THE ROLE OF RESIDUAL STRESS IN THE PERFORMANCE OF GEARS AND BEARINGS

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SUMMARY

Residual stresses are an inevitable consequence of the manufacture and service conditions to which mechanical components are subjected. In this paper, a wide range of evidence is presented to show the decisive effect of residual stress, both pre-existing and service induced, on the performance of gears and rolling element bearings.

The results of measurement of residual stresses arising from a range of manufacturing procedures are presented, particular emphasis being placed on carburized steels. The effect of such stresses on fatigue performance is demonstrated. Possible causes of residual stress change during service are reviewed and the results of new experimental and theoretical work on the role of residual contact stress in a number of relevant tribological failure modes are presented.

INTRODUCTION

Interest in the topic of residual stress comes in waves. Such waves can be created by a wide variety of circumstances. Sometimes the originating disturbance is a practical problem such as was created by stress corrosion following the introduction of high strength aluminium alloys or by the discovery of the effects of grinding abuse in hardened steels. On the other hand, waves of equal ferocity have been generated by the development of new investigative techniques such as the new "fast" Xray diffraction methods and equally as often by theoretical advances such as the application of shakedown theory to rolling contact in the early 1960's.

It is remarkable, however, how little constructive interference there has been between these various sources of interest. In this paper, an attempt is made to review the role of residual stress in performance of gears and rolling element bearings. Particular emphasis is given to relating experimental and theoretical determination of residual stresses to the outcome in terms of performance. To this end, the paper is divided into two sections. The first deals with the - perhaps more widely accepted and understood - topic of the effect of pre-existing residual stress on performance. In the second part of the paper consideration is given to residual stresses arising during service. A new approach to residual stresses in plastically deformed asperities is presented and its consequence on tribological failure modes in aircraft components is discussed.

It is hoped that any ripples of interest which may thus be generated will not be too swiftly attenuated, whatever their wavelength!

PRE-EXISTING RESIDUAL STRESS

When a component has been manufactured, it practically always contains a locked-in stress distribution. In this section the nature of this pre-existing residual stress, its measurement and its effect on performance are considered.

Permitted Stress States

A residual stress state may be defined as one in which the boundary loads on the body in question are zero. Residual stress states are elastic, that is to say that the yield criterion is not exceeded by the residual stresses, and they obey the law of equilibrium. It is instructive to consider some of the restrictions this places on possible residual stress states. In cartesian coordinates, the equilibrium law is (in the absence of body forces) (1):

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} = 0$$

$$\frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} = 0 \qquad (1)$$

$$\frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \sigma_z}{\partial z} = 0$$

If we consider a uniform residual stress distribution near the surface of an infinite half space - a good approximation if the residual stress has arisen from a homogeneous surface treatment of a thick, flat, component - then the derivatives with respect to x and y will disappear giving:

$$\frac{\partial \tau_{xz}}{\partial z} = \frac{\partial \tau_{yz}}{\partial y} = \frac{\partial \sigma_z}{\partial z} = 0 \qquad (2)$$

where z is in the direction of the normal to the free surface.

As all these stresses must be zero at the surface because it is unloaded, then they are identically zero throughout and the only stresses which can exist are σ_x, σ_y and τ_{xy}. The body is in a state of plane stress.

A similar argument can be made for a uniform cylindrical body by expressing the equilibrium law in cylindrical coordinates. For a uniform, cylindrically symetric, stress state we have:

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_\theta}{r} = 0 \qquad (3)$$

This means that the stress perpendicular to the surface, σ_r, is not zero except at the surface but satisfies equation (3). If the surface of the body is at $r=R_0$, then since $\sigma_r=0$ at $r=R_0$ then the sign of σ_r just below the surface depends on the sign of σ_θ (Figure 1).

If σ_θ is compressive, for example, then σ_r will be tensile just below the surface of a cylinder ($r<R_0$) but compressive below the inner surface of a tube ($r>R_0$). Usually, the magnitude of σ_r is small in practice, but an important exception to this arises when a cylinder of small diameter is case hardened (leading to compressive, i.e. negative σ_θ). The magnitude of the tensile σ_r, component can then be quite large, and will rise to a maximum at the case-core boundary. Some case-core separation problems are probably related to this residual stress.

It may be felt by the reader that the necessity for residual stress distributions to satisfy equilibrium is something of a truism. However, many published experimental residual stress distributions do not appear to satisfy this law. For example, Mede et al (2) report residual stress measurements below the surface of a cylindrical body for which $\tau_{r\theta}\neq0$. If this measurement were correct it would imply that the stresses were not cylindrically symmetric and hence should very along the cylinder; such veriation was not reported however. The reasons for this type of discrepency probably lie in the measurement techniques. These are discussed briefly in the next section.

