RELATION OF SURFACE INTEGRITY TO COST AND RELIABILITY OF STRUCTURAL COMPONENTS

by

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1472-207 The surface integrity behavior of important structural alloys, as affected by metal removal methods and variations of these methods, will be briefly reviewed. Specific instances where knowledge of surface integrity behavior has been used to overcome both service and production problems will be cited. Examples of situations where relative insensitivity to metal removal variables has permitted significant cost reduction of components will also be discussed. Methods of manufacturing necessary to achieve adequate surface integrity will be summarized along with suggestions for control of processing through adequate specifications and inspection procedures.
ABSTRACT

Surface integrity data developed in recent years has brought into focus many situations where the characteristics of machined surfaces have exerted a controlling influence on component reliability.

The surface integrity behavior of important structural alloys, as affected by metal removal methods and variations of these methods, will be briefly reviewed. Specific instances where knowledge of surface integrity behavior has been used to overcome both service and production problems will be cited. Examples of situations where relative insensitivity to metal removal variables has permitted significant cost reduction of components will also be discussed.

Finally, methods of manufacturing necessary to achieve adequate surface integrity will be summarized along with suggestions for control of processing through adequate specifications and inspection procedures.

INTRODUCTION

During the past decade, there has been continuous activity in the development of high strength, corrosion resistant materials suitable for a wide variety of aerospace applications. Interest has ranged from advancement of very high strength steels suitable for structural purposes at temperatures near ambient levels to refractory and semi-refractory alloys usable in excess of 2000°F for space shuttle applications. Between these extremes, considerable attention has also been directed at titanium alloy development for the 500-1000°F region and at stainless steels/nickel alloys for the range of 1000-2000°F.

Dynamic loading is a limiting factor in the design of many engineering structures in all types of applications. Wherever dynamic loading is involved, operating stresses are frequently controlled by the fatigue characteristics of the structural materials to be used. Service histories and failure analyses of dynamic components illustrate clearly that fatigue failures often nucleate at the surface of a component. It may thus be inferred that fatigue behavior is sensitive to surface condition. In considering stress corrosion resistance, here again it is recognized that the surface condition of a component is a primary factor in determining susceptibility to attack and subsequent failure. In summary, both fatigue and stress corrosion resistance are important materials properties which are highly surface oriented. Whenever these qualities
are important to the performance of a structure, much attention should be paid to the surface characteristics of components.

Modern metal removal methods, both conventional and those which are electrically assisted, have been revised to more efficiently process the higher strength and high temperature alloys which have evolved in recent years. The newer high performance materials are generally found to be inherently "more difficult" to machine. At the same time, advanced designs have necessitated the requirements of holding closer dimensional control on large surfaces, as well as in areas of more intricate and complex geometry. All of these conditions have intensified the problem of the quality of a machined surface, either in terms of its integrity per se or in terms of distortion resulting from stresses produced in machining.

Considering: 1) the nature of advanced materials offering improved capabilities; 2) the difficulty in machining and finishing these higher strength materials; and 3) the sensitivity to component surface condition inherent in many operational modes to which these parts will be subjected, the need for paying careful attention to the surfaces of finished hardware is brought critically into focus. In machining any component, it is necessary to satisfy the surface quality or surface integrity requirements. Surface integrity has two distinct and important aspects. The first is surface topography which describes surface roughness and other features of the geometry of the surface. The second is the surface metallurgy of the layer produced in machining, including the effect of any alterations with respect to the base or matrix metal which may be present. This second solid state aspect is the prime, but not exclusive area of interest in this report.

The data summarized in this paper is based on four years of effort in the surface integrity field at Metcut Research Associates Inc. sponsored by the Manufacturing Technology Division of the Air Force Materials Laboratory under Contracts F33615-68-C-1003 and F33615-70-C-1589.

