coating of remelted metal deposited on the surface during electrical discharge, electron beam, or laser machining.

The principal causes of the above surface alterations produced by the machining processes are:

2. Types of Surface Alterations (continued)

1. High temperatures or high temperature gradients developed in the machining processes.
2. Plastic deformation.
3. Chemical reactions and subsequent absorption into the nacent machined surface.

3. Examples of Surface Alterations

A summary of the possible surface alterations encountered by conventional and nontraditional metal removal methods are summarized in Table I.

3.1 Conventional Machining Operations

Examples will be cited of the variety of surface layer changes that can occur as a function of gentle versus abusive machining. In chip removal operations such as milling or drilling, the gentle operations are those employing machining conditions which provide long tool life and use a sharp tool (the tool is removed long before it gets too dull). Abusive chip removal conditions, in contrast, are those in which a dull tool is used.

In surface grinding, gentle conditions are those which keep the grinding wheel sharp, while abusive conditions are those which promote wheel dulling. In grinding, there are four important parameters which affect gentle or abusive grinding. They are: wheel grade, wheel speed, downfeed, and grinding fluid.

Gentle and abusive conditions used for surface grinding and face milling steels and titanium are indicated in Tables 2 and 3.

Figure 1 shows the important surface alterations produced by gentle and abusive grinding of 4340 steel, 50 R_C.(1)* Using gentle conditions, as in Table 2, no metallurgical alterations were present. However, when abusive grinding conditions were employed, an untempered martensite layer was produced to a depth of .001 in. Below this untempered martensite an overtempered martensite zone approximately .004 in. deep was produced. The untempered martensite had a hardness of 60 R_C,

*Numbers in parentheses indicate references.

3.1 Conventional Machining Operations (continued)

while the overtempered martensite zone had a reduced hardness of 46 R_c. Under conventional grinding conditions, a very shallow untempered martensite zone was produced by overheating. Abusive drilling and milling of 4340 steel, 50 R_c tended to likewise produce an untempered martensite zone with an underlying overtempered martensite area, Figures 2 and 3.[1]

The presence of either untempered or overtempered martensite on the surface of high strength steels is extremely detrimental to fatigue strength and stress corrosion susceptibility as will be described later.

Additional examples of surface alterations produced by conventional machining are shown in Figures 4 and 5. When abusive drilling of aged 18% nickel maraging steel, 52 R_c an overaged resolutioned layer .001 in. deep was produced at the surface. The hardness of the layer was 37 R_c, Figure 4. Abusive milling of Ti-6Al-4V produced an overheated surface layer about .0015 in. deep. This surface layer was 12 points softer than the base metal. Abusive machining can also produce cracks, laps and tears, or crevice-like defects, see Figure 6.

In general, abusive machining conditions tend to promote higher temperature and/or excessive plastic deformation in metal cutting. Many of the adverse effects are readily evaluated by examination of the surface layer microstructure. The microstructural alterations are usually quite shallow, in many cases less than .001 in. It is, therefore, necessary to employ special procedures for sectioning and mounting specimens so as to maintain edge retention of the critical surface that is to be examined. Special mounting and etching techniques have been developed for this purpose.[2]

3.2 Nonconventional Machining Processes

Electrical discharge machining (EDM) tends to produce a surface which contains a layer of recast spattered metal which is usually hard and cracked. This recast metal is generally quite porous and in many cases contains cracks. The cracks sometimes extend into the base metal, see Figures 6 and 7. Below the spattered and recast metal, it is possible to have the same surface alterations that occur in abusive machining. Other thermal processes such as electron beam machining and laser beam machining tend to produce the same types of surface alterations as EDM.

Electrochemical machining (ECM) is capable of producing a surface which is essentially free of metallurgical surface layer alterations. However, when ECM goes out of control, selective etching or intergranular attack can occur, Figure 6. Abusive (out-of-control) ECM conditions also tend to promote surface roughness. Accidents in ECM can also lead to dangerous surface alterations. A short circuit between the electrode and the work can cause extreme overheating and intergranular cracks. Electrochemical machining also has a tendency to produce a soft layer at the surface. Surface softening of .001 in. to .002 in. deep is also produced by electropolishing and by chemical milling.

4. Residual Stress and Distortion

The machining process imparts a machining stress in a surface layer which has been found to strongly influence the distortion. In grinding, the residual stress tends to be tensile when abusive conditions are used, Figure 8. Notice that the stress may be zero at the surface but becomes tensile below the surface. By using gentle grinding conditions, this stress can be reduced in magnitude and may even become compressive. The greater the area under the residual stress curve, the greater the distortion of the work, compare Figures 8 and 9.

In milling, the residual stress tends to be compressive which, in turn, produces a distortion in the compressive direction on the workpiece. The magnitude of the residual stress and the distortion is also a function of the material being machined. The relative distortion produced by grinding and face milling of three steels and a titanium alloy is given in Figure 10. [3] The abusive grinding and milling produced large distortions compared to gentle machining conditions, see Tables 2 and 3. It is also of interest to note that the maraging steel produced far less distortion than the other alloys and that the titanium produced far more distortion under abusive machining conditions.

5. Effect on Mechanical Properties

The mechanical property which is most sensitive to machining practice is the high cycle fatigue strength. Extensive investigations have been performed on high strength steels. It has been found that abusive grinding of 4340 steel at 50 R_C can reduce the endurance limit by 35% with respect to low stress or gentle grinding. (1) When abusive grinding, there is a tendency to form patches of untempered martensite (UTM) or overtempered martensite (OTM) on the surface. It has been found that the presence of as little as .0005 in. or as much as .0035 in. of either UTM or OTM reduces the endurance limit from 110 ksi down to 70 or 75 ksi, Figure 11. A major reduction in high cycle fatigue strength or endurance limit is produced by abusive grinding of most of the aerospace alloys, Figure 12. (4, 5) When compared with gentle conditions, reductions in endurance limit of titanium alloys are over three times. Very high reductions in endurance limit are also obtained by abusive grinding of nickel base alloys. It should be pointed out that gentle grinding of all the alloys tends to produce the highest fatigue strength possible of any machining operation. The effect of end milling practice on the fatigue strength of various alloys is given in Figure 13. (5) When end milling with the periphery of a cutter, the abusive condition (primarily cutter dulling) tends to significantly reduce fatigue strength. However, when end milling with the end of the cutter, there is very little difference between gentle and abusive conditions. The relative endurance limit of low stress or gentle surface grinding compared to end milling is also shown in Figure 13. (5)

Electrical discharge machining (EDM) produces a marked decrease in endurance limit when compared with low stress grinding, Figure 14. (5) There was little difference in fatigue properties of roughing or finishing EDM conditions. Electrochemical machining (ECM) also produces a decrease in fatigue strength but not as great as that caused by EDM, Figure 15. (5)

The stress corrosion susceptibility of the high strength steels has also been found to be dependent on the presence of untempered or overtempered martensite. The testing for stress corrosion resistance of materials is somewhat difficult since failures by this phenomenon tend to occur over a period of months or years. The presence of UTM or OTM especially in drilled or reamed holes has been found to be one of the major causes of delayed failure on high strength steels.

6. Improvement in Reliability by Control of Surface Integrity

It is obvious that in order to maintain and/or improve reliability of aerospace hardware, it is necessary to first have a knowledge of the effects of surface integrity on the engineering properties of aerospace alloys. The presence of undesirable surface alterations on the fatigue strength and stress corrosion of high strength steels, titanium alloys, and nickel and cobalt base high temperature alloys has been demonstrated. In order to insure high surface integrity, it is necessary under the present state of technology to employ process control.

In order to accomplish this, surface integrity guidelines [6] have been prepared to act as a guide for metal removal operations. Many companies are controlling machining conditions by adding process specifications to metal removal operations. This is particularly important when machining high strength steels or when employing critical operations such as electrical discharge machining and electrochemical machining. Another important method of insuring high quality surface integrity is shot peening which produces a cold worked compressive stress layer. Such a layer generally improves fatigue strength and stress corrosion properties.

It is important also to provide quality control by inspection processes on machined components. Unfortunately, there is a limited number of practical nondestructive testing techniques available for inspection. For example, untempered and overtempered martensite can be determined by a macroetching technique. But this is, of course, only applicable to steels. Penetrant inspection procedures are available for inspection of relatively large cracks. Also there appears to be an extensive development in ultrasonic and eddy current devices for detection of the surface alterations, but there is a need for extensive development to produce reliable NDT equipment for positive identification of surface alterations.

There is also need for a more thorough identification of surface topography. At present, the only practical specification for surface roughness is based upon data produced by a stylus instrument. It is necessary, of course, to determine the surface roughness on the entire surface. On structural applications, the nature of the troughs of the surface is most important; while on bearing applications, the nature of the crests of the surface is more significant. Additional investigations are needed to determine a relation of surface roughness requirements to the application of a component. Some work has been done correlating surface roughness with frictional and bearing applications. However, very little work has been done determining

6. Improvement in Reliability by Control of Surface Integrity (continued)

the relation between surface roughness per se to the fatigue properties and stress corrosion susceptibility of materials. Finally, there is evidence that machining operations and resulting surface layer conditions affect crack initiation and crack propagation and, hence, fracture toughness of material.