Measuring Residual Stresses

It is not always appreciated just how many different, but related quantities are covered by the description "residual stress". A large number of techniques exist for measuring residual stress and of these only one measures the fundamental quantity familiar to engineers. This technique involves measurement of strain relaxation during controlled, incremental removal of material. The commonest variant of the technique is the hole-drilling method, described by Bathgate (3) in which a hole is formed progressively in the surface and the radial strain relaxation measured using a strain gauge rosette. The technique can be made quite reproducible with care but suffers from the disadvantage of poor resolution of stress gradients and of very low sensitivity for depths greater than the hole diameter. It is also, of course, destructive though is not regarded so by some heavy industries where small holes can be tolerated.

Xray diffraction (XRD) techniques are also widely used for residual stress measurement and have become more popular in recent years with the devleopment of more rapid, automated equipment. However, XRD does not measure the same quantity as the destructive techniques and in many circumstances gives results which differ, sometimes by a large margin. The principal of the Xray technique is will understood and is shown in diagrammatic form in Figure 2. A recent review of theoretical aspects by Dölle is highly recommended (4). Measurements of normal displacement of crystal interpanar spacing are made as a function of direction. These may then be converted into stresses using a knowledge of the local elastic properties which must be obtained from a separate calibration experiment.

The XRD method has a number of attractive attributes. One is that it can resolve high stress gradients which can be of great significance in surface treatment technology and it can also detect residual shear stresses within the penetration of the Xray beam. The principal of this is shown in Figure 3. The presence of the shear stress component gives rise to different interplanar spacings with respect to forward or backward specimen rotation. However, Xrays are diffracted only by crystalline material of a particular phase which may not be in the same state of stress as non-crystalline regions (such as subgrain boundaries) or as material of other phases. When and whether such effects are important appears to depend strongly on the material and its strain history. A review of these effects which have been dubbed "pseudomacrostress" has been given by Cullity (5), who shows that magnetic effects, which are also sensitive to the stress, behave as would be expected from the XRD stress measurement.

Residual Stresses and Fatigue in Carburised Steels

In this section, the results of study of the fatigue properties of carburised steels is presented in conjunction with extensive investigation of the role of residual stress. The importance of a complete stress analysis, which includes consideration of residual stresses is demonstrated.

The purpose of the work was to examine the high cycle fatigue behaviour of gear material under conditions as close as possible to those encountered in helicopter gears. In particular, the related variables of tooth-root stress concentration, of carburised case depth and of applied mean stress, were arranged in such a way as to provide a realistic distribution of applied stress whilst still enabling the use of a simple, axially loaded, fatigue specimen. Of particular interest were the tooth root stress characteristics of the Wildhaber-Novikov conformal gears, which are used in the main gearbox of Westland Lynx and Westland 30 helicopters. Details of the tooth root stresses have recently been published by Astridge et al (6) and feature applied mean stresses in the compressive region.

The specimen is shown in Figure 4. Results of a 2-D finite element analysis of the specimen is shown in Figure 5. The stress concentration associated with the notch has a maximum value of about 1.7. Note that the region in which the applied stresses exceed the average stress in the reference section is confined to the carburised case. To find the actual stresses in this region we therefore require a knowledge of the residual stresses in the case.

Manufacture of the test specimens was carried out by techniques closely following those used for real components. The specimen notch was manufactured in the same manner as a preformed gear tooth root; that is by machining followed by heat treatment (case hardening) and finally shot peening. The details are shown in Table 1. The heat treatment adopted is also shown in Table 1. The effect of subzero treatment was investigated by omitting this process on half the specimens.

Residual stresses were measured using an Xray diffraction technique. By selection of suitable diffraction peaks it was possible to obtain residual stress values for both the metallurgical phases (martensite and austenite) present in the specimen case.

The specimens were tested under tensile, zero and compressive applied mean stresses, the ratio of alternating to mean load being held constant througout each series. The testing frequency was approximately 150 Hz. The results are shown in Figure 6 in the form of a Goodman diagram. Here the nominal endurance applied stress range (ignoring stress concentration) is plotted against the nominal mean stress (ignoring residual stress). The mean endurance limits shown were calculated, using a standard curve shape, from the individual fatigue lives.

During the testing it became evident that two types of failure were occurring. One of these involved fatigue initiation in the notch, close to the surface, usually at a depth just below the shot peened layer. The other form of failure originated in the uncarburized core of the specimen, at a number of locations. The proportion of failures obtained of each type was found to depend on the applied mean stress, there being more core-originated failures at compressive applied mean stress.

The performance of the 4% NiCrMo steel is superior under all conditions tested to the 3½% NiCrMo, the preferred steel in the U.S. Subzero treatment had little effect.

The results of the Xray diffraction work are shown in Figure 7. The upper part of the figures show the proportion of retained austenite present as a function of depth. The proportion of this phase is reduced but not eliminated by the subzero treatment.