Examples of Surface Integrity Analyses

Basic surface integrity data usually consists of studying the surface metallography, residual stress profiles and fatigue behavior associated with a particular alloy/metal removal combination. A range of metal removal parameters is usually selected which represents the possible range of conditions to which an alloy might be subjected in a manufacturing situation. The extremes of the metal removal conditions studied, in turn, serve to define the sensitivity of a particular alloy to variations within that particular process. When a large variation in alloy behavior is observed, that material is considered sensitive to process variables and consequently, it is inferred that this process must be carefully controlled at least in critical situations. On the other hand, if little change in alloy response is noticed, it is concluded that the material, for practical purposes, is insensitive to changes in processing parameters for the particular metal removal method involved. This situation then indicates the way for possible cost reduction through the use of increased metal removal rates or other higher productivity situations using that particular process. Examples of surface integrity data in the range of behavior observed are summarized for the following combinations: martensitic steel - surface grinding; titanium alloy - peripheral end milling; nickel base alloy - electrical discharge machining (EDM).

Martensitic Steel

A standard data set analysis (as the basic surface integrity analysis has been labeled) for AISI 4340 steel, quenched and tempered to a hardness of 50 Rc is summarized in Figures 1, 2, and 3. Figure 1 shows photomicrographs of cross sections of surfaces finished by gentle, conventional, and abusive methods. As indicated above, the grinding conditions were selected to illustrate the effects caused by a possible range of variables in the process. Details of the grinding conditions are summarized in Figure 2. It will be noted that the gentle grinding shows no evidence of surface disturbance. This is confirmed visually by the uniformity of the microstructure to the extreme surface of the specimen and also by the absence of any change in microhardness. Abusive grinding, at the other extreme, shows the typical effect of high, localized surface overheating.

Hard, untempered martensite at 60 Rc is formed on the surface for a depth approaching .002". Beneath this untempered martensite is found a layer of overtempered martensite, softened compared to the base metal and in this case at a hardness of 46 Rc. Conventional grinding resulted in occasional thin patches of untempered martensite. The size of these patches was too small to permit microhardness measurements, but they presumably have a hardness in the vicinity of 60 Rc. The presence of a subsurface overtempered, hence softened zone, can, however, be verified by the drop in microhardness to 46 Rc. This general behavior has been observed on many types of metal removal operations applied to martensitic steels and in general will occur whenever a sufficient level of surface heating is associated with the metal removal process.

The residual surface stress profiles, associated with these grinding conditions are shown in Figure 2. Note that gentle grinding, which is frequently referred to as low stress or stress free grinding, produces relatively low residual surface compression. Note also that the stresses at the surface for all of the conditions shown tends to be close to zero. Note further that both conventional and abusive grinding exhibited high-
level residual tension. The peaks are both in the range of 100 ksi, although the abusive grinding produces a more deeply stressed layer than does conventional grinding. This situation is typical of ground martensitic steels. The same type of residual stress distribution is also produced by grinding in titanium and nickel base alloys, even though the martensitic phase change characteristic of the steels either is not predominant or does not occur in these other alloy systems.

The fatigue behavior associated with several different methods of grinding including those just discussed on AISI 4340 is shown in Figure 3. Note that the endurance limits at 10^7 cycles associated with gentle, conventional and abusive grinding are 102, 70, and 62 ksi, respectively. Note also, as shown in Figure 3, that the surface finishes associated with all three conditions are essentially the same, falling within the range of 40-50 AA. This figure also indicated endurance limits associated with a hand grinding or hand sanding operation. Notice that both of these finishing procedures resulted in quite high fatigue strengths even though the surface finish was, in this case, relatively poor, in excess of 100 AA.

Titanium Alloys

A brief summary of the surface integrity behavior of Ti-6Al-6V-2Sn resulting from variations in peripheral end milling is shown in the next three figures. Figure 4 is a summary of surface metallography. Note the surface softening which occurs as a result of both gentle and abusive milling, although a greater magnitude and depth of softening was noted in the abusive situation. Note also the extreme plastic deformation which was associated with abusive cutting.

Residual stress profiles determined for these two surfaces are shown in Figure 5 along with a summary of the milling conditions used for this study. Note that the residual stresses are relatively shallow and that the stress due to abusive cutting has a high tensile peak. Stresses resulting from the gentle condition are also tensile, but of much lower level. The principal factor in differentiating gentle from abusive milling is the sharpness of the cutting tool, although the cutting speed and the presence of a fluid do exert a minor influence. This stress distribution is generally typical of a peripheral end milling operation, but there are occasional exceptions.

