DI-13

OPTIMUM HARDNESS FOR MAXIMUM FATIGUE STRENGTH OF STEEL

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ABSTRACT

Observations relating to an optimum hardness for maximum fatigue strength of steels are reviewed. Data are presented to illustrate the influence of hardness on the mechanical behavior of SAE 1045 steel. Suggested causes for decreased strength and ductility at high hardness are discussed,and the idea is advanced that a transition from shear to tensile governed failure takes place as hardness increases. Resistance to shear stress is envisioned as increasing with hardness while the resistance to tensile stress decreases causing a sharp drop in ductility and strength. This view of the fatigue resistance of hard steels suggests ways to improve performance of hard steels permitting the full strength potential to be realized.

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INTRODUCTION

The work of Garwood, Zurburg and Erickson (1) is often cited to illustrate that the fatigue strength of quenched and tempered steels may not improve and in fact may decrease beyond an optimum hardness (Fig. 1). Though their paper has had a large influence on ensuing investigations (2-9), it is not the first published evidence of an optimum hardness for maximum fatigue strength of steels. Lessells (10) in 1927 and French (11) in 1933 reported similar results.

Yield and fracture strengths also have been shown to decrease at high hardness. As seen in Table 1 a peak in strength with hardness has been measured for the elastic and proportional limit, offset yield strength, ultimate and true fracture strength as well as for the fatigue strength of steels.

The technological importance of improving the strength of hard steels is obvious. If the full strength potential of hard steels can be realized, completely reversed fatigue strengths in excess of 150,000 psi at long lives are possible and, in fact, have been achieved in rare cases (12, 16).

Acknowledgments: This investigation is part of a broad research program on the fatigue behavior of hard steels. The program was initiated in 1962 in the Department of Theoretical and Applied Mechanics at the University of Illinois in cooperation with Caterpillar Tractor Co.

LaSalle Steel Co. and United States Steel Corp. later joined in supporting this research. J. F. Millan, Caterpillar Tractor Co., Dr. J. L. Peterson, LaSalle Steel Co., and J. M. Holt, United States Steel Corp. are presently acting as technical representatives for their respective companies and R. W. Landgraf is in charge of the laboratory work.

LITERATURE REVIEW

Numerous causes for the drop in strength of steels beyond a certain hardness have been suggested in the literature. These have been categorized into three groups and are discussed below in order of their probable importance.

Susceptibility to Flaws and Defects: Inclusions, stringers, voids, microcracks, etc. have long been suspected as major causes for low strength of hard steels. As early as 1931, Lucas (7) observed nearly submicroscopic cracks that "may be starting points for fatigue failure." In the discussion to a paper by French (11), Bain stated "brittleness was associated with the minute cracks described by Lucas." Styri (12) found vacuum melting to improve fatigue resistance by eliminating "major defects in the steel." Olleman, Wessel and Hull (14) state that in monotonic torsion tests of hard steels "defects such as inclusions, porosity, or internal cracks determine the point where fracture will originate by tensile stresses."

Stulen and co-workers (18-21) have systematically investigated the effect of nonmetallic inclusions on the fatigue performance of hard steels. They clearly show fatigue cracks to start at inclusions near the surface, and the scatter in results can be correlated with the size of the inclusion nucleating failure. It was possible to achieve fatigue limits as high as the dashed extrapolated line in Fig. 1, even above 60 R_c (Rockwell Hardness, C scale), provided the maximum inclusion size was kept below about 0.0003 in.

Borik, Justusson and Zackay (16) report fatigue results for ausformed H-11 steel (61 R_c) which they believed to be the highest ever attained. Small elongated inclusions about 0.0005 in. long and about 0.0001 in. in diameter were found oriented parallel to the alternating stress.

Recent work in England by Duckworth and associates (22-24) emphasizes the desirability of ductility and the importance of reducing inclusion size to achieve satisfactory fatigue performance of hard steels. Quoting Duckworth (24); "The requirements for producing steels with a high fatigue limit appear to be a raising of the tensile strength to above 200 tons/sq. in. (450 ksi) while retaining a high ductility, and keeping the size of deleterious inclusions below 10μ (0.0004 in.)."

A little known result of the Garwood, Zurburg and Erickson investigation (1) further indicates that defects control the fatigue behavior of hard steels. They found the fatigue notch sensitivity factor, $q = (K_f - 1) / (K_t - 1)$, to decrease from 1.0 to 0.6 as the hardness was increased from 30 to 55 R_c for a 0.6% C alloy steel. Russell and Walker (5) later corroborated this result and suggested in their closure that hard steel is relatively insensitive to notches because the "smooth" specimens are already effectively notched by the defects.

Detrimental Residual Stress and Microstrain: In addition to their stress raising effect, inclusions are thought to be sites of high residual stresses caused by the differential thermal expansion between the inclusion and matrix. Surface tensile stresses may result from quenching as do high microstrains in the lattice.

Lessells (10) believed unrelieved residual stresses in the quenched condition adversely affected the fatigue strength and estimated a tensile mean (residual) stress of 100 ksi could account for the measured drop in fatigue strength at high hardness. On the other hand, French (11) believed residual quenching stresses were only partially responsible. Garwood, Zurburg and Erickson (1) found the maximum fatigue resistance to occur at a tempering temperature considered as a minimum for adequate stress relief. They concluded, "the decrease in fatigue properties at very high hardnesses is in all probability due to residual quenching stress that has not been relieved by the tempering operation."

Frankel, Bennett and Pennington (8) ventured that tempering below 400°F resulted in "very low fatigue strengths, possibly due to a residual stress pattern different from that in specimens tempered at higher temperatures."

