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BULLETIN 677-1

OBSERVATIONS ON SURFACE RESIDUAL STRESS VS FATIGUE STRENGTH

W.P. Koster, June 24, 1977

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Introduction

Over the past several years, Metcut has conducted investigations in the area of surface integrity primarily under sponsorship of the Air Force Materials Laboratory. The purpose of this effort has been to determine the effect of variations in metal removal methods and parameters on component performance as influenced by the integrity of metal surfaces. In summary, the effects of differences in machining and finishing methods have been measured in terms of a variety of mechanical properties. On some occasions, tensile ductility and stress rupture performance have been affected. Without doubt, an increase in scatter or spread in stress rupture life can be related to surface integrity phenomena, particularly when cast materials are involved. The greatest and most consistent effects, however, have been observed in fatigue behavior. Due to the importance of this subject, this summary Bulletin has been written in order to make available our observations on high cycle and low cycle fatigue properties.

From the outset of our work in this area, it was obvious that variations in metal removal parameters did indeed make a difference in fatigue behavior. Figure 1 is a summary of the high cycle fatigue response of Inconel 718, a typical high temperature nickel base alloy. The response shown is attributable to different metal removal methods and ranges of parameters of several of these methods. Note that fatigue strength varies by a factor of about 3:1 as a result of machining/finishing differences. Figure 2 is a similar summary of low cycle fatigue behavior for the same material. The type and magnitude of variations indicated in Figures 1 and 2 have been observed on other nickel base alloys as well as on aluminum, cobalt and titanium base materials and steels. The high cycle fatigue data summarized in Figure 1

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is the result of cantilever bending tests run in fully reversed bending. Low cycle fatigue data was obtained in the four-point bending strain controlled test mode. All tests were conducted at room temperature unless otherwise noted.

In order to explain observed fatigue differences, a detailed metallurgical study was conducted on both machined coupons and failed test specimens. In some cases, a depression in fatigue strength was related to microcracking in the surface which in turn could be traced to a particular metal removal operation. A small bias in fatigue behavior could frequently be attributed to surface finish differences. The influence of finish was studied at some length; the conclusion reached, however, was that surface finish, per se, is much less significant in determining fatigue strength than has been traditionally accepted. It also appeared that plastic deformation resulting in differing degrees of cold work in the surface occasionally played a role in shifting fatigue strength. A frequent and major factor believed responsible for many fatigue strength differences was the surface residual stress. Many correlations between residual stress and fatigue behavior have been identified. A summary of typical data observed in this area are summarized in this Bulletin.

Another technical area that should be mentioned is the relationship between stress corrosion sensitivity and residual stress. Limited observations indicate clearly that precautions are advisable wherever stress corrosion sensitivity is a factor in component performance. The data available to Metcut are sparse, however, and serve merely to indicate trends rather than to document the situation.

Metal Removal Parameters

To interpret what is meant by variations in metal removal parameters, a few words are in order. Variations in the grinding process include those conditions which result in low level compressive stresses and which produce no detectable surface damage. Such parameters consist of low grinding wheel speeds (2000 ft./min.), the use of grinding oils as fluids, and a low rate of infeed progression. More abusive or damaging combinations of grinding parameters are typified by increased wheel speeds, increased rates of infeed and the use of water-base fluids as coolants. Still greater surface damage can usually be created by grinding without fluid.

Variations in turning and milling are usually relative to the sharpness of the tool. When tool sharpness is lost, as measured by an increase in the cutting tool wearland, larger zones of plastic deformation and higher residual compressive stresses in the machined surface are the typical result. The data shown herein for electrical discharge machining (EDM), electrochemical machining (ECM), chemical machining or chemical milling (CHM) and electropolishing (ELP) are for one or two different sets of parameters. Except in unusual situations, surface integrity variations due to differences in nontraditional machining parameters are small.

Stress Measurement

To quantify the total, relevant residual stress condition in a machined surface, Metcut has worked with residual stress profiles or distribution of stress within a surface layer of a few thousandths of an inch deep rather than on the surface alone. Examples of typical residual stress profiles are shown in Figure 3. This illustration contains data obtained from a quenched and tempered steel finished by grinding. These results are quite typical of those associated with the grinding process. Note that the stresses at the outer fibers (at zero depth) are very low in magnitude, essentially zero. As measurement progresses into the material, peak stresses are identified. The peak stress for the abusive grinding operation in this example occurs at .002 in. beneath the surface.

Referring again to Figure 3, the peak stresses associated with gentle, conventional and abusive grinding as labeled on that illustration would be -25 ksi, +90 ksi and +105 ksi, respectively. It has been found experimentally that a positive correlation exists between such peak residual stresses when plotted against the resulting endurance limit or fatigue strength of a material.