The high cycle fatigue characteristics related to this particular study are shown in Figure 6. Note that the abusive end milling operation resulted in a significant depression in fatigue strength as compared to gentle milling, 45 versus 73 ksi. The low cycle fatigue behavior of the same combination is shown in Figure 7. Note that under conditions which result in fatigue lives of 10,000 cycles or less, the fatigue behavior is unaffected by surface condition. At lower stresses, however, the low cycle fatigue data indicates the beginning of the behavior spread which is shown for the high cycle region, Figure 6.

Nickel Base Alloys

Another specific surface integrity situation, in this case EDM applied to AF 95, is shown in Figures 8, 9, and 10. The presence of a hard, brittle and frequently cracked recast layer results from both finishing and roughing conditions, as shown in Figure 8. The presence of this recast layer as well as occasional subsurface softening is the typical result of the EDM process.

Residual stress profiles of these two surfaces, along with an outline of the EDM procedures is shown in Figure 9. Note residual stresses are very shallow and also very high in tension for the extremes of the EDM conditions studied.

The high cycle fatigue behavior resulting from EDM on AF 95 is shown in Figure 10. Note that the endurance limits associated with both finishing and roughing EDM, 40 and 35 ksi, are considerably lower than that associated with gentle grinding, 75 ksi. Note also as shown in Figure 10, that a substantial elevation in fatigue behavior can be accomplished by shot peening the EDM surface. As applied to AF 95, shot peening can be considered as a very successful method of improving fatigue response. This data, however, is for room temperature exposure and, of course, is applicable only to the AF 95 material. In general, shot peening has been shown to produce this type of effect, although the magnitude of fatigue strength improvement is not the same for all combinations of the alloys and processing methods which have been studied.

Summary of Surface Integrity Data

A summary of most of the available high cycle fatigue data resulting from surface integrity investigations to date at Metcut is contained in Figures 11 through 16. These figures present, in bar graph form, a summary of the endurance limits (10^7 cycles) of a large number of alloys/process combinations. The heat treatment conditions and resulting hardnesses of each alloy are specified. All of these data were obtained from cantilever bending fatigue tests run at room temperature and 1800 cycles per minute, unless otherwise specified. Conventional testing procedures were used. These charts contain much specific data. Many details, conclusions and comparisons can be extracted from them. A few general comments and observations may be appropriate:
1. All of the alloys studied have displayed the greatest sensitivity range of fatigue behavior as a result of surface grinding. Data is summarized in Figure 11. Titanium alloys are the most drastically affected by grinding variables, although the nickel base materials are close behind. The ferrous materials are less sensitive to grinding variables than these other alloy groups, although very significant losses in fatigue strength associated with both conventional and abusive grinding must be reckoned with.

2. Hand grinding or hand sanding generally results in fatigue strength levels only slightly lower than those produced by gentle or low stress grinding, see Figure 12. With one exception, the materials studied were not sensitive to variations in hand sanding processes over the range studied.

3. Peripheral milling when performed with sharp tools (gentle cutting) results in fatigue strengths at least as good as those associated with gentle grinding. Significant fatigue losses are encountered, however, when peripheral milling cutters are allowed to lose their sharpness. These data are indicated in Figure 13.

4. End milling-end cutting generally results in fatigue behavior as good as that associated with low stress grinding, also as noted in Figure 13. The most significant exception was in the case of 4340 modified, although AISI 4340 also exhibited a fatigue strength due to end cutting lower than that observed for gentle grinding. In the case of these particular alloys, it is believed that the formation of trace amounts of untempered and overtempered martensite on the surface is predominant in their fatigue behavior.

5. Electrical discharge machining (EDM) as a process is characteristic thought of as producing a minimum range of fatigue strength on materials to which it is applied. EDM data are summarized in Figure 14. This does not imply a condemnation of the process, but rather points to the need for applying some corrective post-treatment to EDM surfaces whenever high levels of stress are involved. It is also significant to note that alloys are not particularly sensitive to variations in EDM processing. The presence of a very thin or almost invisible recast layer is just about as detrimental as an extremely heavy or thick recast layer resulting from roughing type EDM operations.

6. Electrochemical machining (ECM), as indicated in Figure 15, results in an intermediate surface integrity level somewhat below that associated with gentle grinding. ECM is considered to result in a stress free surface, as are chemical machining (CHM) and electro-polishing (ELP). The fatigue behavior associated with all three of these processes is about the same. As can also be seen in Figure 15, the fatigue behavior associated with ECM is relatively independent of the type of cutting conditions used. One should not be misled by this last statement, however, since there are a number of situations known for material not covered in this paper for which the fatigue behavior varies quite widely with changes in ECM processing.