Quenching stresses have been used in attempts to explain maxima in deformation resistance as well as in fracture resistance. For instance, Muir, Averbach and Cohen (2) stated, "the indications are that internal stresses due to hardening or quenching . . . have a detrimental effect on the elastic limit." According to them, the ideal temperature for annealing would give "an optimum combination of stress relief and retention of strength." Shih, Averbach and Cohen (3) showed quenching stresses to be relieved by annealing at 600-800°F where the elastic limit is also maximum.

Sachs, Sell and Brown (13) measured the surface residual tensile stresses and microstrains in several steels over a range of high hardness. They found both to increase with hardness and state, "microstrains cause early deviation of the stress-strain curve from linearity and tend to depress the elastic limit and yield strength." Tensile surface stresses in quenched samples of approximately 100 ksi were also measured, " arising primarily from compressive plastic surface deformations occurring during the quenching cycle." Borik, Justusson and Zackay (16) measured residual compressive stresses of approximately 40 ksi at the surface of ausformed steel specimens. These workers observed unusually high fatigue strengths while Sachs and others found little improvement beyond a certain hardness.

Metallurgical Factors: In addition to defects, quenching stresses and microstrain, other factors associated with metallurgical changes during the quenching and tempering operation and strain induced changes in the steel structure must be considered.

Muir, Averbach and Cohen (2) believed retained austenite that is removed above the optimum annealing temperature may play an important role, "but cannot be the only factor," In the discussion to their paper, Polakowski cites the concept of the Russian Kishkin, who "believes that tempering increases and not decreases the initial hardness of martensite" (25). Polakowski later expands this theory to explain the drop in elastic limit and fatigue strength at high hardness (26). He postulates that untempered martensite is initially soft but capable of rapid strain hardening. Although the bulk indentation hardness may be high since large strains are involved, fresh martensite may be as soft as 300-400 BHN which accounts for low elastic and fatigue limits at high apparent hardness. Our work and the work of Read, Marcus and McCaughey (27) support this idea since the monotonic strain hardening exponent for steel increases at high hardness after going through a minimum at an intermediate hardness.

There is conflicting evidence in the literature over the relative importance of retained austenite on the fatigue behavior of steels. For instance, French (11) believed that fatigue properties are actually enhanced by the retention of austenite. He looked upon the relatively soft ductile austenite as a cushion against fatigue failure under repeated stressing. On the other hand, Borik, Chapman and Jominy (6) found small percentage of nonmartensitic products to adversely affect fatigue strength. Frankel, Bennett and Pennington (8) showed retained austenite to reduce the fatigue strength, "apparently due to a transformation of some of the austenite that was observed to take place during fatigue stressing." Refrigerated samples (hardnesses below the optimum) had improved fatigue resistance. They hypothesized "that localized stresses resulting from an austenite-martensite reaction may nucleate submicroscopic cracks that lower the fatigue strength of steel."

Shih, Averbach and Cohen (3) who also refrigerated specimens to further transform the retained austenite, found that "the elastic limits of these specimens were identical with those of unrefrigerated specimens" and discount the importance of retained austenite. The importance of retained austenite is further discounted by Borik, Justusson and Zackay (16) who measured austenite contents in ausformed steels ranging between 5.5 and 7.4%; percentages which Frankel et al (8) reported to be deleterious in fatigue. Yet, for the ausformed steels, "high fatigue resistance was sustained in spite of such amounts of retained austenite." It is significant to note that the high strength ausformed steels exhibited ductilities in excess of 45% reduction in area though the hardness was over 60 R_c.

Role of Ductility: So far, emphasis has been placed on strength maxima at high hardness, with little consideration being given to the importance of ductility and toughness. The general trends in deformation resistance for quenched and tempered steels are as follows: Ductility as measured by tensile reduction in area (2, 3) and toughness (15) decrease slightly with hardness up to the strength maxima where they drop sharply approaching nil ductility for the quenched condition.

At the root of a notch or near an inclusion the magnitude of the cyclic strain is nearly proportional to the cyclic nominal stress on the member although the local cyclic stress may be less due to local plastic deformation. Fatigue life of the member which is governed by failure at the discontinuity will be determined by the capacity of the metal to resist repeated strain. The resistance of a metal to repeated strain is a combination of its resistance to cyclic plastic strain (fatigue ductility) and its resistance to cyclic elastic strain (fatigue strength). Thus, ductility as well as strength is important particularly when defects control fatigue behavior.

SHEAR TO TENSILE TRANSITION IN FAILURE MODE

Singly, the above suggested causes do not satisfactorily explain the poor mechanical resistance of hard steels, although each may be a contributor to a broader concept based upon a shear to tensile transition in failure mode as hardness increases.

Monotonic Torsion Behavior of Steel: Two distinct types of fracture result when steel is tested in monotonic torsion over a range of hardness (4, 14, 15). These are shown schematically in Fig. 2 and are labeled shear and tension failure corresponding to ductile transverse shear separation and brittle helical tensile fracture. Shear separation strength is believed to increase with hardness while tensile cleavage strength decreases with hardness as shown in Fig. 2. Maximum strength is achieved when the steel is in a condition such that shear and tensile fracture are equally probable. In this optimum condition mixed shear and tensile fractures occur causing the specimen to "shatter".