Residual stresses can be measured in a variety of ways. Both a surface dissection method and x-ray diffraction techniques have been used to obtain the data summarized in this document. Surface dissection involves the preparation of a rectangular strip approximately 1 in. by 4 in. by .080 in. on which one of the sides has been finished using the set of machining/finishing parameters to be evaluated. Experimentally, the curvature of this strip is very carefully measured at the outset and sequentially after the removal of very thin layers of stressed metal by either etching or electrochemical methods. The mathematical procedure for calculating residual surface stress using this dissection method has been available for many years and is well documented.

X-ray diffraction is now in widespread use for making residual stress measurements. This technique involves the determination of lattice strain, hence stress, by determination of the shifting of diffraction peaks. To obtain a stress profile like that shown in Figure 3, diffraction readings are taken on a surface initially and again after layers are incrementally removed by an appropriate etching procedure. At the present time, surface dissection has been almost completely phased out here at Metcut in favor of the measurement of stresses by x-ray diffraction.

It should be added that with x-ray diffraction stresses can be measured in an infinite number of directions in any flat or plane surface. In the case of the data summarized in this Bulletin (and most of the work in this technical area completed by Metcut to date) the residual stress data, when correlated with fatigue strength, are reported in the direction parallel to the application of the applied fatigue or cyclic stress.

Observed Correlations

Much work has been done on the grinding of high strength steels to identify surface integrity effects. Many alloy modifications of AISI 4340 at several different hardness levels have been involved in this effort. The most complete study carried out at Metcut, performed on 4340 quenched and tempered to a hardness level of R_C 50, was run in conjunction with a processing parameters program. The range of parameters used was as follows:

Grinding Wheel Abrasive: Aluminum Oxide
Grinding Wheel Speed: 2000 to 6000 surface feet per minute
Grinding Wheel Hardness: H to M
Infeed: .0002 to .003 in./pass
Fluid: Water Soluble, Oil, Dry
Wheel Dressing Procedure: Coarse, Fine

Ultimately, fifteen groups of fatigue specimens, ten specimens per group, were produced using fifteen different sets of grinding parameters. Each group of specimens was run in fatigue to determine the 10^7 cycle endurance limit. Separately, coupons produced by each of the fifteen different sets of grinding parameters were evaluated to determine the residual stress profile associated with each. A plot of the resulting peak residual stress versus fatigue data is shown in Figure 4. As peak residual stress varied from 160 ksi in tension to about 35 ksi in compression, the associated fatigue strength

ranged from 45 ksi to an average of about 120 ksi. This observation supports the contention that at least a 3:1 variation in fatigue strength may be observed in steel as a result of variations in surface finishing parameters. As indicated earlier, this is not an isolated case; similar behavior has been observed on several other types of steels. This example is reported, however, since it summarizes the most complete example of the effects of grinding on the surface integrity of steels available in Metcut's files.

Figure 5 is a compilation of similar data obtained on 17-4 PH which is a precipitation hardening stainless steel. In this work, the 17-4 PH alloy had been solution treated and precipitation hardened to the fully aged or H900 condition. A consistent trend similar to that shown in Figure 4 is observed among the three points of grinding data available. The single data points related to EDM and CHM are reasonably consistent with the grinding behavior. The data points for milled surfaces however, appear to deviate somewhat from the fatigue strength trend suggested by grinding. This is not frequently the case, but in this situation may perhaps be related to two simultaneous effects. On one hand the milling operation is expected to produce compressive stresses in a surface which increase in magnitude as the tool becomes dull (see △1 versus △2 in Figure 5). But in this alloy, the localized surface heating related particularly to the dull cutting tool (△2) may have served to significantly over-age the surface layer, thereby reducing its inherent fatigue strength. Superposition of the two effects results in lower fatigue strength than would be predicted from residual stress data alone.

Fatigue versus residual stress summaries for a number of nickel base alloys are shown in Figure 6. Data for ground, milled, turned, EDM, ECM and CHM surfaces are indicated on these plots. Note again that there is a reasonably consistent trend evidenced by all of these materials, generally irrespective of the metal removal method used to produce the various surfaces being studied.

Figure 7 summarizes data available on two different titanium alloys. Notice again that the peak residual stress correlates rather well with fatigue behavior.

Conclusions

A positive correlation has been found to exist between peak surface residual stress and fatigue behavior. This correlation is found not only among variations in a single process such as grinding, but also transcends the methods of metal removal involved and can be shown to exist within a given material for a wide variety of metal removal processes. Generally, tensile residual stresses reduce fatigue strength while compressive residual stresses tend to increase fatigue strength when compared to that associated with the nominally stress free condition as a baseline. It may also be said that the higher the level of these stresses, the greater the influence that is usually exerted by them.

In seeking to identify the possible relationship between surface residual stress and fatigue strength, it was found that the peak stress in the surface profile (not necessarily at the surface) rather than the stresses at the outer fibers of the surface provided the most consistent correlation.

An overall summary of the surface integrity work at Metcut by no means leads to the conclusion that surface residual stress is the only factor influencing fatigue variations as a result of surface effects. On the other hand, residual stress variations are significant, may exert a pronounced influence on fatigue behavior, and must be reckoned with whenever components are fatigue-limited in their design.