7. The surface finish of a component is not as significant in determining its fatigue behavior as has been commonly or traditionally believed. In the normal range of surface finishes characteristic of a particular process, the contribution to fatigue behavior made by the surface finish level is generally overshadowed by the effects of residual surface stresses, and the presence of metallurgically changed phases, plastically deformed metal, and tears, laps, etc. As indicated in Figure 16, the finish of gently ground surfaces does have some influence on fatigue strength. Notice, however, that in the case of abusively ground surfaces, a further effect is noticed which overshadows that of surface finish. Observe also that in the case of milling cuts applied to titanium and facing cuts applied to Inconel 718 that no effect at all was exerted on fatigue behavior over a relatively wide range of resulting surface finish.

In analysing this surface finish information, it is not implied that the effect of scratches, tool marks, sharp corners and other geometric considerations can be overlooked. The effect of these factors as producers of stress concentration leading to premature fatigue failure are well established. The point to be made is that microscopic changes in stress concentrations associated with the range of surface finishes studied are not, in and of themselves, as significant as has been traditionally accepted.

**Cost and Reliability**

At this point, it has been demonstrated in a number of situations that changes in metal removal variables can result in marked changes in the structural behavior of machined components, as indicated by variations in fatigue response. Specific data have also been presented which summarize the behavior of typical structural materials processed by a variety of metal removal and finishing methods. Two general areas for application of this type of information are evidenced:

1. Surface integrity data provides information to permit the intelligent selection of an alloy and a machining/finishing method for highly stressed situations. Where a material is to be used at its maximum performance level, data
A few examples of the application of surface integrity information in solving production problems and in achieving cost reductions are now to be considered. In the grinding of nickel base alloys, three turbine engine manufacturers with which we have been in contact during the past two years have experienced very similar problems. The first of the group was having difficulty grinding a relatively small turbine blade from a cast nickel base alloy. The rejection rate due to zyglo indications after grinding was approximately 60%. Following a subsequent five-hour green run of the assembled engine, two-thirds of those blades which had been previously accepted were found to be cracked, again as judged by zyglo inspection. This made for a gross scrap rejection rate of approximately 90%, when comparing number of castings going into the machining processes with number of blade castings which were acceptable after engine green run. In examining the blades metallographically and also from reviewing the grinding processes used, it was evidenced that the grinding process used was abusive to this particular alloy, although it was quite conventional insomuch as standard grinding of medium-hard materials is concerned. Limitations to the production equipment would not permit a complete conversion to nominal gentle grinding conditions. A compromise set of grinding parameters was developed based on surface integrity considerations and the manufacturing equipment converted to operate under those conditions. Once converted, the aggregate scrap rejection rate from blade castings to finished blades accepted as the green run fell from 90% to less than 2%.

In a similar situation, another turbine engine manufacturer was experiencing an approximate 50% scrap rejection rate from a dovetail grinding operation. In their situation, it was possible to convert the grinding equipment to align almost perfectly with the normal type of gentle grinding procedure as had been developed and as outlined in Figure 2. The zyglo inspection rate immediately fell to zero.