Ross, Sernka and Jominy (4) point out that shatter fractures "represent transition from shear to tensile failure with increasing hardness." In the discussion, Scott aptly states the concept of a transition in failure mode:

> "The cause of the maximum in static torsional strength is obvious enough if one examines the fracture surfaces in great detail. Olleman, Wessel and Hull have done so and find that maximum shear stress determines fracture on the softer side of the maximum, maximum tension stress on the hard side. Evidently shear fracture strength increases with hardness while the brittle or tension fracture strength is falling. Since the shear and tension stresses on their respective planes of maximum value are equal in the torsion test, a maximum in torsional strength occurs at the hardness level where the shear and tension fracture strengths are equal."

Effect of State of Stress: To illustrate the influence of state of stress, consider a steel at the hardness giving equal shear and tensile strengths and hence exhibiting maximum strength in torsion. Shatter fractures will occur in torsion; but in a tension test, failure will be by tensile fracture; while in a compression test, shear separation failure will take place as illustrated by the Mohr's circle in Fig. 3. It would be necessary to reduce the hardness somewhat before an optimum is reached in tension. Accordingly, when the hardness is such that the shear strength is approximately half the tensile strength, the optimum hardness for the tension test is reached. In the compression test no peak in strength should be reached by increasing the hardness since tensile stress is not present and shear separation strength, which increases with hardness, is the governing factor. Thus, for a given state of stress, the peak in strength for a particular steel is at a hardness which represents the optimum state of the material to resist with equanimity the shear and tensile stresses present.

The above discussion of the effect of state of stress on the optimum hardness for maximum static strength serves as a useful model for describing the drop in strength observed in the tension test, the peak in torsion strength at a higher hardness, and the absence of a peak in compression. However, it does not explain why there is a decrease in tensile strength at high hardnesses; instead it simply assumes there is a decrease. Neither does the supposed transition in failure mode explain why ductility and toughness generally decrease with hardness, nor does it indicate why the resistance to small inelastic deformation (elastic limit) also decreases beyond an optimum hardness.

Reduced deformation and fracture strength at high hardness, however, can be rationalized somewhat if one considers the level of microscale lattice distortions necessary to create high shear strength. Small amounts of inelastic strain may be triggered at low stresses because of the microstrains, and an effective reduction of the tensile strength may result from superposition of the applied and local stresses, resulting in localized brittle rupture and an attendant reduction in apparent ductility and toughness. Internal flaws, tensile macro residual stresses and weak metallurgical constituents may each contribute to the tendency for brittleness as suggested in the literature review.

Shear-Tensile Transition in Fatigue: One purpose of this paper is to examine the applicability of the above concepts to the fatigue behavior of hard steels. First, it is helpful to review theories of fatigue mechanisms. Virtually all fatigue theories are concerned with the classic question of why metals are weaker under repeated stress than under static stress. Three widely quoted theories are outlined below:

Griffith (28): Local brittle fracture is said to occur either in shear or tension depending upon the material and the stress state. The stress causing the local rupture is produced by volume changes in the slip bands due to repeated plastic slip (shear controlled). A local microcrack thus formed creates a stress concentration, allowing a greater amount of repeated slip at the crack tip, and the process is repeated. Eventually, the crack becomes energetically unstable as described by Griffith and sweeps across the entire specimen in a brittle tensile fashion.

Orowan (29): Orowan's approach is similar to Griffith's in that local fracture is said to be caused by cyclic intensification of the local stress. The local stress is said to build up due to repeated slip at discrete spots causing cyclic strain hardening. When the local stress reaches the fracture strength of the material, local rupture occurs. The process is repeated until culminated by brittle tensile fracture of the entire specimen.

Wood (30): At short lives, Wood accepts Orowan's theory of fatigue. At longer lives, however, Wood does not believe that the repeated plastic slip is large enough to cause cyclic strain hardening. Instead, the local fracture strength is reduced by repeated to-and-fro fine slip which causes abnormal lattice distortions leading to observable fissures early in the fatigue life. The weakening process is thought to be associated with a coalescence of point defects, surface intrusions and extrusions or perhaps a process of progressive unbonding. The distinctive feature of Wood's theory for "pure fatigue" is that the slip does not cause the local stress to increase to the local fracture strength, but causes the local fracture strength to be reduced to the local stress.

It is seen that these fatigue theories are based, in fact, upon a local transition from ductile to brittle behavior in the early stages leading to a larger scale transition

to brittle behavior as the crack elongates until the entire specimen fails by brittle rupture. The theories differ only in the mechanistic details by which the above processes are thought to occur.

Each theory hinges on a mechanism whereby the local stress and strength cyclically approach one another either by increasing the stress or by decreasing the strength as a result of repeated slip. In addition to the requirement of slip, there are also some fairly obvious facts about the brittle nature of fatigue.

1) The role of repeated slip is that of increasing the stress or decreasing the strength so that local rupture can take place.

2) Nuclei for cracks are initially present or may be created within only a few cycles from "flawless" material by minute ruptures set up by repeated slip.

3) Final failure is by brittle fracture.

The controlling factor in fatigue damage is normally the resistance to slip and shear fracture. Both are reflected by the indentation hardness which measures the resistance of a metal to large inelastic shear strains. However, at high hardness, it is suggested that resistance to shear stress is no longer the controlling factor in fatigue. Rather there is a transition to a tensile controlled fatigue process much the same as exists for monotonic fracture.

Fractographic Evidence: A number of direct references to a shear-tensile transition in fatigue can be found in the literature. Representative quotes are given below:

Forsyth and Ryder (31): "The striations observed in fatigue surfaces are of complex structure and could be produced by a brittle fracture/ductile fracture sequence in which voids are formed ahead of the crack tip." "From the evidence presented it is clear that the alternate dull and bright zones visible on fatigue fractures examined at low magnifications result, respectively, from fast tensile and slow fatigue crack growth." "The variation of growth rate along the crack front eventually leads to an unstable configuration and a burst of fast fracture ensues".... " It is now convenient to consider the fatigue specimen as a tensile test piece with a slowly moving Griffiths crack."