A complex residual stress state is present. Very high compression is present at the surface and persists to a depth of about 0.1mm. This is the area affected by shot peening. At greater depths but still within the carburised case, a more moderate compression is present in the martensitic phase, but tensile stresses are present in the austenite. The stress in the austenite could not be measured for depths below 0.3mm for the subzero treated specimens and about 0.65mm for the untreated specimens because the diffraction peak became too weak, with declining austenite content, to locate sufficiently precisely. Subzero treatment, although reducing the total amount of austenite present, also has the effect of increasing the tensile stress in this phase. On the other hand, the compression in the martensite is increased by subzero treatment. In the core, the stresses are tensile.

The combined effect of the notch and the residual stresses are that both alternating and mean stresses differ between the two failure origin locations. In Figure 8 the real stresses at the endurance limit are plotted in the form of a Smith diagram for the standard material condition. Two series of approximately straight lines are obtained which coincidentally converge to the proof stress value for the core. Portrayal of the data in this form provides all the fatigue information required whilst at the same time allowing extrapolation to cases where the residual stress state is not the same. An important example of this occurs if the proportion of case to core varies from that used in the present experiments. Higher proportions of case give rise to higher tensile stresses in the core.

<u>Residual Stress and Critical Defect Size</u>

All materials contain defects. The size and distribution of such defects have a very substantial affect on fatigue performance especially for high strength steels of the type used for aircraft triboiogical components. In this Section an example is given of the analysis of the fatigue behaviour of a gear containing such defects in order to demonstrate the large effect of residual stress.

A service failure had occurred of a pinion gear. Investigation showed that the origin of the failure was in the (uncarburised) core, a region which was known to be very mildly stressed. However, the initiation of the failure was associated with a small pre-existing crack-like defect which had probably arisen during manufacture. Defects of this nature could be shown to reduce fatigue life in coupon tests but it was required to know whether such a defect could propagate under service conditions. An analysis was therefore undertaken, using linear elastic fracture mechanics, in order to determine the effect of service stresses on such defects.

It soon emerged that one of the major unknowns was the residual stress. A tensile residual stress acting transversely to the defect would allow crack opening over a much larger proportion of the stress cycle and would thus accelerate propagation. Equally, tensile stress would allow smaller defects to propagate at a stress which might otherwise be below the threshold. The effect of a constant tensile stress on the critical defect size to give the failure life is shown in Figure 9. Measurement of the actual residual stress in the bore of the gear shaft proved impossible but test pieces of similar section treated in the same way showed substantial tensile stresses of approximately 300 MPa. The critical flaw size was therefore of the order 10^{-1} mm, comparable with that of the observed defects.

The effect of flaw size on life for different constant residual stresses is shown in Figure 10. The residual stress has an overwhelming effect on performance. This investigation culminated in the removal both of the damaging residual stress and of the defects, by modification of the manufacturing route. At the same time, a new differential eddy-current inspection technique was introduced to give further assurance of freedom from surface flaws.

Residual Stress and Rolling Contacts

The effect of residual stress on concentrated contacts is a more difficult problem than that considered in the last section because of the complexity of the applied stress field. The simplest form of the problem is the effect on the static strength of concentrated contact. This merely requires the superposition of residual and applied stress fields and the application of a yield criterion to the resultant. Hills and Ashelby (7) and Broszeit et al (8) have recently pursued this line of work. In general, uniform compressive residual stress is beneficial, despite the compressive nature of the applied stresses, because it has the effect of reducing the difference between the principal stresses in the region beneath the contact and hence reducing the maximum shear stress. Yield is consequently inhibited. The compressive residual stresses produced by carburising, nitriding, mild grinding, shot peening etc therefore act to increase the static load carying capacity of surfaces.

However, the performance limiting factor for many aircraft gears and rolling element bearings is not static behaviour but pitting fatigue. This phenomenon is still not well understood despite having been the subject of much research. It does seem, however that compressive residual stress can improve pitting life (9). Equally, tensile stresses can reduce performance although it seems that the effect varies withthe direction of the tensile stress. Czyzewski (10) investigated the effect of a tensile hoop stress in a bearing race such as may occur when an inner race is shrink fitted onto a shaft or when an outer race is subjected to high centrifugal forces. He found a large reduction in life together with a change in cracking mode to give fracture of the race rather than pitting. Foord et al (11) and more recently Doumas (12) have applied tensile stress perpendicular to the rolling direction in combined bending/rolling experiments with soft, high carbon steels. The results show a small life reduction.

Much work still needs to be done in this area both in relation to residual and to combined applied stresses. One problem is that in pure rolling, failure does not occur until applied loads approach the elastic limit. This means that the real stress field changes during running. Even when sliding is applied, some plastic deformation is still likely under conditions which enable surface asperities to come into contact. These possibilities are further explored in the next section.