In a third situation, a fabricator of large nickel alloy turbine blade castings was also experiencing difficulty with a high percentage of scrap rejection due to zyglo indications. Many of the indications proved, on subsequent metallographic analysis, to be very superficial and probably attributed to small amounts of microporosity inherent in the alloy. Some of these zyglo indications, however, were more serious in that intergranular cracking was also present. In this instance, conversion of the massive blade-grinding equipment involved to be completely in accord with the standard range of low stress grinding procedures was prohibitively expensive. Furthermore, the time cycle necessary to accomplish this was out of the question. An experimental program was quickly put together to explore the relationship between grinding procedure and zyglo indications. It is to be pointed out here that even though most of the zyglo indications which were associated with porosity indicated a condition not particularly harmful to the part, their presence interfered with the detection of actual microcracks. Residual surface tension due to the grinding process caused an "opening up" of microscopically porous area, allowing the zyglo materials to penetrate and...
indicate a surface flaw. Therefore, as a practical matter, it became necessary to modify grinding procedures both so that microcracking would not be produced by grinding and further so that microshrinkage would not be "opened up", also leading to zyglo indications. The key to the solution of this problem was to develop a grinding method which would ideally produce zero surface stress or at best a minimum level of surface tension. Several different sets of grinding parameters, ranging in severity from gentle to abusive were evaluated on the material in question. Complete discussion covering the operating parameters used in gentle and abusive grinding have been previously discussed elsewhere. (1, 2, 3) Figure 17 illustrates the type of zyglo indications that were associated with the range of grinding parameters studied. These illustrations made with ultraviolet illumination show indications due to both microporosity and microcracking. The solution to the particular production problem involved not only the elimination of microcracking, but further permitted arrival at a minimum cost solution in terms of feasible changes in grinding conditions on one hand, and minimizing the incidence of zyglo indications on the other. A knowledge of the surface integrity behavior associated with several variables of the grinding process permitted rather direct arrival at a set of conditions which would meet both requirements.

In a reverse situation of a grinding production problem, we are aware of one instance where low stress grinding had been in use in making components from a low ductility, high strength nickel alloy. Low stress techniques were adopted several years ago because it was found impossible to grind this material with conventional procedures. As additional surface integrity data became available, it was evident that certain increases in productivity could be accomplished. Changes in procedures were made improving the productivity rate by 40%, largely by a change in the feed rates used for the grinding process. In the place of .001 in./pass in roughing, .003 in./pass down to the last .008" of material was used. In addition, a heavy controlled flow of coolant was incorporated. The final surface was the result of a few passes at .001" and final sparkout. In this situation, not only was productivity increased, but the need for the acquisition of additional expensive vertical turret grinders to meet increased production requirements was obviated.

Thinking for a few moments of airframe structures directs attention to milling of all types and also to drilling and reaming holes for fasteners. In airframe design, much attention is paid to the lightening of components by a variety of pocketing operations to remove metal where not structurally required. Likewise, the methods used for assembly and attachment of airframe structures are a critical design and manufacturing consideration. One of the most significant keys to success in airframe design is to accomplish attachment of components to each other in such a way as to avoid the effects of stress concentrations at attachment holes. Much of the science of fasteners is devoted to putting a hole in a part (which provides a stress concentration) and then devising some technique whereby the effect of this concentration can be mitigated. Thus can be easily recognized that the surface integrity of holes in structures can be a limiting factor in performance and reliability.

Aluminum, a structural workhorse, has been relatively forgiving with regard to the surface condition of holes placed in it. High strength steels, however, have a somewhat different disposition. There has been considerable difficulty in the airframe industry in very recent years associated with the surface integrity of holes in the newly introduced steel structures. A number of production difficulties as well as failure of steel structures both in test stands and in flight have occurred. In investigating some of these problems, the types of conditions shown in Figures 18 and 19 have been found. In drilling and reaming of high strength steels at intermediate hardness levels, it is relatively easy to form unwanted, untempered and overtempered martensite. Both of these conditions have resulted in nucleating fatigue and also static cracks which have led to subsequent failure. Likewise, tears and laps produced in surfaces under far less than optimum machining conditions have undergone crack extension and led to ultimate failure of the structure.

In critical situations of this type, is it not both technically and economically prudent to be certain that the surface quality and specifically the surface integrity of attachment holes is adequate for the requirements of the structure?

In another area related to airframe structure, a potential cost savings is indicated by surface integrity data in milling. The limited information available shows that at least in end milling-end cutting operations, the characteristic fatigue strength associated with the process is relatively independent of surface roughness. In peripheral end milling, surface finish again apparently plays a small role in fatigue behavior as long as good cutter sharpness is maintained. This suggests a potential for substantial cost savings by relaxing as-milled surface finish requirements and by minimizing the extensive amount of hand sanding or other hand reworking which is performed on milled surfaces. If the fatigue strengths of the as-milled surfaces at 60 or even 100 AA are as good as the much smoother hand sanded surfaces, why bother hand sanding? This comment would not apply to radiusing or working tool marks out of corners or mismatched surfaces. Nevertheless, these appear to be a lot of latitude in this area to save production hours, hence dollars.