Stubbington and Forsyth (32): "At some stage in the fatigue life of all the specimens examined the failure changed from shear-mode to tensile-mode growth." "As the stress was reduced, the proportion of shear-mode growth to tensile-mode growth increased." "In the overaged condition (for aluminum) only tensile-mode crack growth was observed."

Christensen (33): "It may therefore be theorized that the mechanism of fatigue damage during crack propagation is nothing other than a series of progressive minute static ruptures."

Later micrographic studies of striation and ripple formation on fatigued surfaces by Forsyth (34) and Stubbington (35) further substantiate the shear-tensile nature of fatigue crack growth. Laird and Smith (36, 37) have interpreted the formation of ripples in a way that indicates the importance of local ductility. They believe the fatigue crack is advanced each cycle by blunting during the tensile portion of a fatigue cycle then "squeezed" together and sharpened during the compressive portion. The blunting is a result of excessive plastic deformation in the material just ahead of the crack.

While, the Laird-Smith model of crack growth and ripple formation may be appropriate for ductile metals in the low cycle fatigue region, it is not clear to what extent these ideas apply to the fatigue process in hard steels. Certainly quenched steel does not possess enough ductility to permit the necessary flow to blunt the crack tip as suggested by Laird and Smith. Instead, it seems more probable that local brittle rupture would occur first.

In conjunction with the preliminary experimental program on hard steels about to be described in the next section, fractographic characteristics of fatigued hard steel samples were studied (38). Increased areas of apparent brittleness and a lack of ripple marks were observed in fatigue specimens as the hardness was increased. The fatigue fracture surface of the quenched specimens was practically featureless.

MECHANICAL BEHAVIOR OF QUENCHED AND TEMPERED STEEL

We have found it difficult to locate in the literature comprehensive mechanical test data for a single heat of steel over a range of high hardness. It was, therefore, decided to investigate as completely as possible the mechanical properties and behavior of a typical quenched and tempered plain carbon steel (SAE 1045).

Monotonic Stress-Strain Properties: The early portions of the monotonic stress-strain curves are retraced in Fig. 4. Monotonic strength properties are shown in Fig. 5 as a function of hardness. A slight peak is observed in the yield strength and a somewhat larger peak in ultimate and true fracture strength. Of particular interest is the compression test result for the quenched condition. The compressive strength lies upon the extrapolation of the line for the true fracture

strength in tension. Failure was by violent shear separation on inclined planes, indicating no drop in shear strength at high hardness.

True fracture ductility is seen in Fig. 6 to decrease with hardness. Near the optimum there is a sudden decrease to virtually nil ductility. Also shown is the monotonic strain hardening exponent. It decreases with hardness up to a level of about 400 BHN then increases. In the quenched condition, the strain hardening exponent reaches a value almost as large as found in the fully annealed state. This observation is similar to that made by Read, Marcus and McCaughey (27).

Cyclic Stress-Strain Behavior: Uniaxial push-pull, load controlled fatigue tests were conducted on this steel (39). A large amount of cyclic softening was observed in the intermediate hardness range where the initial strain hardening exponent is low. Two examples of cyclic softening are shown in the lower portions of Fig. 7. Figure 8 further illustrates the pronounced cyclic softening. A small hysteresis loop began to develop at 40 cycles and continued to grow in width up to fracture at 245 cycles. Note that the cyclic stress amplitude of ± 170 ksi is considerably less than the initial yield strength of 198 ksi.

Even more surprising is the cyclically stable behavior (see upper portion of Fig. 7) at high hardness. In fact, a slight amount of cyclic hardening was observed in the quenched condition.

Fatigue Strength Properties: Fatigue strength properties as defined in Ref. (40) were determined at five high hardness levels of this steel. Stress-life plots for two conditions are shown in Fig. 9. The quenched steel is seen to have a lower fatigue strength than does the slightly tempered steel. The equations shown in the figure embody the fatigue strength properties. We have found the fatigue strength exponent to be consistently between -0.07 and -0.08, independent of the hardness in this high hardness range. From the fatigue properties, the fatigue strengths at various lives were determined and are plotted in Fig. 10 as a function of hardness. A decrease in fatigue strength at the highest hardness is evident but not as large as expected on the basis of data in the literature such as shown in Fig. 1.

Other Properties: X-ray determinations of microstrains have been reported for similar steels over the same hardness range by Evans, Ricklefs and Millan (41). Their work is reproduced in Fig. 11. The microstrains are seen to increase with hardness similar to the observations of Sachs et al (13) and Taira and Honda (42). Microstrains are reduced by surface cold working (shot peening) at high hardness and increased by working at low hardness. No change is seen at about 500 BHN.

Fracture toughness of the same steel has been determined by Sailors (38) and is found to decrease sharply above 500 BHN as shown in Fig. 12.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The observations on SAE 1045 steel coupled with the literature review permit the generalizations listed below to be made concerning the influence of hardness on the mechanical behavior and properties of quenched and tempered steels.

Summary of Results: For the purpose of this summary the potential hardness range for a given steel is divided into three regions designated as low, intermediate and high hardness.

1) Ultimate, fracture and yield strength increase linearly with hardness, deviate from linearity at high hardness, go through a maximum and may drop beyond an optimum hardness.

2) Compressive fracture strength, which is actually a measure of shear separation strength, does not drop from the linear relation at high hardness, indicating that shear strength continues to increase.