7. Conclusions

In order to improve the reliability of mechanical hardware, it is first necessary to be aware of the possible damage or surface alterations that can be imparted to a material when it is machined by conventional or nonconventional methods. It is then necessary to control the machining operation to minimize undesirable surface damage. It is possible at times to apply post machining operations such as heat treating or shot peening to impart conditions which will provide a predetermined desirable surface which may guarantee consistent desirable mechanical and physical properties.

Until more definite relationships between machining and its effect are developed, guidelines for machining should be used to institute some degree of process control. Such a set of guidelines have been prepared (6) and will be supplemented from time to time.

Finally, it must be emphasized that conditions for developing surface integrity should not be imposed unless service requirements so dictate. Also, experience has shown that it is highly desirable to develop surface integrity data for specific situations. Only in the absence of specific data should general guidelines be employed or considered for manufacture of critical components.

REFERENCES

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4. Koster, W. P.; Field, Michael; Fritz, L. J.; et al. 1970. Surface integrity of machined structural components. AFML-TR-70-11. Cincinnati, Ohio: Metcut Research Associates Inc.

5. Koster, W. P., and Kohls, J. B. 1972. Relation of surface integrity to cost and reliability of structural components. SME Paper No. IQ72-207. Dearborn, Michigan: Society of Manufacturing Engineers.

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TABLE 1 - SUMMARY OF POSSIBLE SURFACE ALTERATIONS ENCOUNTERED BY METAL REMOVAL PROCESSES

Material	Conventional Metal Removal Methods: Milling, Drilling or Turning	Grinding	Nontraditional Removal Methods: EDM	ECM & CHM
Steels				
Nonhardenable (1018)	Roughness Plastic Deform. Laps and Tears	Roughness Plastic Deform.	Roughness Microcracks Recast Metal	Roughness Selective Etch Intergranular Attack
Hardenable (Alloy) (4340) (D6ac)	Roughness Plastic Deform. Laps and Tears Microcracks Untemp. Mart. Overtemp. Mart.	Roughness Plastic Deform. Microcracks Untemp. Mart. Overtemp. Mart.	Roughness Microcracks Recast Metal Untemp. Mart. Overtemp. Mart.	Roughness Selective Etch Intergranular Attack
Tool Steel, D2	Roughness Plastic Deform. Laps and Tears Microcracks Untemp. Mart. Overtemp. Mart.	Roughness Plastic Deform. Microcracks Untemp. Mart. Overtemp. Mart.	Roughness Microcracks Recast Metal Untemp. Mart. Overtemp. Mart.	Roughness Selective Etch Intergranular Attack

Abbreviations:

Plastic Deform. - Plastic Deformation
Untemp. Mart. - Untempered Martensite
Overtemp. Mart. - Overtempered Martensite

(Table 1 - page 1)

TABLE 1 - SUMMARY OF POSSIBLE SURFACE ALTERATIONS ENCOUNTERED BY METAL REMOVAL PROCESSES (cont.)

Material	Conventional Metal Removal Methods: Milling, Drilling or Turning	Conventional Metal Removal Methods: Grinding	Nontraditional Removal Methods: EDM	Nontraditional Removal Methods: ECM & CHM
Stainless (Martensitic) (410)	Roughness Plastic Deform. Laps and Tears Microcracks Untemp. Mart. Overtemp. Mart.	Roughness Plastic Deform. Microcracks Untemp. Mart. Overtemp. Mart.	Roughness Microcracks Recast Metal Untemp. Mart. Overtemp. Mart.	Roughness Selective Etch Intergranular Attack
Stainless (Austenitic) (302)	Roughness Plastic Deform. Laps and Tears	Roughness Plastic Deform.	Roughness Microcracks Recast Metal	Roughness Selective Etch Intergranular Attack
Precipitation Hardening (17-4PH)	Roughness Plastic Deform. Laps and Tears Overaging	Roughness Plastic Deform. Overaging	Roughness Microcracks Recast Metal Overaging	Roughness Selective Etch Intergranular Attack
Maraging (18% Ni) (250 Grade)	Roughness Plastic Deform. Laps and Tears Resolutioning Overaging	Roughness Plastic Deform. Resolutioning Overaging	Roughness Recast Metal Resolutioning Overaging	Roughness Selective Etch Intergranular Attack

Abbreviations:

Plastic Deform. - Plastic Deformation
Untemp. Mart. - Untempered Martensite
Overtemp. Mart. - Overtempered Martensite

(Table 1 - page 2)

TABLE 1 - SUMMARY OF POSSIBLE SURFACE ALTERATIONS ENCOUNTERED BY METAL REMOVAL PROCESSES (cont.)

Material	Conventional Metal Removal Methods: Milling, Drilling or Turning	Conventional Metal Removal Methods: Grinding	Nontraditional Removal Methods: EDM	Nontraditional Removal Methods: ECM & CHM
Nickel and Cobalt Base Alloy Inconel 718, Rene' 41, HS 31, IN 100	Roughness Plastic Deform. Laps and Tears Microcracks	Roughness Plastic Deform. Microcracks	Roughness Microcracks Recast Metal	Roughness Selective Etch Intergranular Attack
Titanium Alloy Ti-6Al-4V	Roughness Plastic Deform. Laps and Tears	Roughness Plastic Deform. Microcracks	Roughness Microcracks Recast Metal	Roughness Selective Etch Intergranular Attack
Refractory Alloy Moly TZM	Roughness Laps and Tears Microcracks	Roughness Microcracks	Roughness Microcracks	Roughness Selective Etch Intergranular Attack
Tungsten (Pressed and Sintered)	Roughness Laps and Tears Microcracks	Roughness Microcracks	Roughness Microcracks	Roughness Selective Etch Microcracks Intergranular Attack

Abbreviations:

Plastic Deform. - Plastic Deformation
Untemp. Mart. - Untempered Martensite
Overtemp. Mart. - Overtempered Martensite

(Table 1 - page 3)

Table 2

Surface Abrasive Grinding Conditions

	Maraging Steel 50 R_c		4340 Steel 50 R_c		D6AC Steel 50 R_c		Ti-8Al-1Mo-1V 35 R_c	
	Gentle	Abusive	Gentle	Abusive	Gentle	Abusive	Gentle	Abusive
Type Wheel	A46HV	A46MV	A46HV	A46MV	A46HV	A46MV	C60HV	A46MV
Wheel Speed, ft./min.	2000	6000	2000	6000	2000	6000	2000	6000
Cross Feed, in./pass	.050	.050	.050	.050	.050	.050	.050	.050
Table Speed, ft./min.	40	40	40	40	40	40	40	40
Down Feed, in./pass	L.S.*	.002	L.S.	.002	L.S.	.002	L.S.	.002
Grind Fluid	HCO**	Dry	HCO	Dry	HCO	Dry	HCO	Dry

Machine: Norton 8" x 24" Hydraulic Surface Grinder
Total Stock Removed = .010"

* "L.S." Down Feed: .008" stock removed at .0005 in./pass
last .002": .0004, .0004, .0002, .0002
.0002, .0002, .0002, .0002

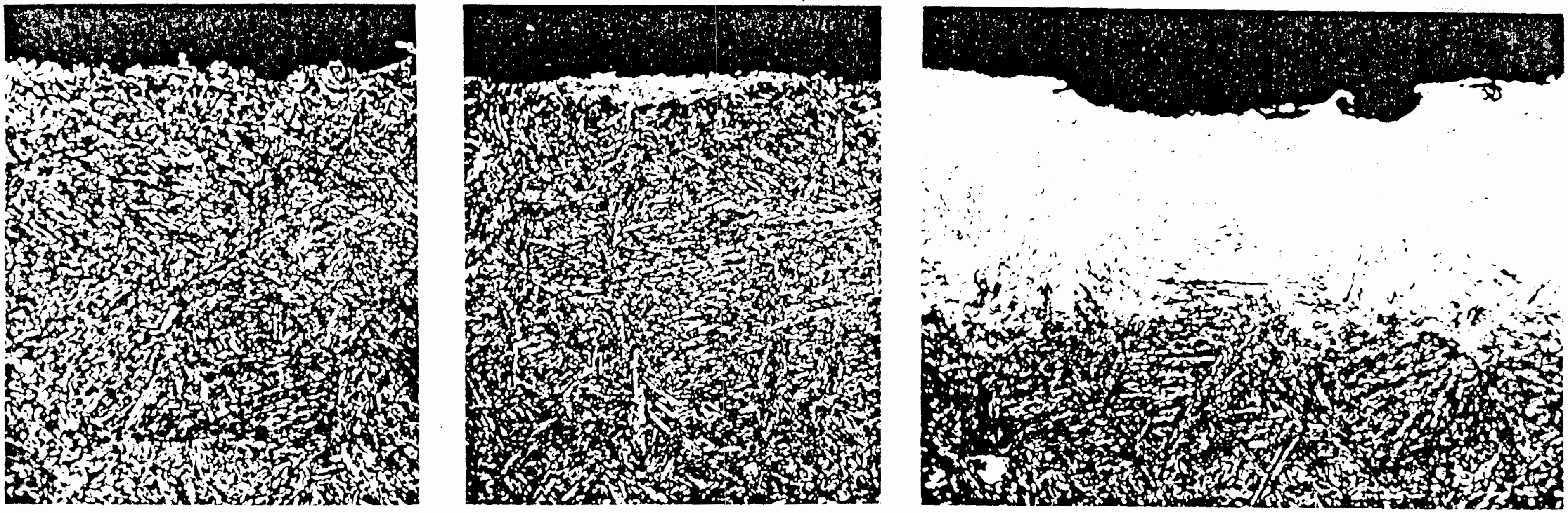
** HCO = Highly Chlorinated Oil

Table 3

Face Milling Conditions

	Maraging Steel 50 R_c Gentle	Maraging Steel 50 R_c Abusive	4340 Steel 50 R_c Gentle	4340 Steel 50 R_c Abusive	D6AC Steel 50 R_c Gentle	D6AC Steel 50 R_c Abusive	Ti-8Al-1Mo-1V 35 R_c Gentle	Ti-8Al-1Mo-1V 35 R_c Abusive
Cutter Axial Rake, Deg.	-15	-15	3	3	3	3	10	10
Cutter Radial Rake, Deg.	-7	-7	-18	-18	-18	-18	0	0
Tool Material (Carbide)	C-2	C-2	C-6	C-6	C-6	C-6	C-2	C-2
Feed per Tooth, ins.	.005	.005	.005	.005	.005	.005	.005	.005
Cut Speed, ft./min.	180	180	150	150	150	150	350	350
Tool Flank Wear, ins.	0-.004	.045-.050	0-.004	.045-.050	0-.004	.045-.050	0-.004	.045-.050