SERVICE INDUCED RESIDUAL STRESS

A number of ways exist in which the residual stress state in a component can change during its service life. All can play a decisive role in gear and bearing failure modes.

Thermal Stress Relief

Carburised steels of the type used in many gear and bearing applications at low temperature (Westland practice for carburised 4% NiCrMo steel is to temper at 140°C). Some bearing rolling elements are tempered at temperatures as low as 125°C. In the case of carburised steels, the effect of heating the component at a higher temperature than this is two-fold. One effect is to change the hardness: the effect of overtempering on the microhardness profile of a carburised case is shown in Figure 11. The surface hardness is in fact for moderate tempering periods at up to 200°C in this steel.

In addition, the residual stress distriubtion changes during overtempering. Kirk (14) showed that the beneficial compressive residual stresses produced during case hardening in the surface of the workpiece are rapidly relieved by thermal treatment in the range 100-200°C for ½% NiCrMo (8620 H) steel. He showed a corresponding reduction in fatigue properties. A similar investigation has recently been carried out at Westland for the 4% NiCrMo carburised steel, using 14 mm diameter specimens in rotating bending (zero applied mean stress). Again a significant reduction in fatigue performance has been observed even under circumstances where the surface hardness has not been reduced below the normally accepted minimum (Figure 12). Both these studies lead to the conclusion that satisfactory surface hardness does not imply that the performance capability of a component is uneffected after an overheating event; residual stresses may have been changed in a detrimental manner.

Residual Contact Stress

Of course it should not normally be the case that the operating temperature of a component exceeds its tempering temperature. However, when these temperatures are quite close as they often are for gear and bearing steels, changes which mimic overtempering may occur during running. The dark area sometimes observed in rolling element bearings of 1% CCr steel after long running times probably arise from this source. Thermal and/or cyclic softening allows plastic deformation to occur during prolonged running under the influence of applied loads.

The nature of the stress distribution which is induced by contact at loads above the effective yield has recieved much study and a review of the relevant theory has recently been presented by K.L. Johnson (14). If the applied loads exceed yield by only a small margin as is common in practical situations, the approach of Merwin (15) may be used in which the total strain is equated to the elastic strain. This is reasonable because the plastic deformation is contained by elastic material to a small sub-surface region. A practical consequence of this is that such plastic deformation is impossible to detect metallographically. Nevertheless the stresses generated may be large. Figure 13 shows the residual stress distribution in identical rollers measured in one instance without running and in another after running in a disc machine at an applied Hertzian stress of 2.8 GPa at a slide roll ratio of 0.026. An increase in the case compression has apparently occurred during running. The nominal applied loads are close to the elastic limit but slightly below it. Evidently under real running conditions some plastic deformation has indeed occurred leading to the increased compression. Thermal and cyclic effects may again be significant here.

Residual Asperity Stresses

One of to the most important problems now being tackled by tribologists is the modelling of rough surface contact. Significant advances have recently been made in dry (16) and in lubricated (17) rough surface contact for situations in which the contact is fully elastic. However, it is well established from both theoretical and experimental evidence that plastic deformation may occur on an asperity scale when rough surfaces come into contact (18). Such plastic deformation will inevitably produce residual stresses. A simple way to calculate such residual stresses has recently been devised in a collaborative project between the Mechanical Engineering departments of Cambridge University and Imperial College, London (19). It is based on the assumption that the asperity loads may be high enough to be in the fully plastic range. Such conditions are believed to occur during gear tooth and race/roller contacts when the surfaces are rough and when the lubricant film thickness is low, especially though not exclusively, during running-in. This problem, of stress analysis of fully plastic contacts,has recently received much attention, the most popular recent approach being that of the finite element method. Curiously enough, no complete stress distributions based on this technique have been published, however. Fortunately, a much simpler approach is possible using slip-line field theory which allows an analytical solution to be obtained. Slip-line field theory has been used previously for asperity plastic deformation problems, notably by Green (20) Johnson (21) and Challen and Oxley (22). The residual stresses are obtained by using the elastic solution, for the same pressure and tangential force distribution, as is obtained from the plastic analysis: the asperity is "elastically unloaded".

The results of these calculations are reproduced in Figure 14. They show some startling effects. The unloaded contact surface is left in a state of high residual tension. Some subsurface stresses are also tensile, but not in the region immediately beneath the contact where a high, predominantly hydrostatic residual compression is predicted. The subsurface, tensile, residual stresses have a characteristic inclination related to the direction of tangential force. There is a close parallel between the direction of this (calculated) residual tension and the direction in which cracks are observed to form during the early stages of rolling fatigue and related forms of failure. Such cracks form at a shallow angle to the surface (Figure 15) and depend on the direction of applied tangential force in a similar manner to the calculated residual stresses. No detailed understanding of the mechanism of formation of rolling fatigue and micropitting cracks is currently available, but it does seem likely that the presence of residual tension acting perpendicular to the embryonic crack would assist its development in the manner mentioned earlier and hence favour crack formation in the observed direction.