3) Ductility and fracture toughness are high and reasonably constant in the low hardness region, decrease steadily with hardness in the intermediate region and drop abruptly at high hardness.

4) The strain hardening exponent decreases with increasing hardness, goes through a minimum in the intermediate region and then increases, approaching values at high hardness that are as large as observed at low hardness.

5) Microstrain, which is an indication of lattice distortion, increases with hardness. Cold working causes a decrease at high hardness, increases it at low hardness and causes little change in the intermediate hardness region where the strain hardening exponent is minimum.

6) Pronounced cyclic softening takes place during fatigue of intermediate steels while quenched steels cyclically harden and slightly tempered steels are stable.

7) Fatigue strength increases linearly with hardness up to a point then deviates and may go through a maximum and drop at high hardness.

Causes suggested in the literature for the poor fatigue strength of high hardness steels include:

1) Increased susceptibility to defects and flaws, particularly nonmetallic inclusions.

2) Detrimental residual stresses and microstrains caused by quenching that are unrelieved at low tempering temperatures.

3) Weak metallurgical constituents that cause low fracture strength and low deformation resistance.

We have interpreted the drop in strength in a mechanics of materials sense as a transition from shear to tensile governed failure. Shear strength is believed to increase and tensile strength to decrease with increasing hardness. Accordingly, hardness is not a valid measure of fatigue resistance at high hardness since if a correlation exists between resistance to tensile stress and indentation hardness it must be an inverse relation.

By regarding the poor mechanical resistance of hard steels as stemming from a transition in mode of failure, practical ways of avoiding the transition suggest themselves and many interesting problems for further research and study may be formulated.

Improving Fatigue Performance of Hard Steels: The suggested shear to tensile transition in fatigue failure mode furnishes a model to guide the selection, processing and application of hard steels to resist fatigue.

To select the best carbon content for achieving high fatigue strengths in steels requires a compromise between potentially high shear strength and high tensile strength. While the shear strength is potentially larger for high carbon steels the tensile strength may be low. On the other hand, a low carbon steel cannot develop the shear strength necessary for high fatigue resistance. Thus, medium carbon steel appears to be the best choice for optimizing fatigue strength, particularly when the ratio of tensile to shear stress present in the application is large.

Cleanliness is essential for high fatigue strength in hard steels. The maximum size of the defects (usually inclusions) in high stress regions is more important than their number. Inclusions smaller than about 0.0001 in. in diameter have little effect on fatigue behavior even in the hardest steels. Defects larger than about 0.001 in. in diameter will probably have a detrimental effect and limit maximum strength achievable.

From a practical viewpoint a good measure of the suitability of a steel from a defect viewpoint is the tensile ductility at the hardness to be used. If the % RA is greater than about 50% there should be no serious problems with flaws controlling behavior. If the % RA is less than about 25% flaws will probably control behavior and reduce the potential fatigue strength unless something is done during processing to reduce their influence.

Processing the metal should be done in such a way that the shear strength is increased without decreasing the tensile strength. Although this may at first seem impossible, ausforming apparently accomplished the desired effect.

Another way to avoid the transition to tensile governed failure is to avoid high tensile stresses at critical locations of parts. The surface is usually critical and can be thermally and mechanically treated to introduce large compressive residual stresses. Shot peening and surface rolling are popular production processes for this purpose. The benefit of surface cold working is at least two-fold. In addition to the introduction of desirable compressive surface stress, the high lattice distortions that are present in quenched steels are reduced lowering the tendency toward brittle behavior.

The large benefit to be derived from learning to induce the proper residual stresses at the surface of hard steels is illustrated by the following example. At Caterpillar Research, completely reversed bending fatigue tests have been conducted on untempered SAE 1045 steel (63 R_c) at stress levels approaching ± 225, 000 psi without failure in 10^7 cycles. To achieve this spectacular fatigue performance a surface compressive stress of approximately 250, 000 psi was introduced by a special severe quenching procedure.

Lastly, the shear-tensile concept of fatigue suggests that the type of application is important in determining the benefit of hardening the steel to improve fatigue performance. In members and situations where the applied tensile stress is large compared to the shear stress, excessive hardening might lead to difficulties. For example, consider several typical members such as beams, torsion shafts and contact rolling elements. The ratio of shear to tensile stress, as well as the optimum hardness, for these members increases in the order listed.

Areas of Further Study: Some of the topics presently being investigated are listed below along with a brief discussion of their significance.

1) The effect of mean stress on the fatigue behavior of hard steel is being studied from the standpoint of a shear-tensile transition. A tensile mean stress should lower the optimum hardness whereas a compressive mean stress should raise it. Information of this nature is needed to quantitatively evaluate the potential benefits to be derived from mechanically prestressing hard steel members.

2) Strain controlled fatigue tests are being conducted for comparison with fatigue behavior under stress control. Resistance to repeated strain is more appropriate for application to the fatigue behavior of large notched members since the material at the root of a discontinuity or near an inclusion is subjected more nearly to repeated strain than to repeated stress. The optimum hardness for resisting repeated strain is found to be lower than the optimum for repeated stress. The difference should be larger the shorter the desired fatigue life.

3) Cyclic stress-strain curves are being determined using the incremental step test described in Ref. (40). Several high hardness steels are being studied to determine the changes in the cyclic stress-strain behavior during fatigue. The pronounced cyclic softening observed in the intermediate hardness region and the cyclic hardening of quenched steels are of particular interest.

In addition to the above, further fractographic work is needed on fatigued samples of hard steel. Most of this type of research in the past has been done on aluminum with little attention being given to steels, especially hard steels. Of particular interest would be a detailed study of the role of defects such as non-metallic inclusions on the nucleation and propagation of fatigue cracks.