A significant potential exists for the use of residual stress measurements as a quality control tool. In many situations, x-ray diffraction may be considered nondestructive. Even where subsurface peak stresses need to be identified, the thin layers removed by electropolishing in order to make such measurements may not in themselves be destructive to the component being inspected.

Fatigue behavior data also indicate clearly the importance of exercising control in the manufacture of fatigue test specimens. In materials application programs, the specimen finishing method must relate to the hardware or production situation if the data produced are to be truly applicable. In data generation or materials characterization programs, close manufacturing control will greatly reduce the scatter typically found among specimens made at different times or by multiple sources.

Closure

This Bulletin, based on work carried out by Metcut under sponsorhsip of the Air Force Materials Laboratory, was written to alert the metalworking industry to the often significant relationship between machining/finishing processes and resulting component fatigue strength. It is not intended to be a stand-alone fully referenced technical document. Complete details, supporting all of the information presented herein as well as data on other specific alloy systems are available from Metcut on request.

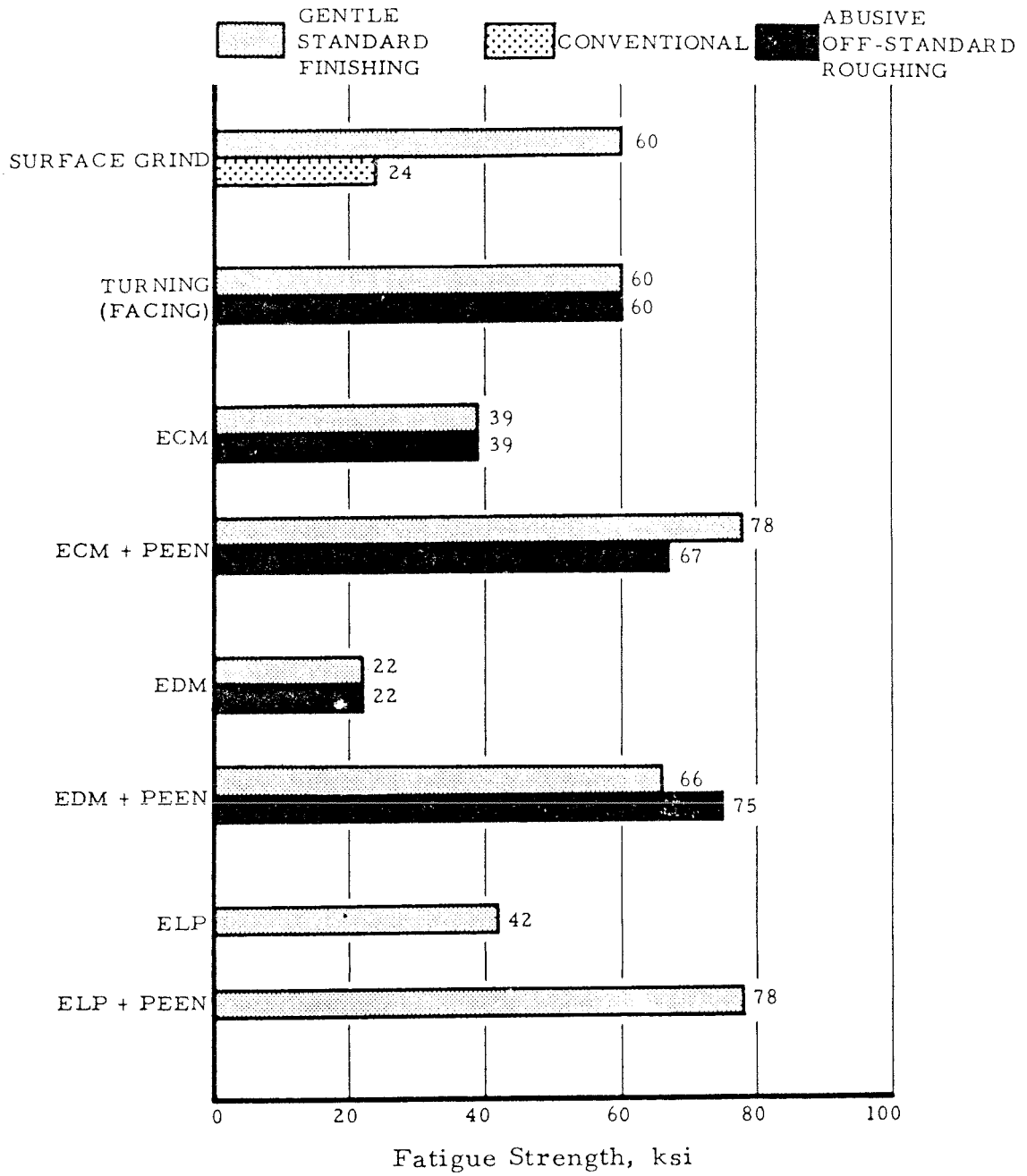


FIGURE 1 - SUMMARY OF HIGH CYCLE FATIGUE BEHAVIOR OF INCONEL 718, SOLUTION TREATED AND AGED (R_c 44)