Machine: No. 2 Cincinnati Vertical High Speed Dial Type Miller
Cutter: 4" dia., single tooth face mill;
45° corner angle; 5° clearance
Depth of Cut: .010"
Width of Cut: 3/4"
Cutting Fluid: None



(a) Gentle Conditions

(b) Conventional Conditions

(c) Abusive Conditions

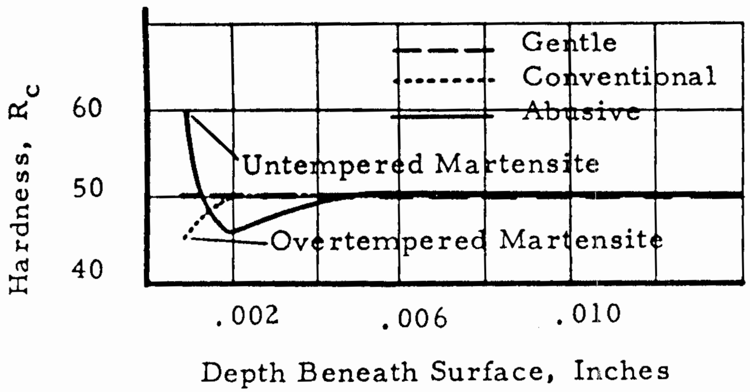
Gentle grinding produced no visible surface alterations. Conventional grinding shows evidence of spotty surface rehardening and underlying overtempering or softening. Abusive grinding produced a rehardened surface layer averaging .001" deep and an underlying overtempered zone approximately .004" deep.

Suface Finish: 45AA

Surface Finish: 40AA

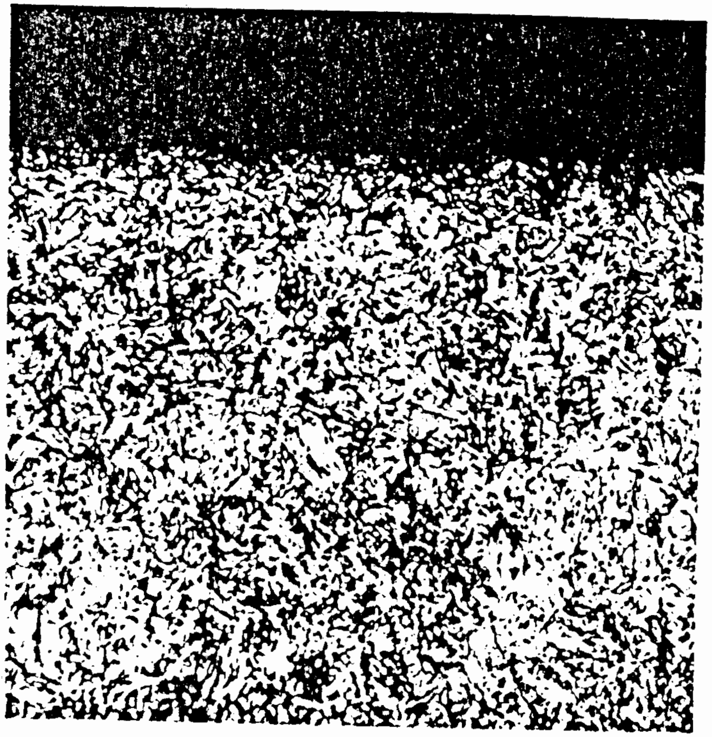
Surface Finish: 50AA

1000X

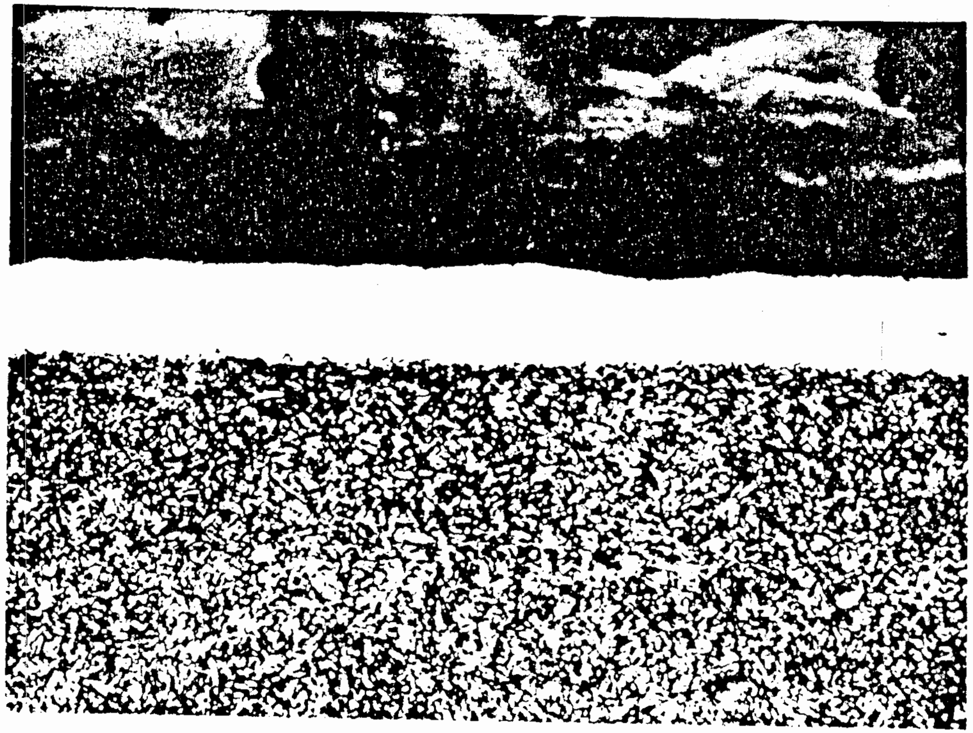


SURFACE CHARACTERISTICS OF
AISI 4340 (Quenched and Tempered, 50 R_c)
PRODUCED BY GRINDING

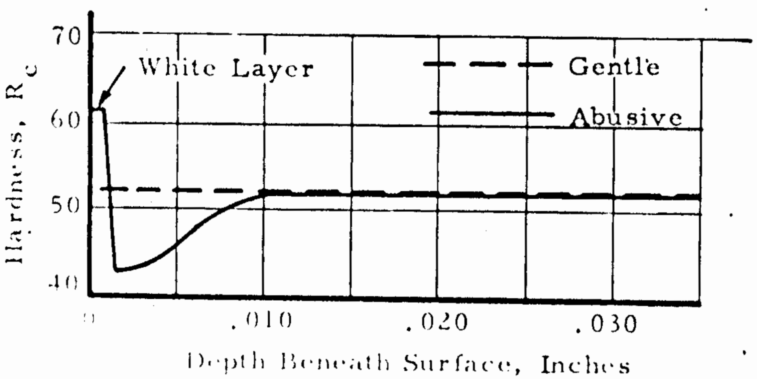
Figure 1



(a) Gentle Conditions - No noticeable microstructural surface alterations.
500X

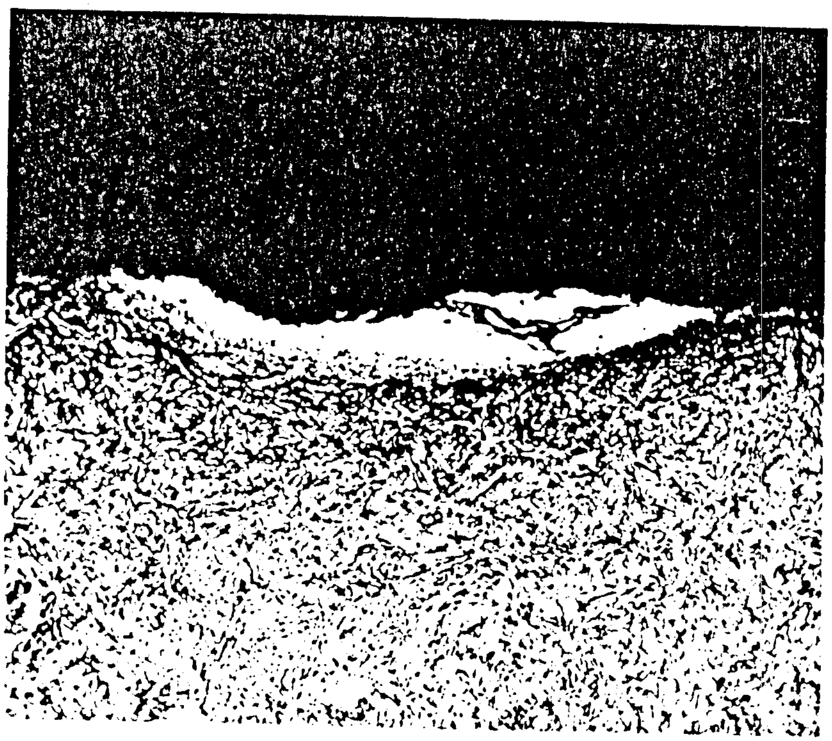


(b) Abusive Conditions - Rehardened primary martensite layer, 61 R_c, approaching .001" deep. Subsurface overtempered zone having hardness as low as 43 R_c. Total depth of effect is .010".
500X