There are many other interesting and worthwhile areas of study involving the mechanical behavior and properties of hard steels. Improved mechanical test equipment made available in the last few years and increased technological interest in improving fatigue performance of hard steels make this area of materials research most timely.

In conclusion, it is our opinion that the optimum hardness for maximum fatigue strength of steels may well be the fully hardened condition provided the shear to tensile transition can be avoided by reducing flaw size, introducing surface compressive stresses and by further developing processing techniques capable of producing high strength while maintaining the ductility.

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TABLE 1

SOME EXPERIMENTAL EVIDENCE CONCERNING AN OPTIMUM HARDNESS FOR MAXIMUM STRENGTH IN STEELS

Authors	Ref.	Year	Strength Property Measured*	Remarks
Lessells	(10)	'27	Bending Fatigue Limit	Also Proportional Limit
French	(11)	'33	Bending Fatigue Limit	Thorough Investigation
G. Z. & E.	(1)	'51	Bending Fatigue Limit	Optimum at 45-55 R_c
Styri	(12)	'51	Bending, Torsion and Contact Fatigue Strength	No Obvious Peaks for 52100 Steel
S. S. & B.	(13)	'59	Bending Fatigue Strength	Also other Properties
F. B. & P.	(8)	'60	Fatigue Strength, 10^5 cycles	Optimum Higher than (1)
M. A. & C.	(2)	'55	Elastic Limit	Also other Properties
S. A. & C.	(3)	'56	Elastic Limit	Also other Properties
S. S. & B.	(13)	'59	Elastic Limit	Tension and Compression
Lessells	(10)	'27	Proportional Limit	No Peak in Ultimate
S. A. & C.	(3)	'56	Proportional Limit	Also other Properties
O. W. & H.	(14)	'54	Offset Yield Strength	Torsion, 0.35% Offset
M. A. & C.	(2)	'55	Offset Yield Strength	Tension, 0.2% Offset
S. A. & C.	(3)	'56	Offset Yield Strength	Tension
R. S. & J.	(4)	'56	Offset Yield Strength	Torsion
R. S. & J.	(7)	'58	Offset Yield Strength	Torsion
S. S. & B.	(13)	'59	Offset Yield Strength	Tension and Compression
M. A. & C.	(2)	'55	Ultimate Tensile Strength	Weak Peak in Some Steels
S. A. & C.	(3)	'56	Ultimate Tensile Strength	Also Impact Data
S. S. & B.	(13)	'59	Ultimate Tensile Strength	Optimum at 60 R_c
M. A. & C.	(2)	'55	True Fracture Strength	In Tension
S. A. & C.	(3)	'56	True Fracture Strength	In Tension
Emmons	(15)	'33	Fracture Stress in Torsion	No Peak in One Steel
O. W. & H.	(14)	'54	Fracture Stress in Torsion	Helical Fractures above Peak
R. S. & J.	(7)	'58	Fracture Stress in Torsion	Helical Fractures above Peak

* Peak in strength with hardness was observed unless otherwise noted.

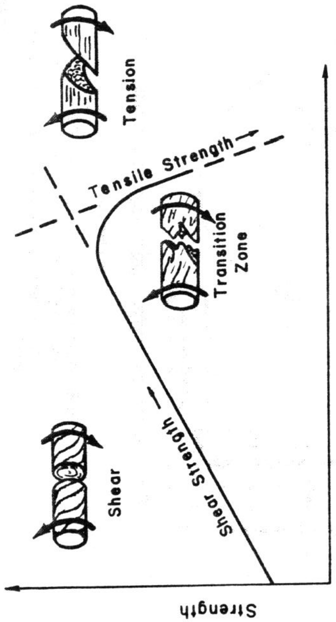

Fig. 2 Shear to Tensile Transition in Fracture Mode Due to Increasing Hardness

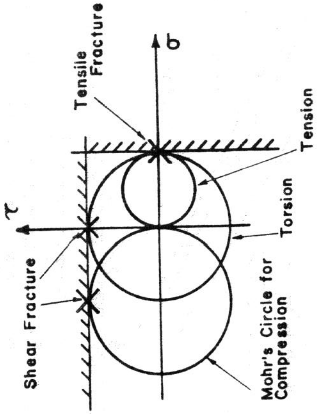

Fig. 3 Effect of State of Stress on Fracture Mode

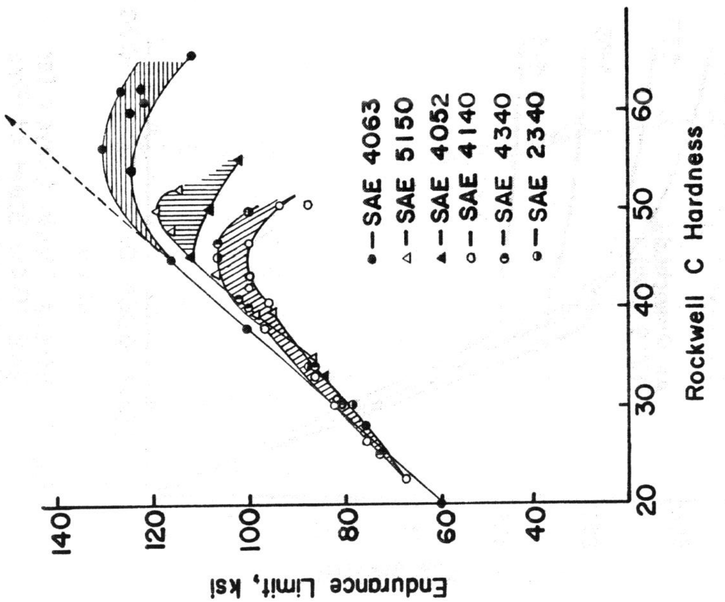

Fig. I Optimum Hardness For Maximum Fatigue Strength of Steels(I)