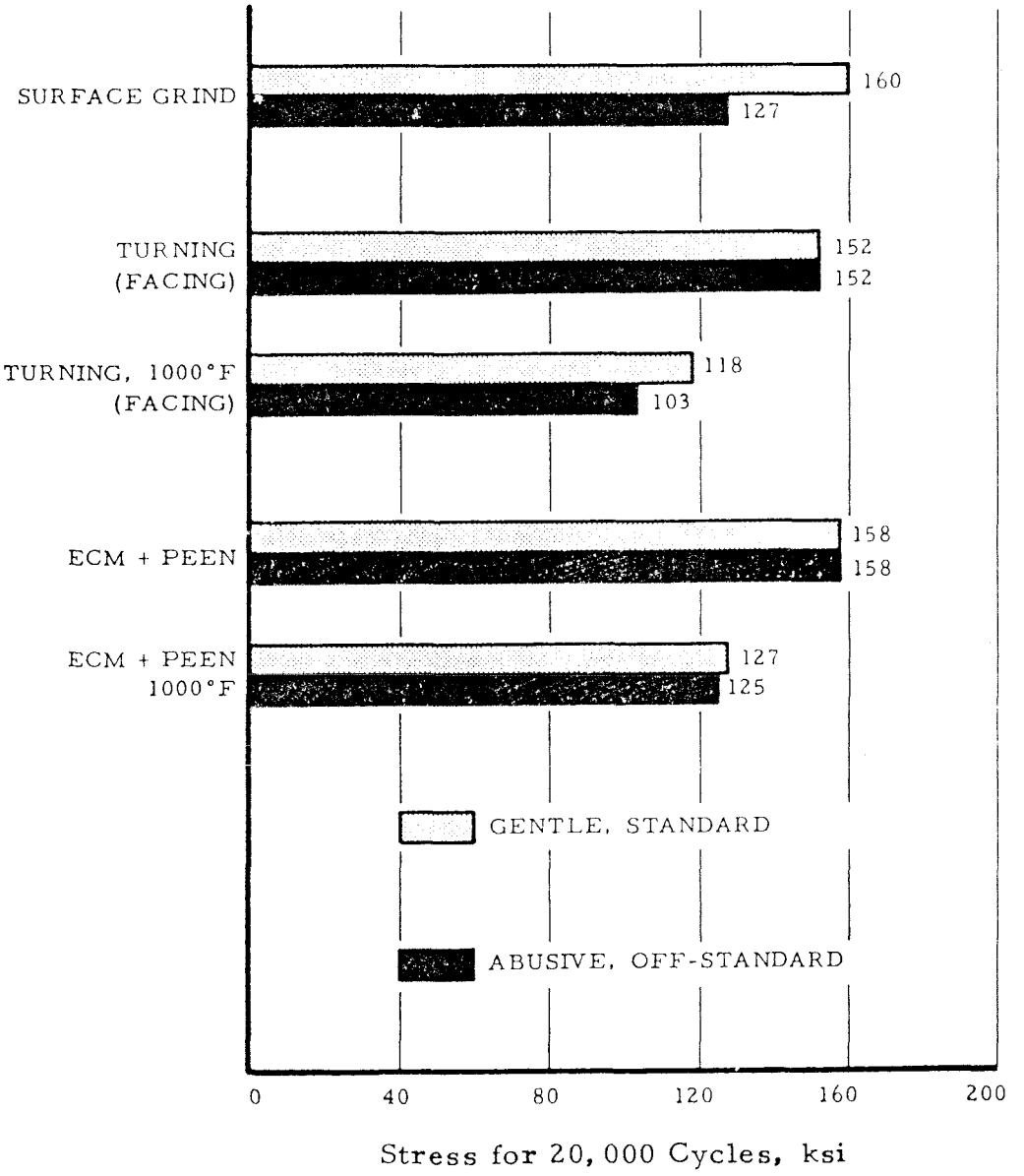


FIGURE 2 - SUMMARY OF LOW CYCLE FATIGUE BEHAVIOR OF INCONEL 718, SOLUTION TREATED AND AGED (R_c 44)