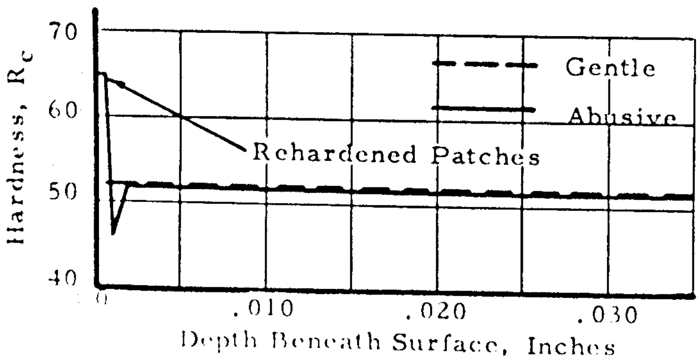


SURFACE CHARACTERISTICS OF
AISI 4340 (Quenched and Tempered, 52 R_c)
PRODUCED BY DRILLING

Figure 2

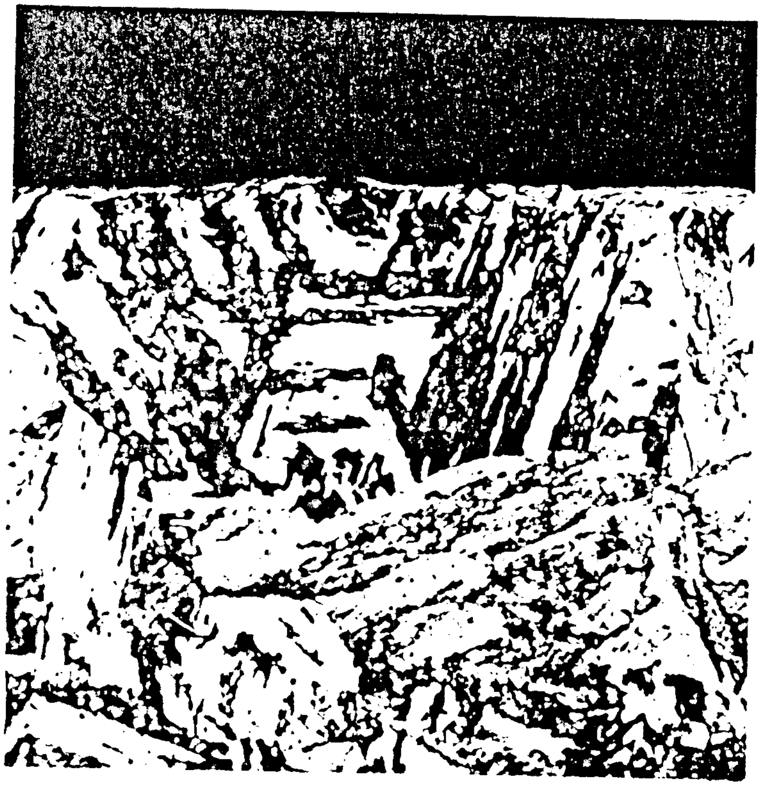


Abusive Conditions - Photomicrographs at 1000X (left) and 250X (right) showing white rehardened patches of martensite. The interval of the patches corresponds to the feed of the cutting tool. Thin zones of overtempered martensite .001" deep with hardness as low as 46 R_c are found beneath each patch.

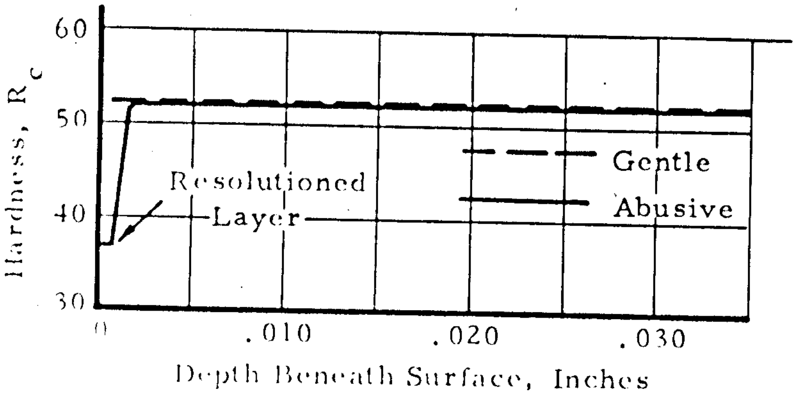


SURFACE CHARACTERISTICS OF
AISI 4340 (Quenched and Tempered, 52 R_c)
PRODUCED BY FACE MILLING

Figure 3



(a) Gentle Conditions - Very thin trace of cold work may be seen on the surface.
500X



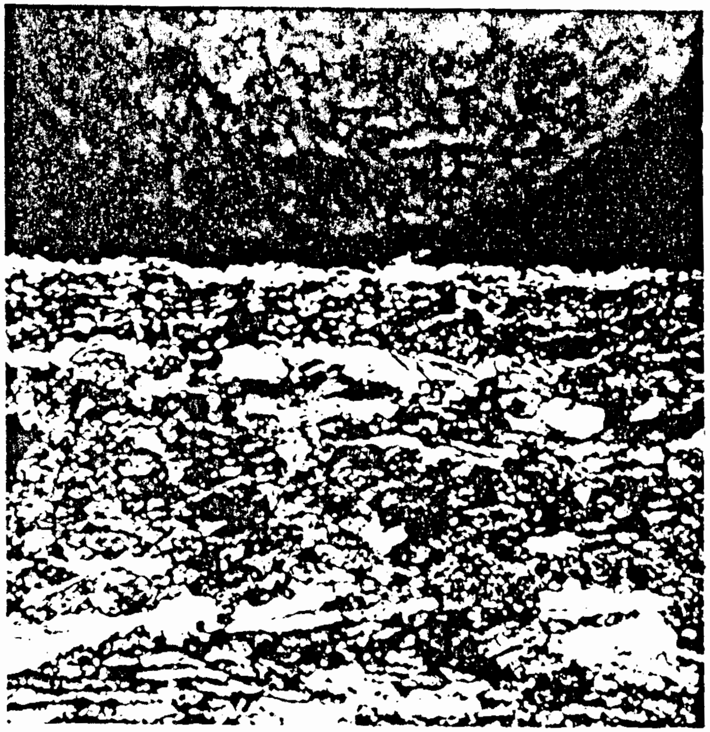
(b) Abusive Conditions - An overaged or resolutioned layer .001" deep at 37 R_c is found on the surface. Total affected depth is approximately .002".