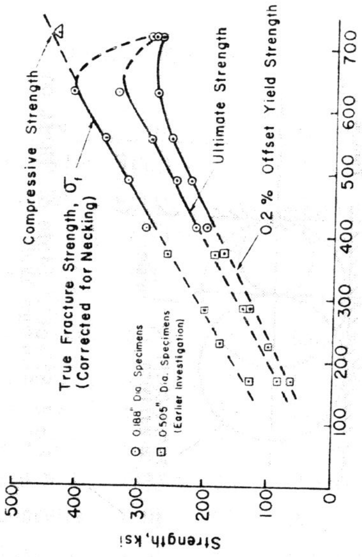

Fig 5 Monotonic Strength of SAE 1045 Steel as a Function of Hardness

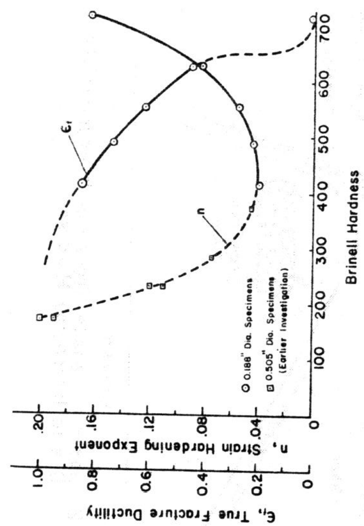

Fig. 6 Minimum in Strain Hardening Exponent at about 450 BHN and Drop in Ductility with Increasing Hardness for SAE 1045 Steel

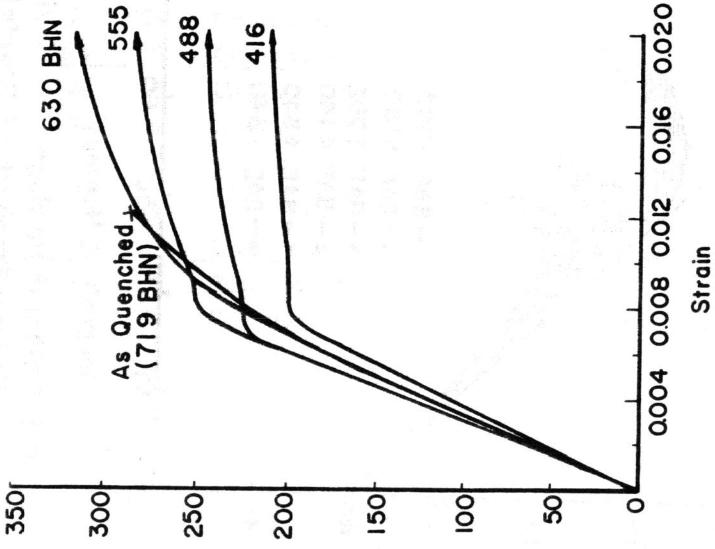

Fig. 4 Stress Strain Curves for SAE 1045 Steel at Five Hardness Levels

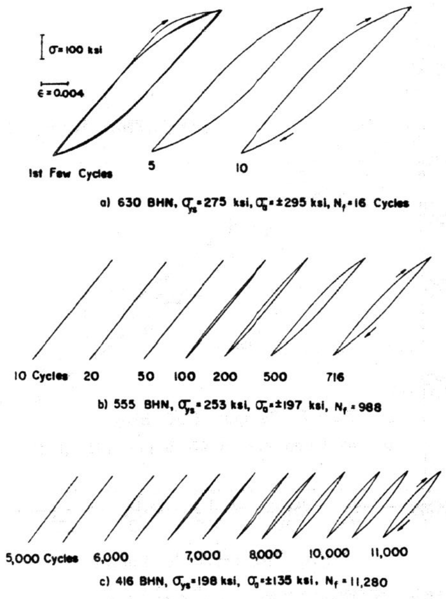

Fig. 7 Hysteresis Loops During Stress Cycling of SAE 1045 Steel at Three Hardness Levels