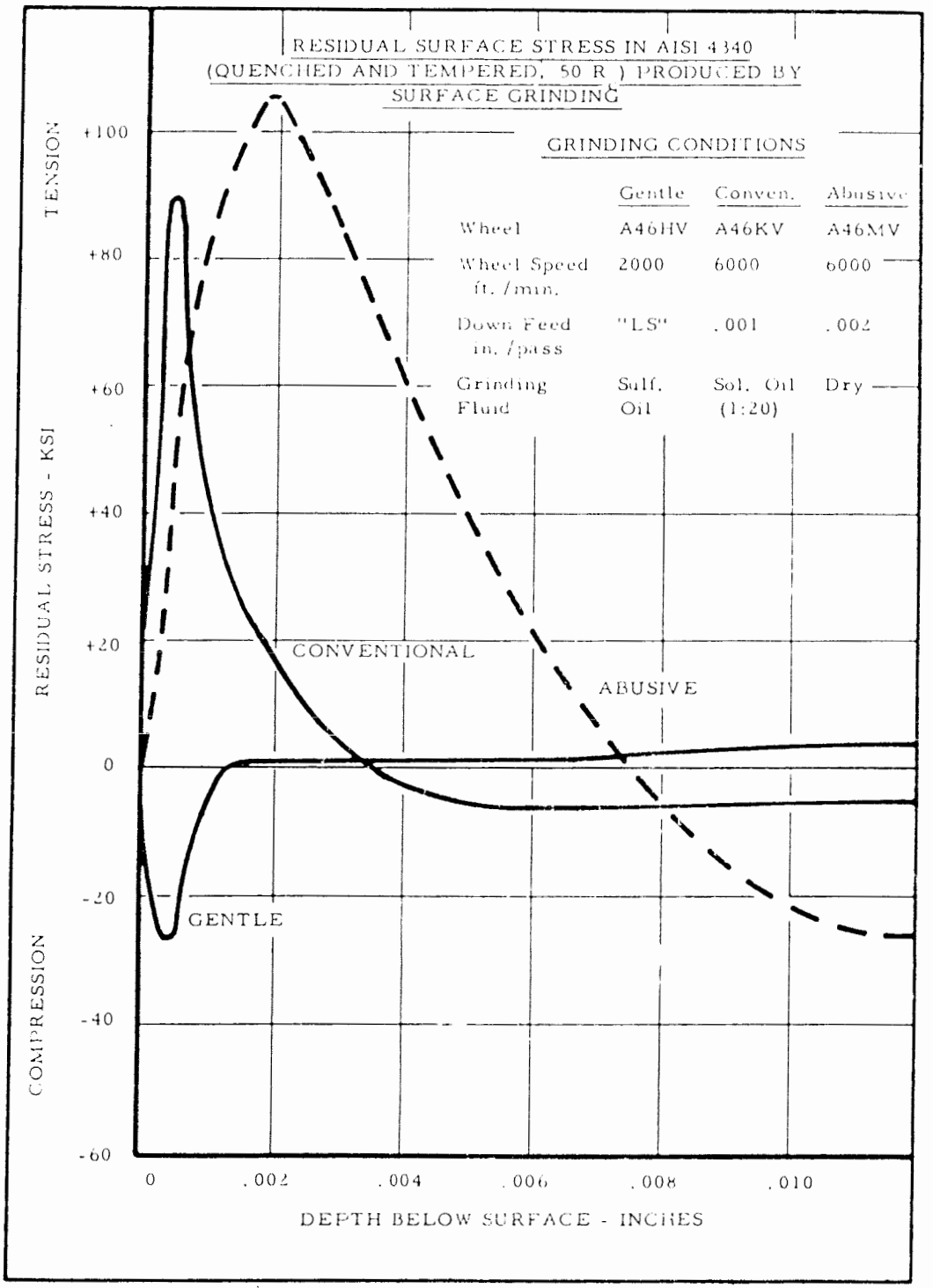


FIGURE 3 - RESIDUAL STRESS IN AISI 4340: SURFACE GRINDING

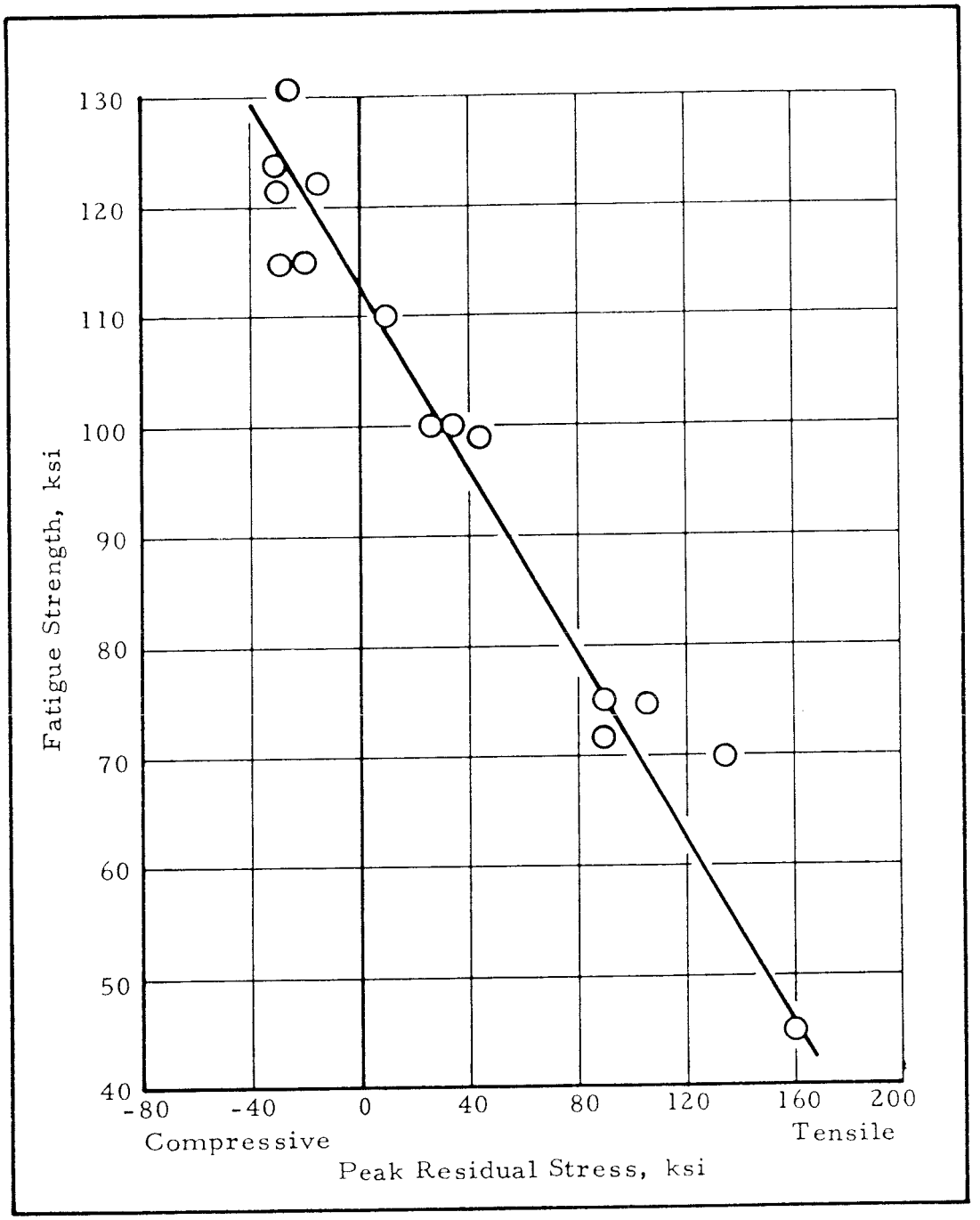