Considering this last point, but relating it to another engine application, there is a case history on record involving the machining of nickel alloy turbine discs. Surface integrity data developed and subsequently
rechecked indicated that this particular alloy was relatively insensitive, as far as its fatigue strength was concerned, to surface roughness within the range of 15 to 200 AA. This data resulted in a relaxation of finish requirements for the turned surfaces of these components. The allowable finish was changed from 90 to 125 AA on compressor spools and from 63 to 125 AA on discs. An average 10% reduction in machining time was experienced for both parts with the relaxed surface finish requirements.

Summary

In summary, it is indicated that the availability of adequate surface integrity information permits the design of a specific alloy surface system to meet a critical need. By surface system we mean the selection of the alloy, the heat treatment, the machining, and the finishing of a component as an integral package. This capability can result in production of a component having adequate surface integrity for a particular requirement at a minimum cost. The same type of information will also provide confidence for the use of higher production, lower cost finishing methods where design will permit. Surface integrity information also allows manufacturing engineers to take advantage of areas of relative insensitivity to the surface machining factors, when a cost saving could be achieved. The surface integrity approach is seen, therefore, as being an enabling force to provide high quality, high reliability hardware from high strength structural materials at a minimum necessary cost.

References

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. Indicated hardness data are Rc values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

SURFACE CHARACTERISTICS OF AISI 4340 (QUENCHED AND TEMPERED, 50 Rc) PRODUCED BY GRINDING

ORIENTATION: LONGITUDINAL GRIND. SURFACE SECTIONS PERPENDICULAR TO GRINDING LAY.
FATIGUE CHARACTERISTICS OF AISI 4340 (QUENCHED AND TEMPERED, 50 R)
METAL REMOVAL CONDITIONS: SURFACE GRINDING, HAND GRINDING, ELP
MODE: CANTILEVER BENDING, ZERO MEAN STRESS
TEMPERATURE: 75°F

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<td>ABUSIVE HAND GRIND</td>
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<td>F</td>
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Figure 3
HIGH CYCLE FATIGUE CHARACTERISTICS OF Ti-6Al-6V-2Sn (SOLUTIOK TREATED AND AGED, 42 R.C.) PRODUCED BY END MILLING - PERIPHERAL CUTTING

MODE: CANTILEVER BENDING, ZERO MEAN STRESS TEMPERATURE: 75°F ORIENTATION: LONGITUDINAL MILL. FATIGUE STRESS PARALLEL TO LAY.

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LOW CYCLE FATIGUE CHARACTERISTICS OF Ti-6Al-4V-2Sn
(SOLUTION TREATED AND AGED, 42 Rc)
PRODUCED BY END MILLING - PERIPHERAL CUTTING.
MODE: FOUR-POINT BENDING, CONSTANT STRAIN, ZERO MEAN STRESS
TEMPERATURE: 75°
ORIENTATION: LONGITUDINAL MILL. FATIGUE STRESS PARALLEL TO LAY.

SURFACE CHARACTERISTICS OF AF95
(SOLUTION TREATED AND AGED, 50 Rc)
PRODUCED BY EDM

EDM typically shows the presence of a recast layer on the surface. As current density is increased when shifting from finishing to roughing conditions, the thickness of the recast layer also is increased. A slight softening is observed beneath the recast layer. The presence and hardness of the recast layer is probably the most significant metallographic feature. Note, also, the crack in the roughing sample which penetrates into the base metal. Indicated hardness data are Rc values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X
RESIDUAL SURFACE STRESS PROFILES IN 4F5S (SOLUTION TREATED AND AGED, 50 R.) PRODUCED BY EDM

FINISH EDM
ROUGH EDM

FREQUENCY, kc 260 16
AMPERES 1 4-5
CAPACITANCE, μfd 0 2
VOLTAGE 70 80

DEPTH BELOW SURFACE, INCHES

Figure 9

HIGH CYCLE FATIGUE CHARACTERISTICS OF 4F5S (SOLUTION TREATED AND AGED, 50 R.) PRODUCED BY EDM

Figure 10
RESEARCH FROM DIFFERENCES IN GRINDING PRACTICE

Figure 19

Low Stress, Grid with Oil

Conventional Grid, Grid with Oil

Conventional Grid with Oil

Alpine Grid, No Coolant

Wheel at 4800 ft./min.

Wheel at 6000 ft./min.