In conclusion, it seems a mistake to assume, as is frequently done, that the operating conditions of tribological components are entirely in the elastic range. A knowledge of the effects of service-induced plastic deformation, leading to characteristic residual stress distributions is expected to make a major contribution to the understanding of contact failure modes which currently limit the performance of gears and rolling element bearings.

CONCLUSIONS

The aerospace industries of the world - quite correctly - expend substantial effort in order to determine the applied stress regime to which components and materials are subjected. However it is becoming increasingly evident that a full understanding of the performance-limiting failure modes requires consideration of residual as well as applied stresses. This is particularly true of tribological failure modes where the applied stresses are predominantly compressive.

This paper has given some examples of the use of residual stress analysis, both theoretical and experimental in the development of such understanding. It is to be expected that many potential improvements in performance and reliability of aircraft transmission systems could result from the development and exploitation of residual stresses, especially in the design of new materials and processes. A prerequisite to such advances is the ability to predict residual stresses and to verify such predictions by accurate measurements.

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1. Composition

Element		C	Ni	Cr	Mo	Si	Mn	S	P
Weight %	4% NiCrMo	0.15	4.15	1.12	0.25	0.26	0.37	0.005	0.006
	3½% NiCrMo	0.16	3.29	0.99	0.24	0.22	0.46	0.006	0.005

2. Manufacture

Both steels were manufactured by consumable electrode vacuum arc remelting.

3. Treatment

The specimens were carburised 925°C to give a surface carbon content of 0.8±0.05% to a nominal case depth of 1.5mm. The temperature was then reduced to 850°C for 1h before air cooling. After carburising the specimens were annealed at 650°C for 6h and furnace cooled. The remainder of the treatment was as follows:

Hardening:	Reheated to 790°C for 1h, oil quenched
Subzero:	Cool to -60°C for 1h
Tempering:	140°C 4h
Shot Peening:	Almen intensity 0.35mm A2 using S170 shot

4. Core Static Tensile Properties

	Ultimate tensile stress/MPa	0.2% Proof/MPa	Elongation	Reduction of Area
4% NiCrMo	1413	1312	15%	60%
3½% NiCrMo	1397	1253	14%	62%

Table 1 Material and Heat Treatment Details for 4% NiCrMo and 3½% NiCrMo Gear Steels

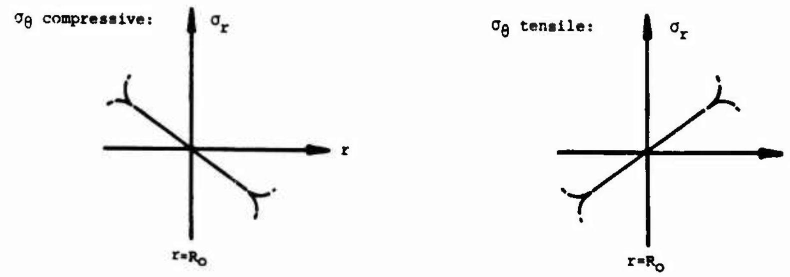
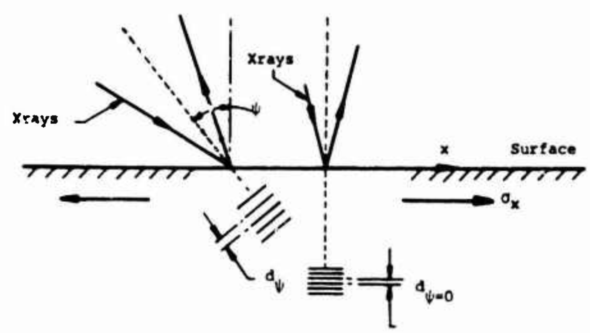