FIGURE 4 - FATIGUE STRENGTH VS PEAK RESIDUAL SURFACE STRESS IN GROUND AISI 4340, R_c 50

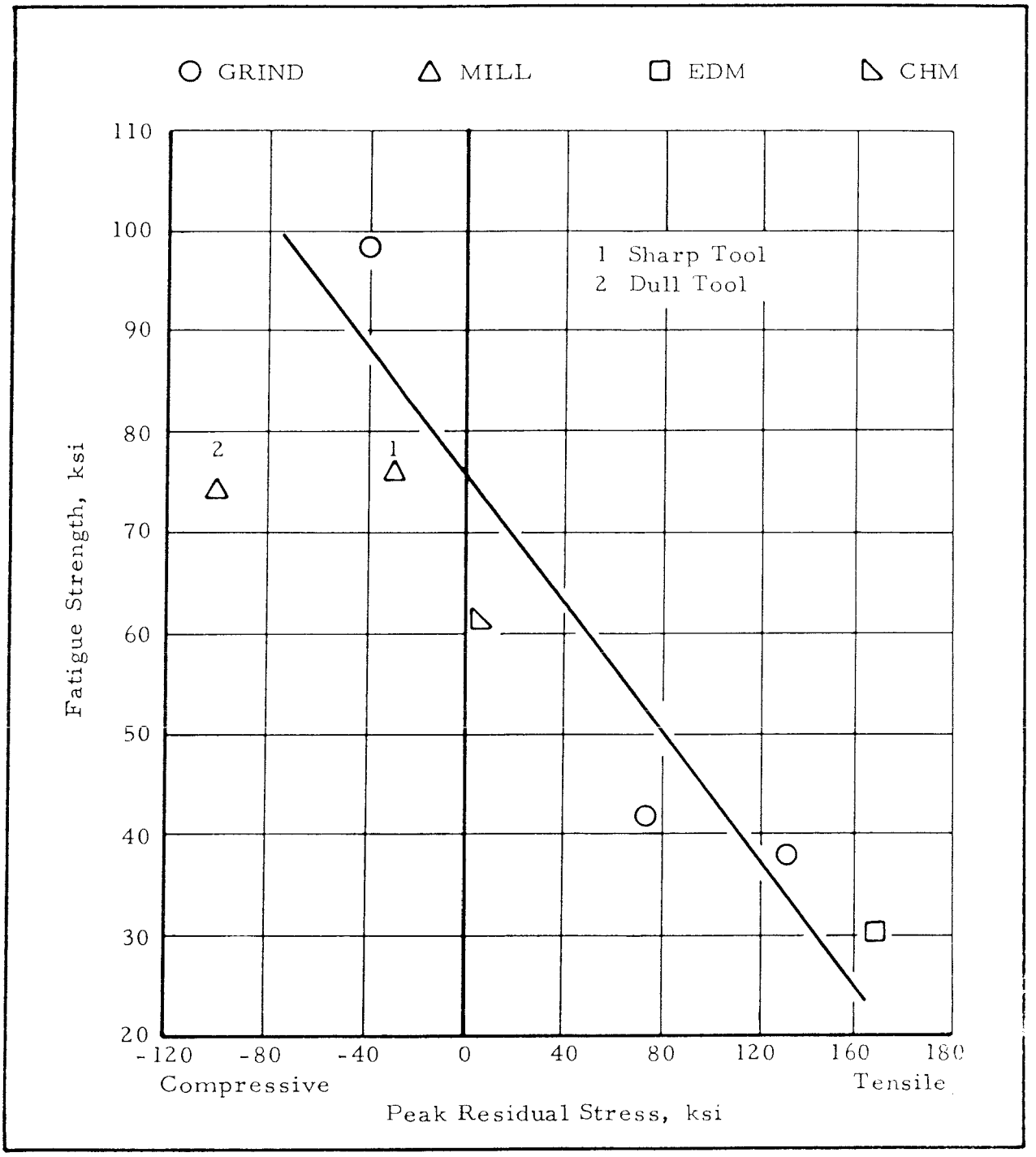


FIGURE 5 - FATIGUE