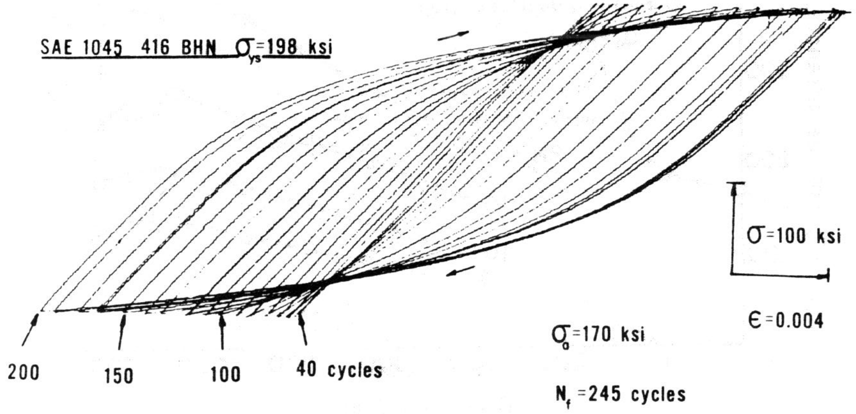

Fig. 8 Cyclic Softening of Medium Hardness Steel

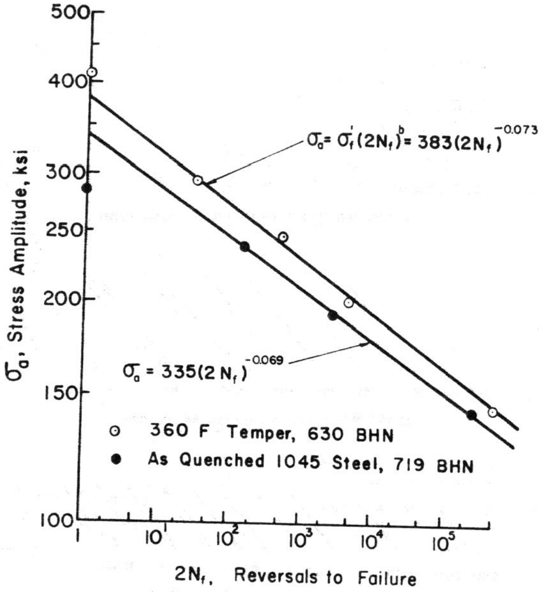

Fig. 9 Gain in Fatigue Strength Due to Slight Temper

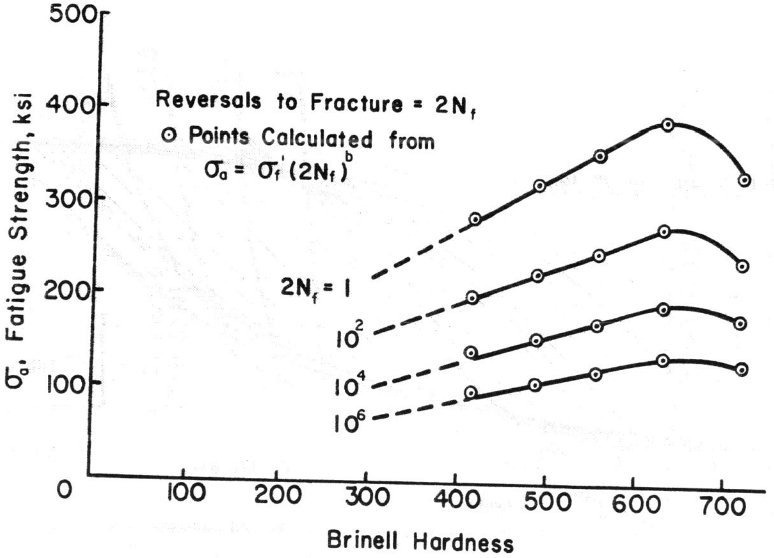

Fig. 10 Fatigue Strength of SAE 1045 Steel as a Function of Hardness and Life

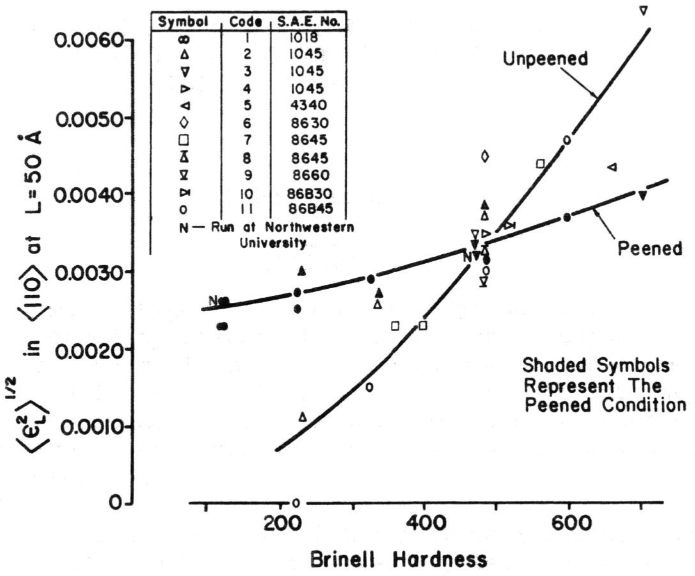

Fig. 11 Effect of Hardness and Peening on RMS Microstrain (41)

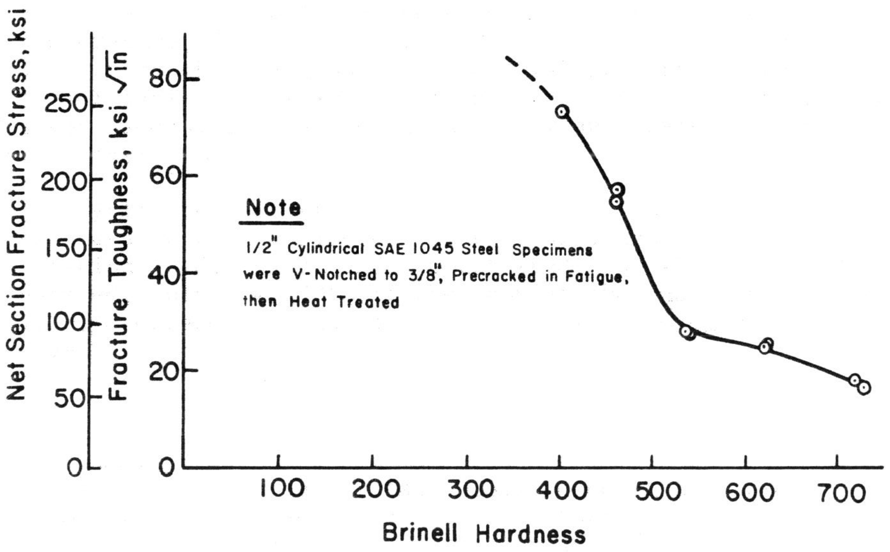

Fig. 12 Decrease in Fracture Toughness at High Hardness