Figure 1
Radial Residual Stresses Near a Cylindrical Boundary



If σ_x is tensile $d_\psi > d_o$ $\quad \frac{d_\psi - d_o}{d_o} = \sigma_x$

Figure 2
Principal of Residual Stress Measurement by Xray Diffraction

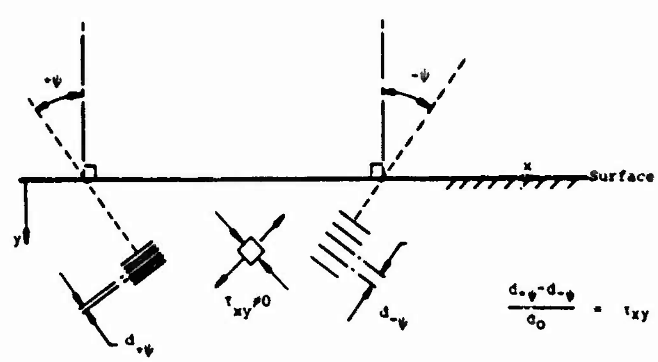


Figure 3
Principal of Residual Shear Stress Measurement by Xray Diffraction

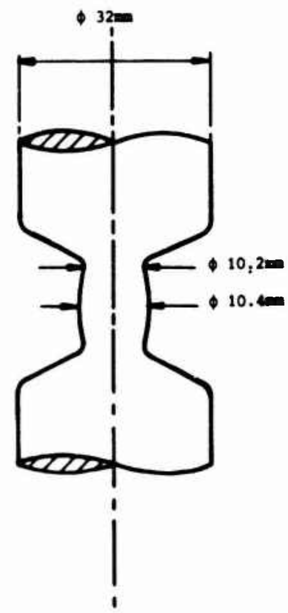


Figure 4
Direct Stress Specimen for Simulation of Tooth Root Fatigue Failure

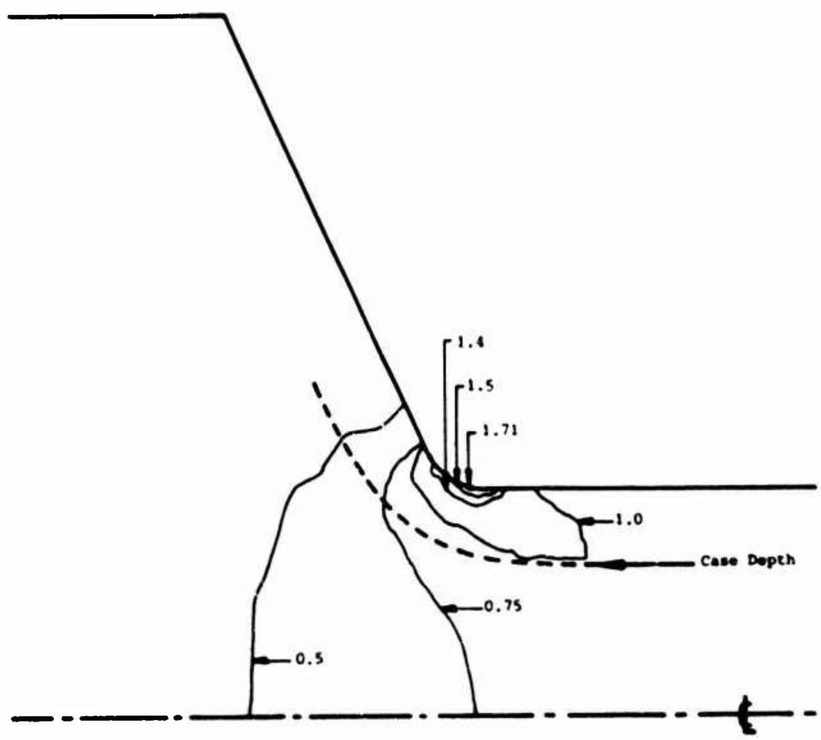


Figure 5
Finite Element Results for Fatigue Specimen Showing Contours of Stress Concentration

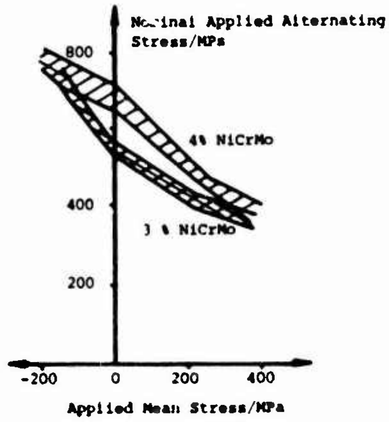
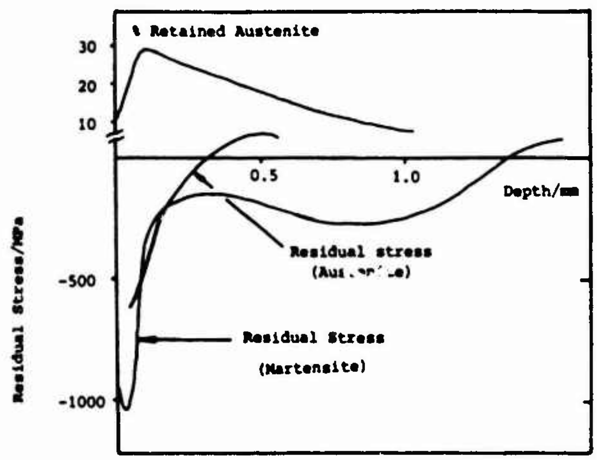
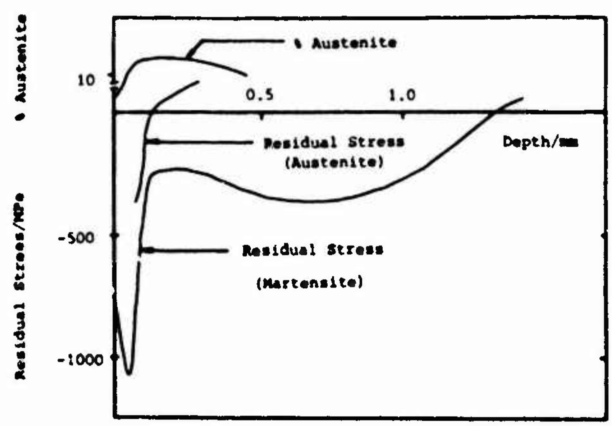