STRENGTH VS PEAK RESIDUAL STRESS IN 17-4 PH, H900 CONDITION

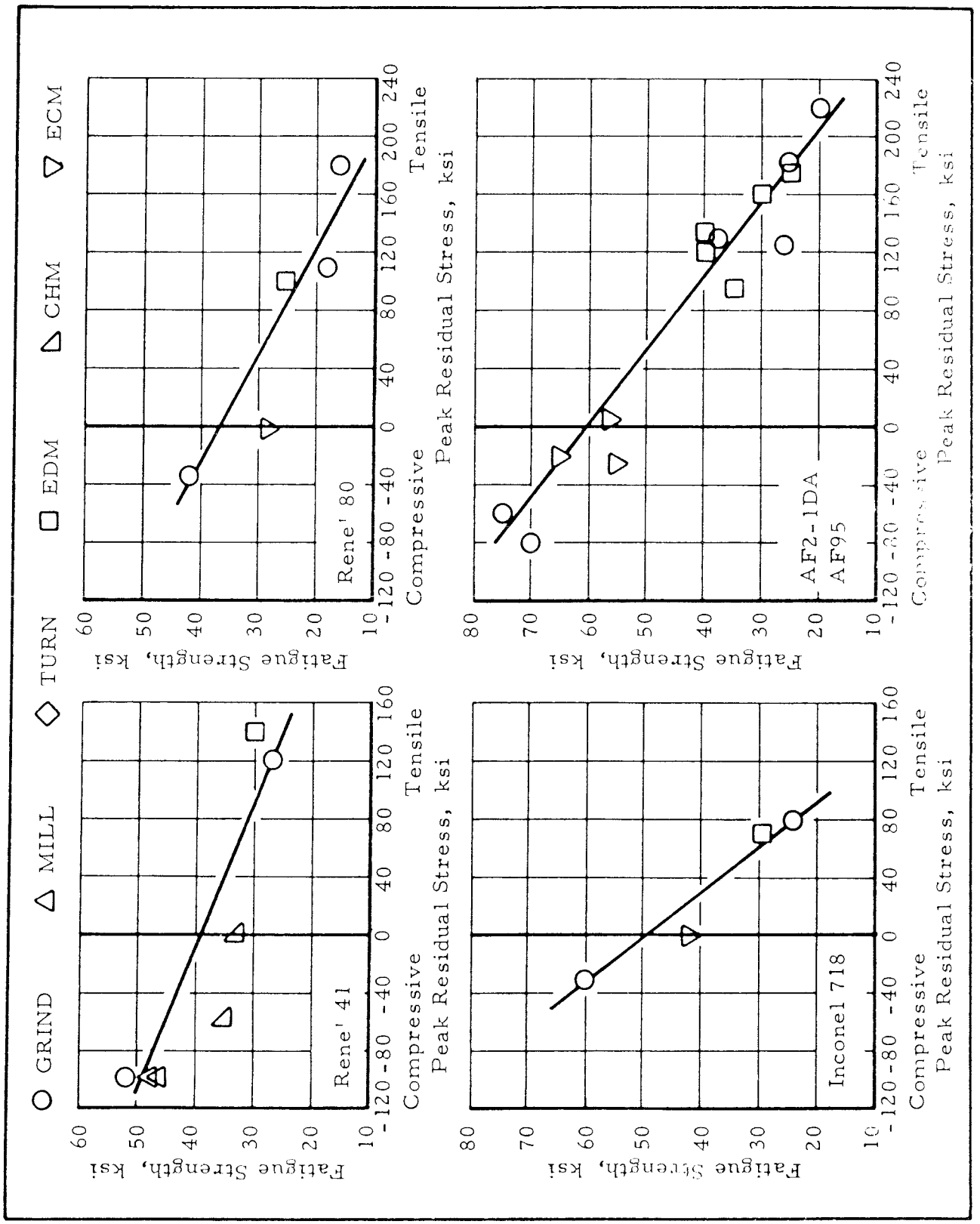


FIGURE 6 - SURFACE INTEGRITY SUMMARIES FOR A NUMBER