500X

SURFACE CHARACTERISTICS OF
18% NICKEL-MARAGING STEEL (Grade 250, Aged, 52 R_c)
PRODUCED BY DRILLING

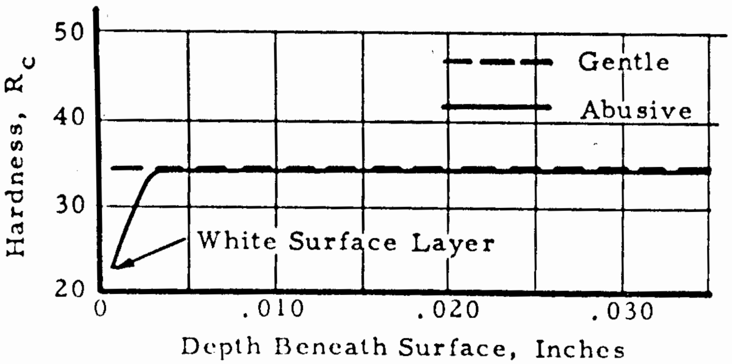
Figure 4

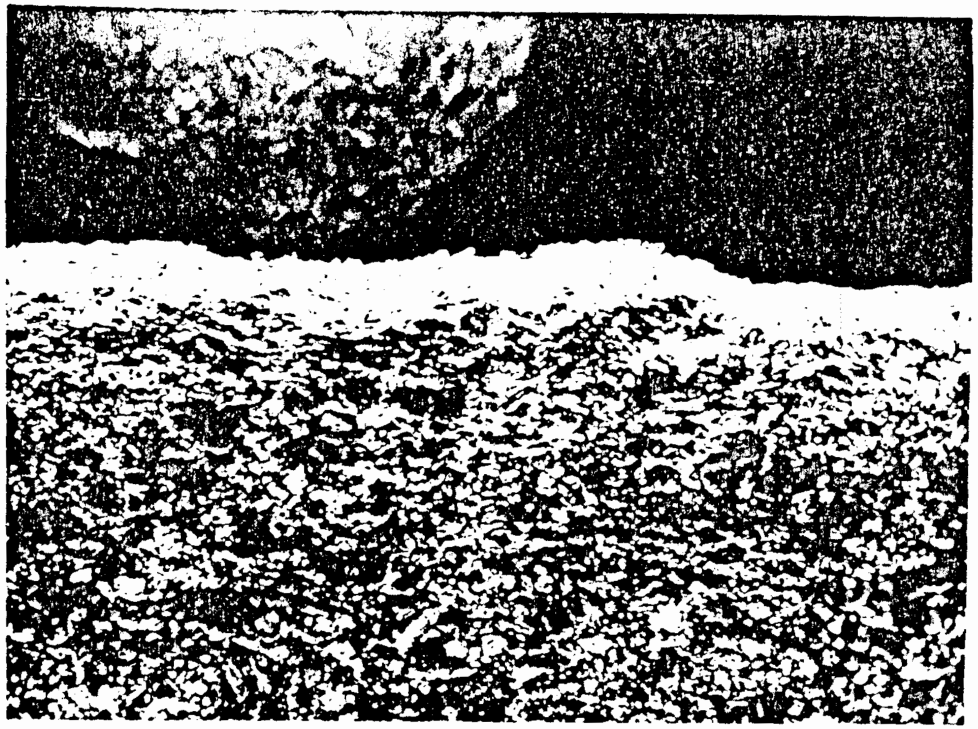
Figure 5



(a) Gentle Conditions - A slight white layer is visible but without detected microhardness change.

1000X

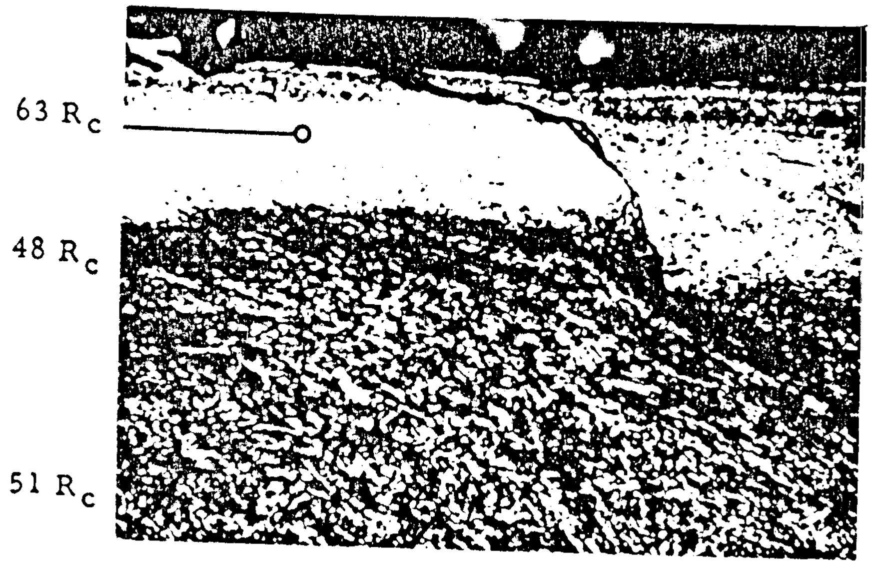




(b) Abusive Conditions - An overheated white layer about .0004" deep and a plastically deformed layer totaling .0015" deep are visible. Microhardness measurements show a total affected zone .003" deep.

1000X

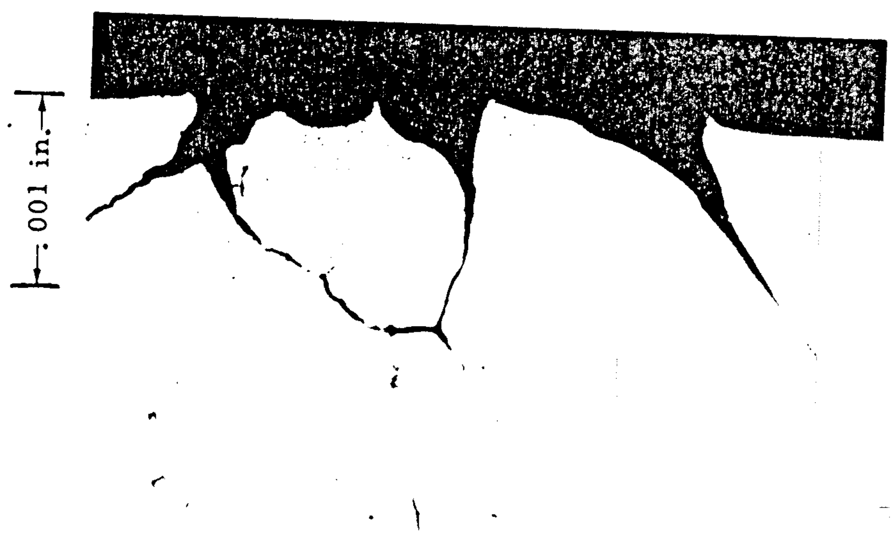
SURFACE CHARACTERISTICS OF
Ti-6Al-4V (Aged, 35 R_c)
PRODUCED BY FACE MILLING