Figure 6
Goodman Diagram (RM Diagram) Showing Endurance Limits for 4% NiCrMo ar
3½% NiCrMo Steel



(a) Without Subzero Treatment



(b) With Subzero Treatment

Figure 7
Residual Stresses and Retained Austenite Content in 4% NiCrMo Carburised Steel

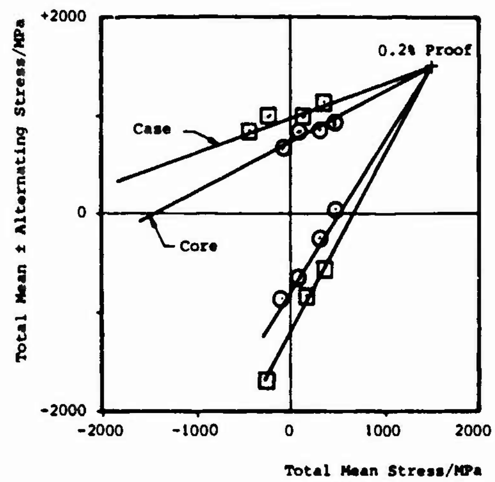


Figure 8
Total Stresses at Endurance Limit in 4% NiCrMo Steel

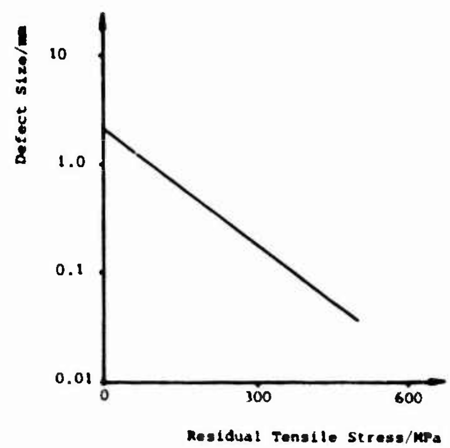


Figure 9
Effect of a Constant Tensile Stress on the Critical Defect Size to give a Constant Fatigue Life

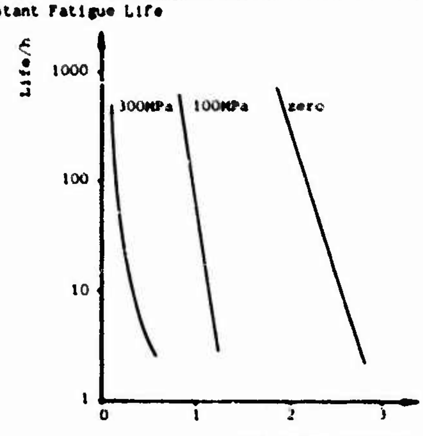
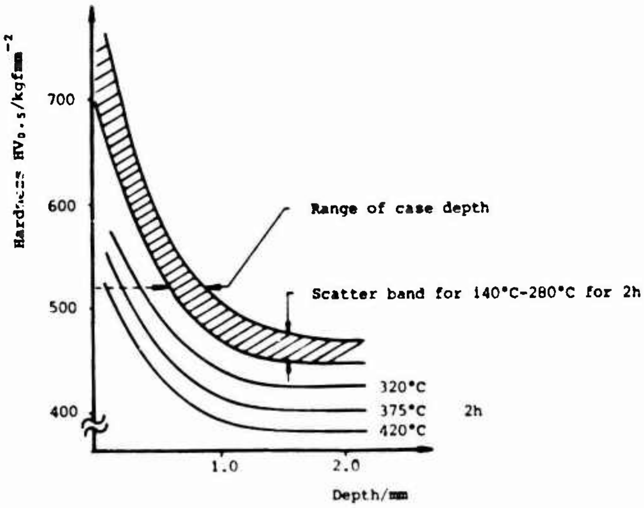
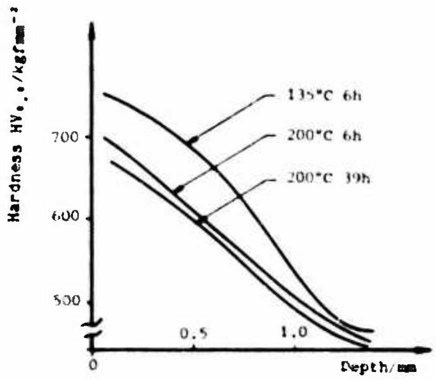