OF NICKEL-BASE ALLOYS

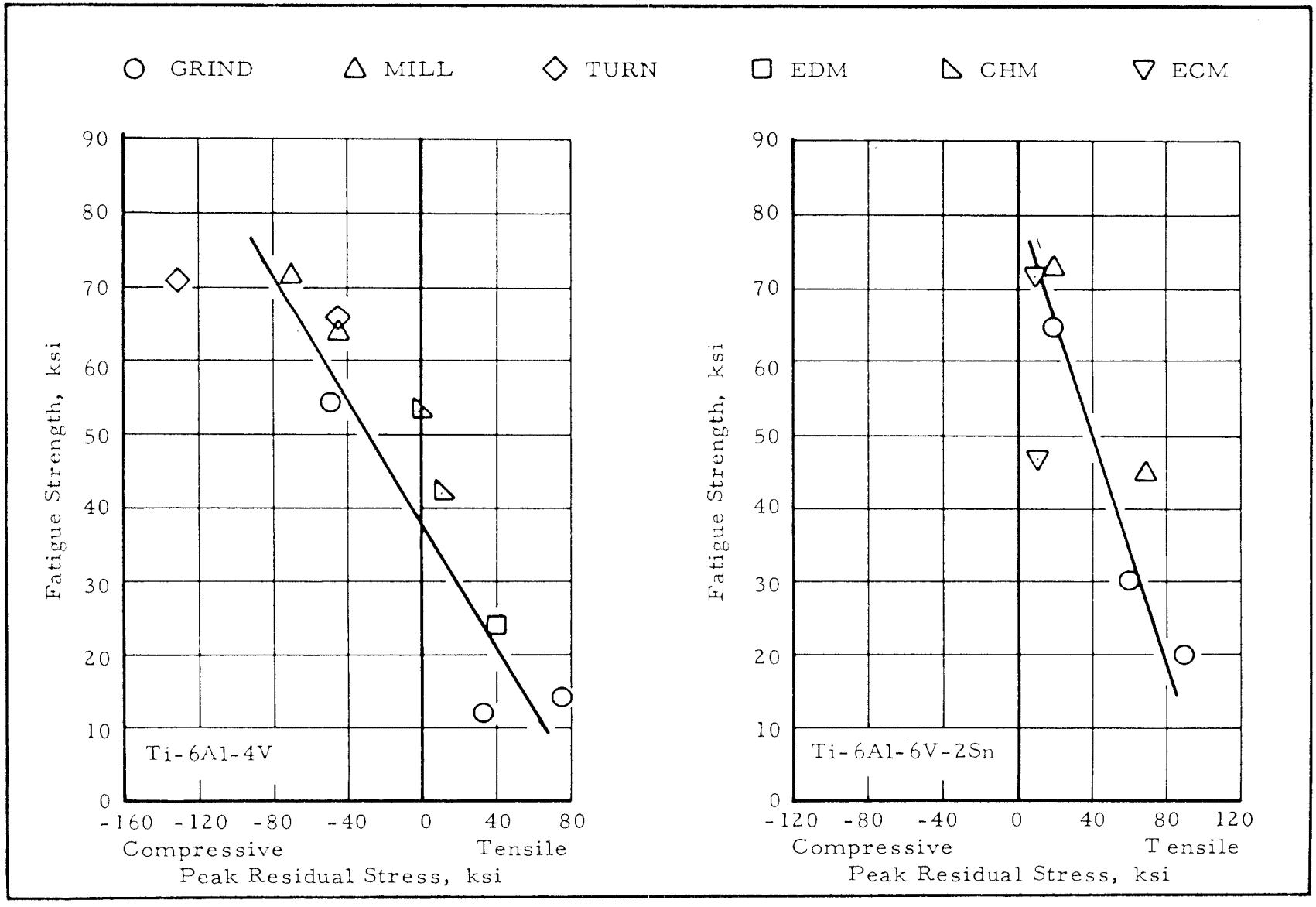


FIGURE 7 - FATIGUE STRENGTH VS PEAK RESIDUAL STRESS IN Ti-6Al-4V AND Ti-6Al-6V-2Sn