Drilling 4340, 51 R_c, with Dull Drill
White (Untempered Martensite) Layer

EDM on D2 Tool Steel, 61 R_c
Redeposited Metal on Surface

Reaming 4340, 53 R_c, with Dull Reamer
Tears from Built-Up Edge



ECM of Waspaloy, Aged, 40 R_c
Intergranular Attack

SURFACE ALTERATIONS PRODUCED BY ABUSIVE MACHINING

Figure 6

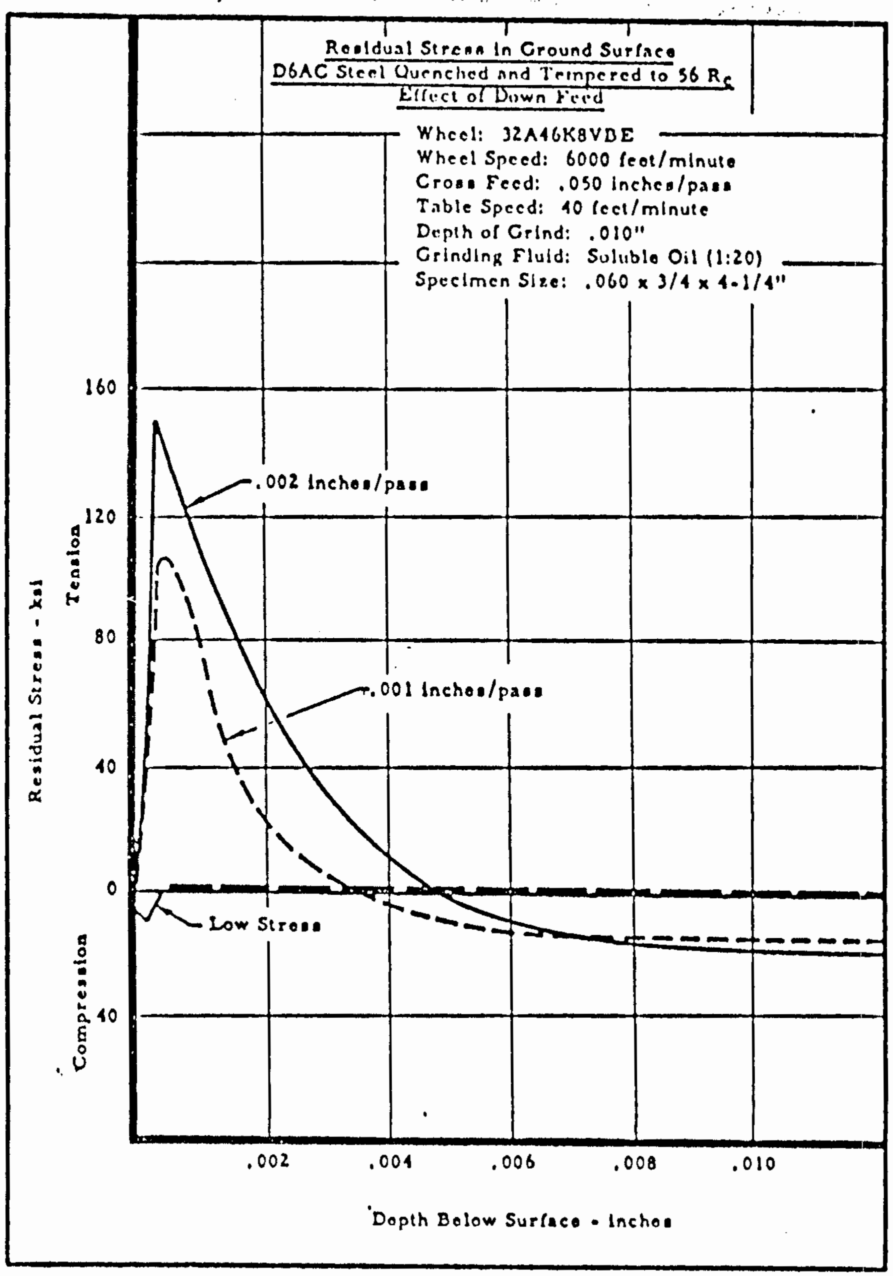


Figure 8

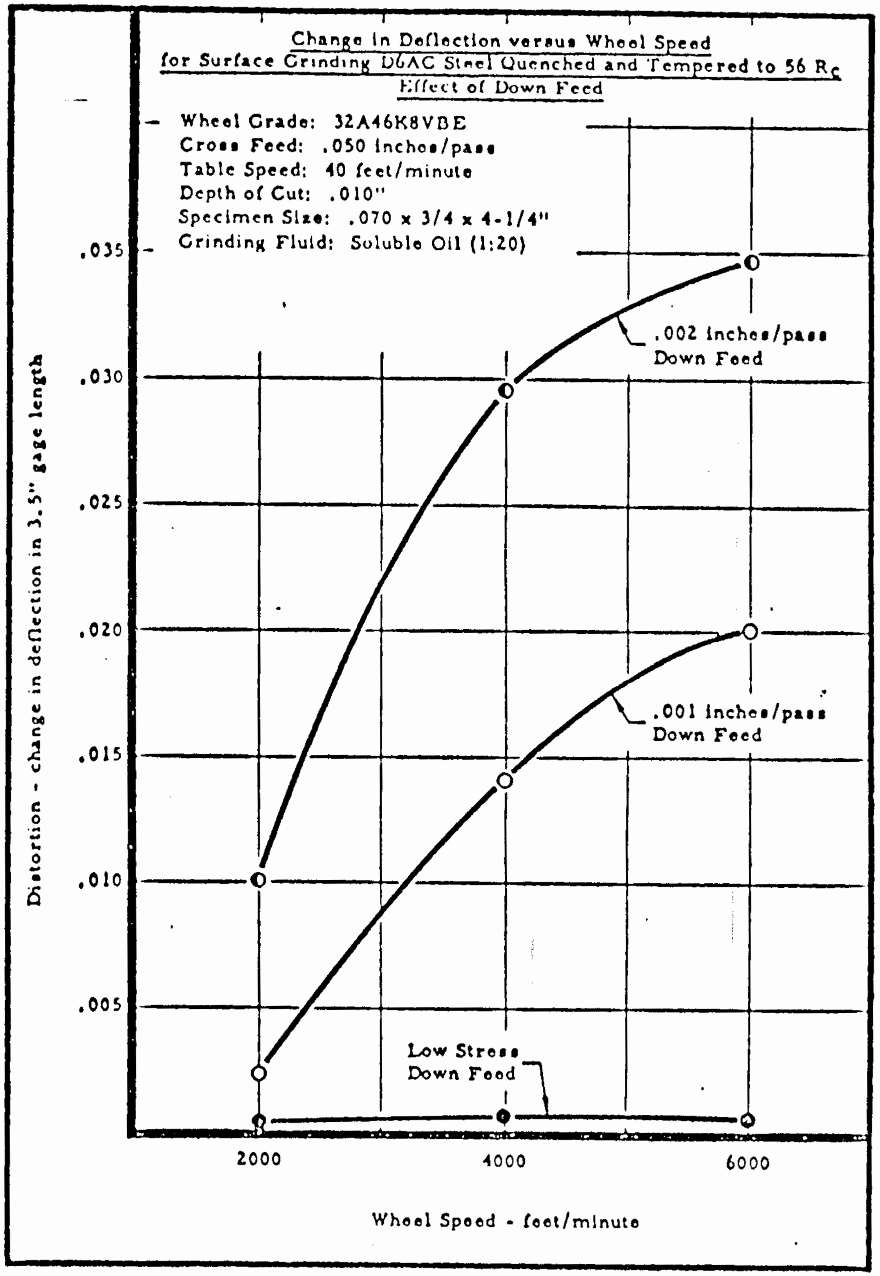
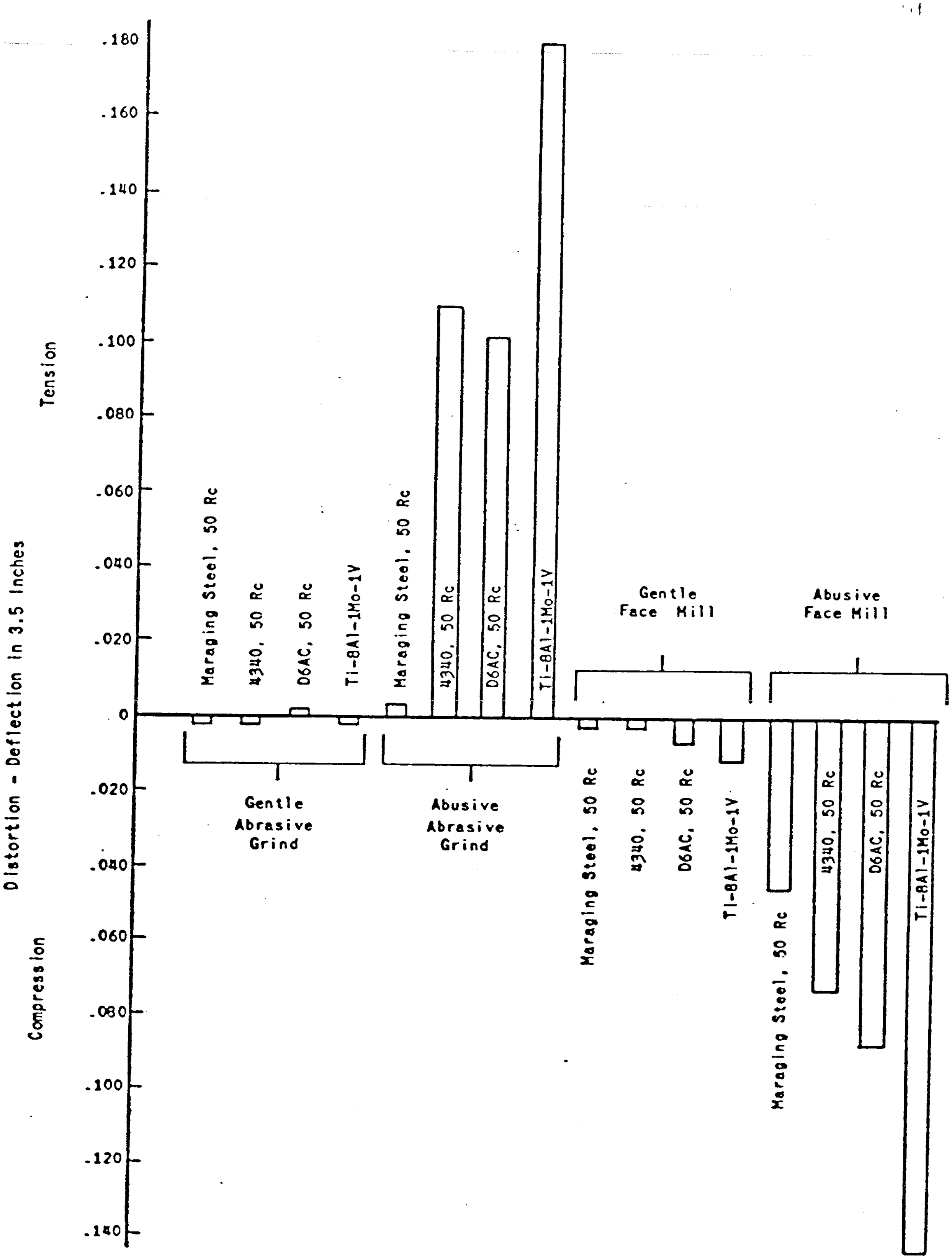
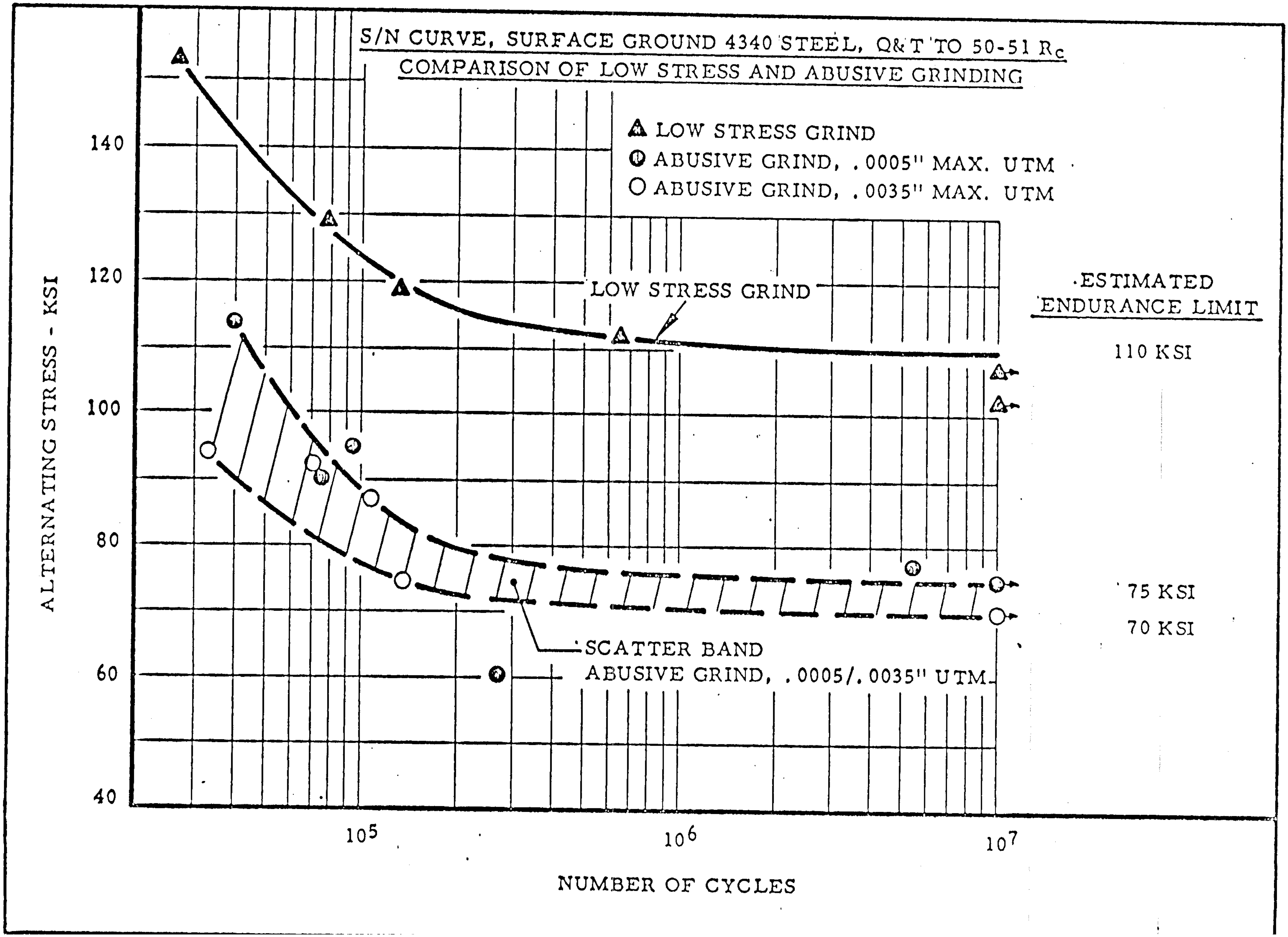