Figure 10
Effect of Defect Size on Fatigue Life for Different Constant Residual Stresses



(a) Short Term Tempering Data for 4% NiCrMo Steel
Carburised 8h, Reheated 790°C 30min, Oil Quenched,
Deep Frozen -65°C 1h, 140°C 2h, Retempered as shown



(b) Longer Term Tempering of 4% NiCrMo Steel, treated as for (a)

Figure 11
Effect of Tempering Temperature on the Case Microhardness Profile of Carburised 4% NiCrMo Steel

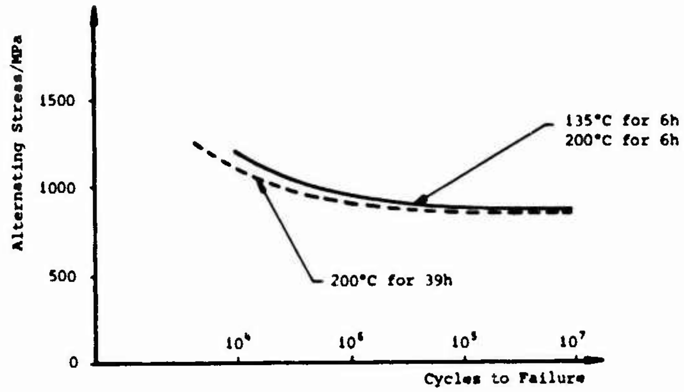


Figure 12
Effect of Overtempering on Rotating Bending Fatigue Properties of 4% NiCrMo Steel.
Test Section: 14 mm diameter

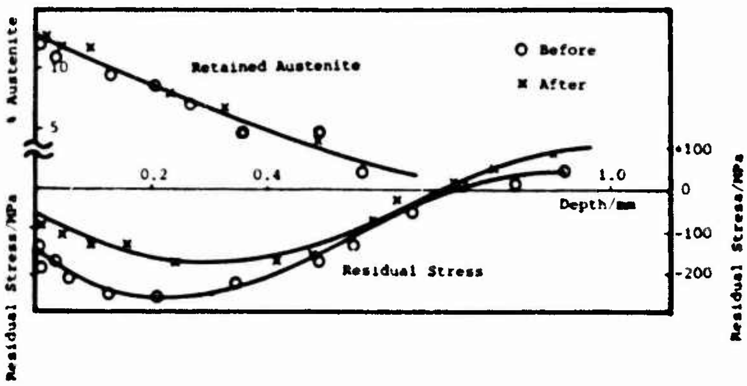
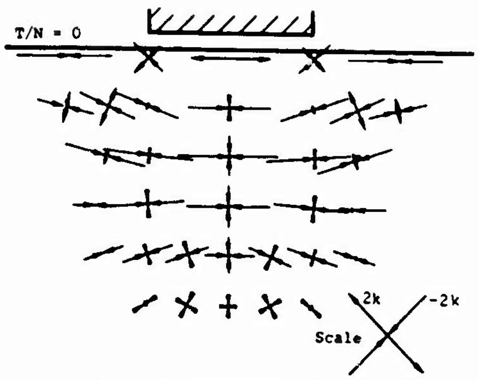
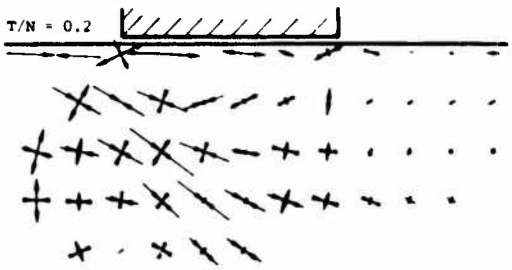


Figure 13
Residual Stresses in Disc Machine Roller Before and After Running at 2.8 GPa, 0.026 Slide/Roll for $2.2x10^6$ Stress Cycles



(a) Zero Tangential Load



(b) Ratio of Tangential to Normal Load = 0.2

Figure 14
Residual Stress Distribution, Calculated Using Slip-line Field Theory, for a Plastically Deformed Asperity Contact
k = yield stress in shear

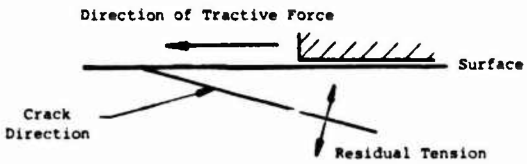


Figure 15
Crack Initiation Direction in Micropitting, Showing Relationship to Inclined Subsurface Residual Tension