Figure 9



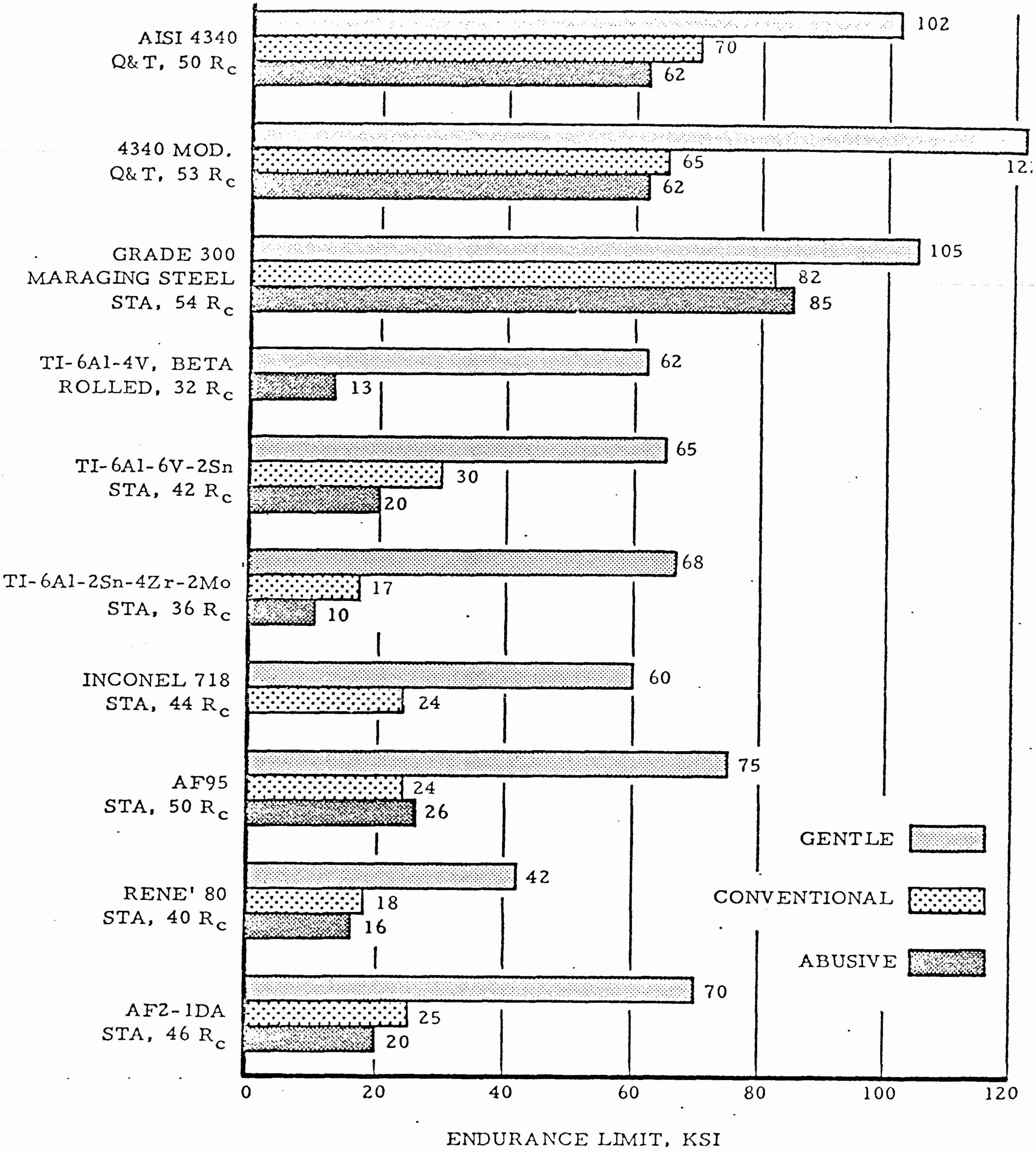
SPECIMEN DISTORTION PRODUCED BY CONVENTIONAL MACHINING METHODS.

Figure 10



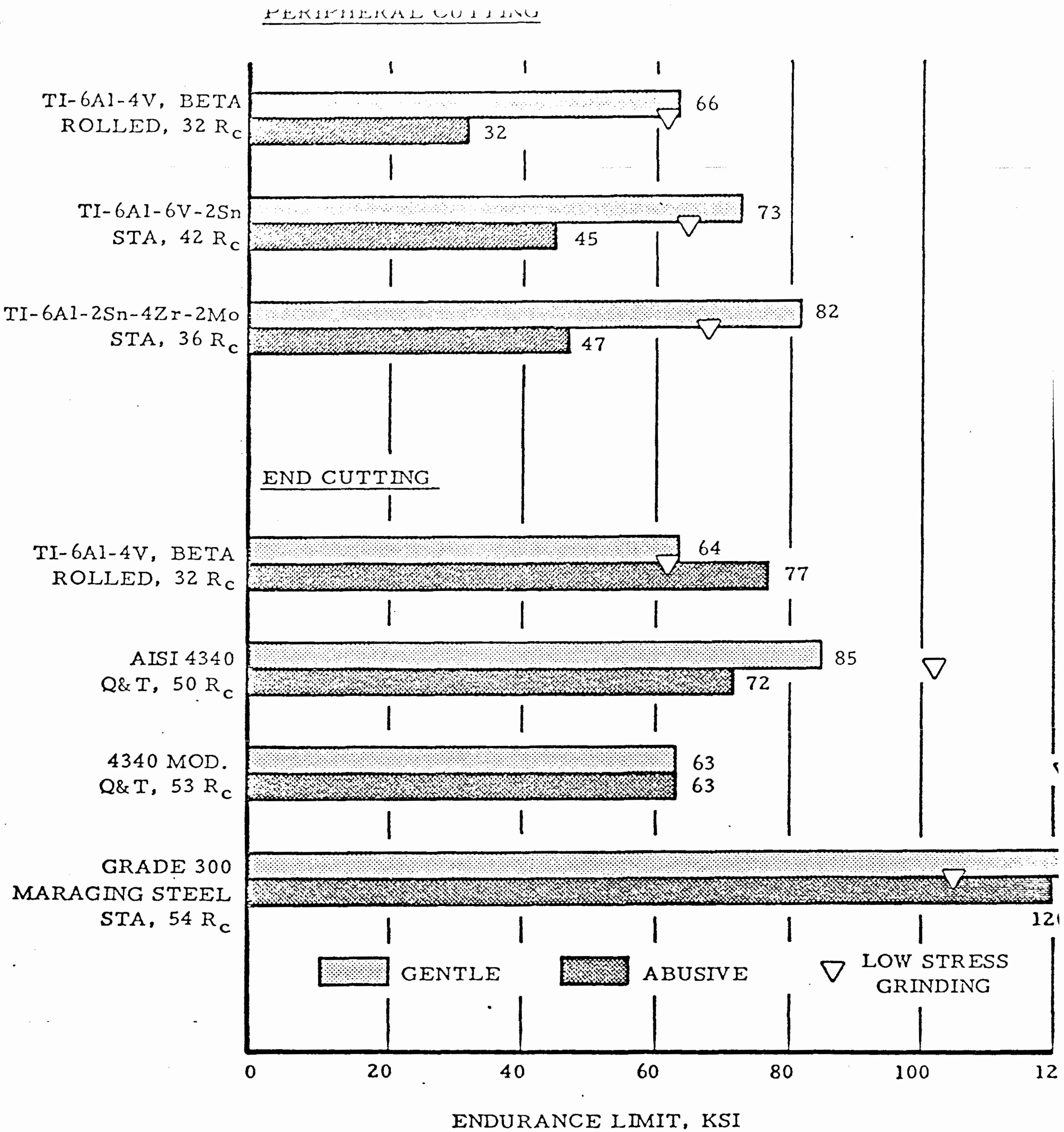
S/N CURVE, SURFACE GROUND 4340 STEEL, Q&T TO 50-51 Rc
COMPARISON OF LOW STRESS AND ABUSIVE GRINDING
LOW STRESS GRIND
ABUSIVE GRIND, .0005" MAX. UTM
ABUSIVE GRIND, .0035" MAX. UTM
LOW STRESS GRIND
ESTIMATED ENDURANCE LIMIT
110 KSI
75 KSI
70 KSI
SCATTER BAND
ABUSIVE GRIND, .0005/.0035" UTM
ALTERNATING STRESS - KSI
140
120
100
80
60
40
10^5
10^6
10^7
NUMBER OF CYCLES

Figure 11



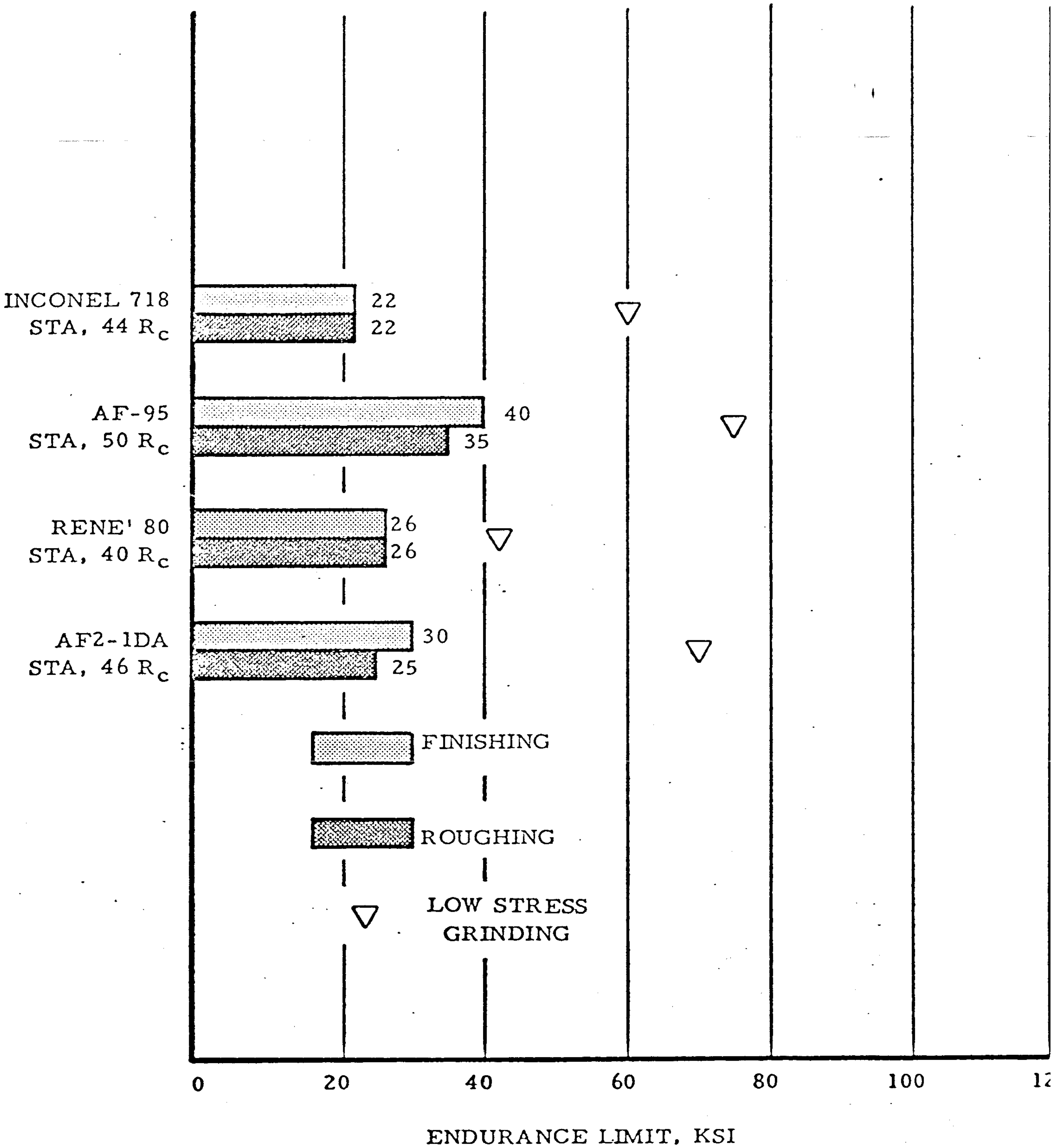
SUMMARY OF HIGH CYCLE FATIGUE RESPONSE: SURFACE GRINDING

Figure 12



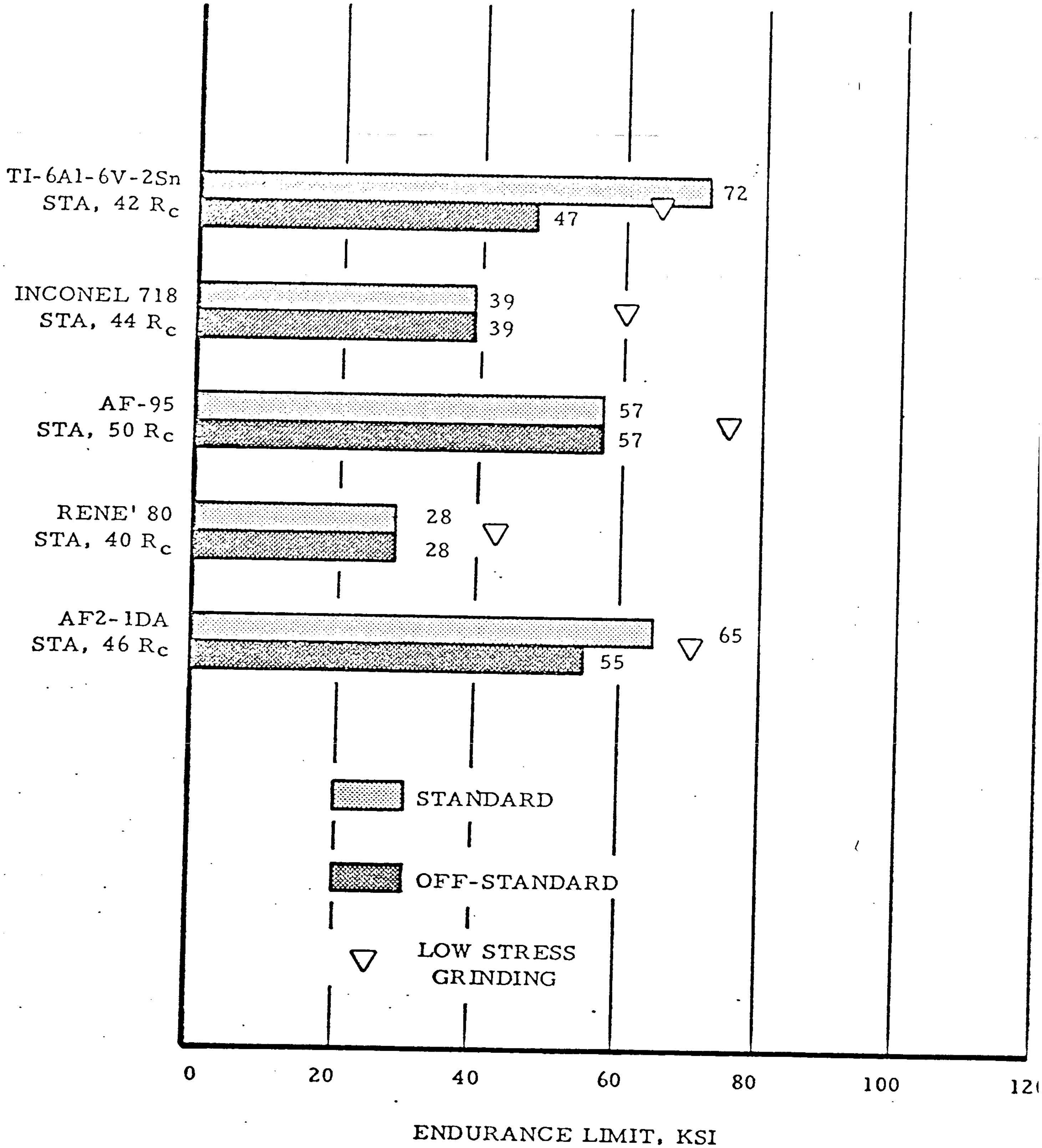
SUMMARY OF HIGH CYCLE FATIGUE RESPONSE: END MILLING

Figure 13



SUMMARY OF HIGH CYCLE FATIGUE RESPONSE: EDM

Figure 14



SUMMARY OF HIGH CYCLE FATIGUE RESPONSE: ECM

Figure 15