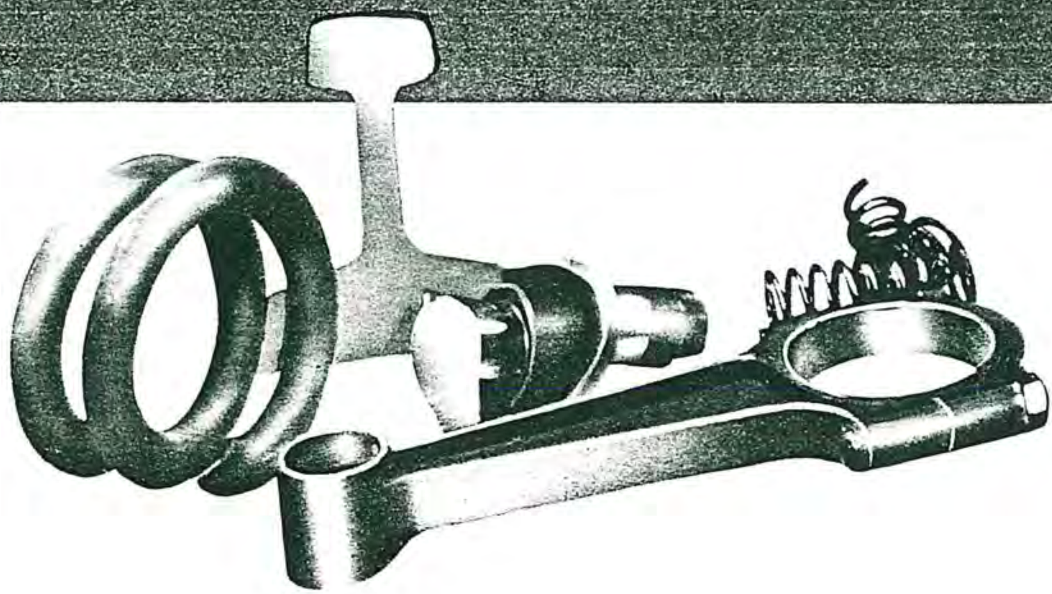
Fatigue WEAKNESS OF SURFACES



J. O. ALMEN

RESEARCH LABORATORIES DIVISION, GENERAL MOTORS CORPORATION

Shortcomings in current testing procedures and concepts that should be corrected by careful analysis and evaluation of the weakness of the surfaces of materials in fatigue. Machine parts are so far removed from ideal laboratory fatigue specimens that the latter are misleading as measures of worth.

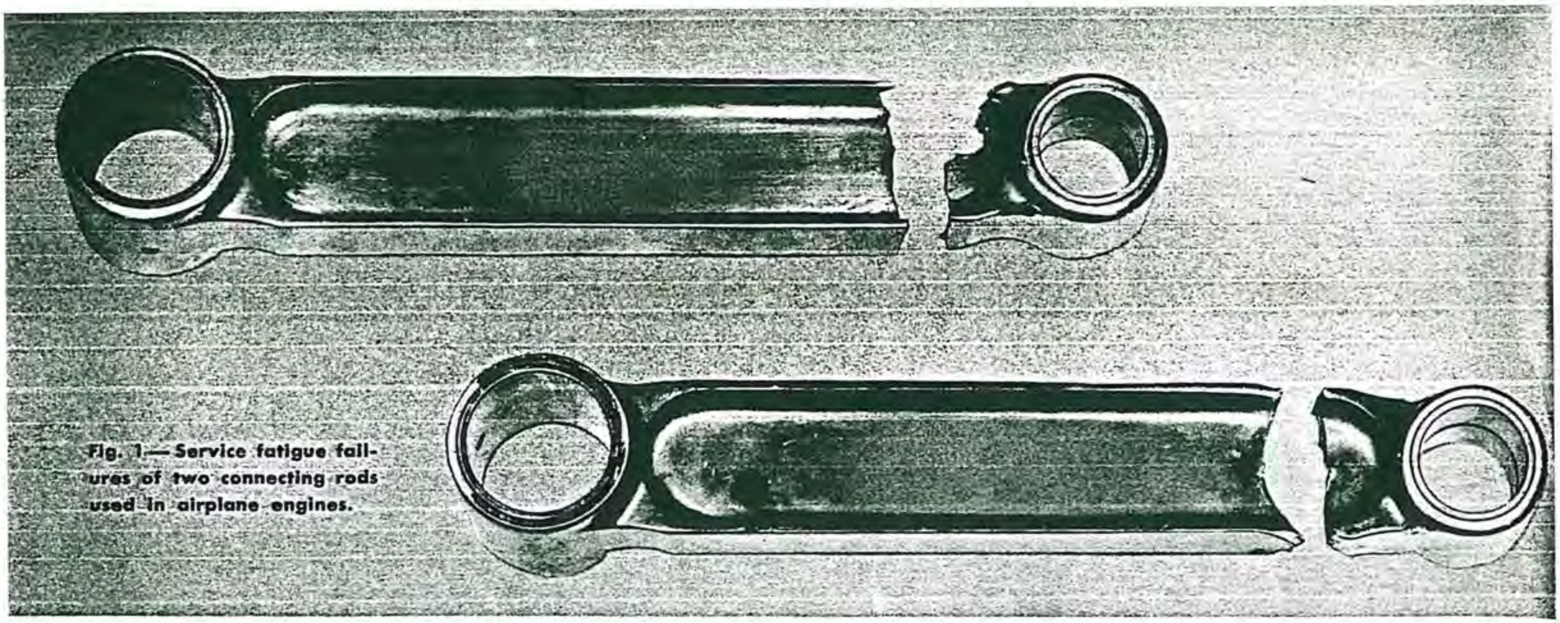


Fig. 1—Service fatigue failures of two connecting rods used in airplane engines.

Strength Theories Are Misleading

THE commonly accepted theories by which we try to explain fractures that occur in structural materials are based upon data obtained from static tests. These theories work well enough when applied to the kind of loads from which they were derived, but they fail when the conditions of loading are changed. We are now slowly awakening to the fact that these theories are incomplete, inaccurate, and often misleading.

The remarkable progress that has been made toward more effective use of materials in modern machine structures has been accomplished in spite of our faulty understanding of the behavior of metals under the various kinds of loads that are encountered in practice.

Because of inadequate understanding of the fundamentals that are involved, designers of high duty machines cannot proceed by orderly application of engineering principles. Instead, machine parts are dimensioned by a curious mixture of engineering formulas, empirical correction factors, and plain guessing based on unorganized experience. Under the present circumstances, experience is far more important in solving machine design problems than training in engineering "fundamentals."

No doubt progress will be more rapid and superior designs will be produced as we more clearly comprehend the fundamental nature of failure under each of the various methods of loading. It is hoped that the following discussion of surface weakness will help in some small measure toward a more complete understanding of problems associated with strength of materials including the role, for good or for evil, that is played by manufacturing processes.

Fatigue Weakness of Surfaces

Surfaces of structural materials, regardless of smoothness, are much weaker in fatigue than are sub-surface materials. As indicated by available data, the surface strength of steel fatigue specimens may be only a half that of the sub-surface metal. Because of the great difference in these fatigue strengths, almost all the tests that are intended to establish the fatigue strength of metals succeed in measuring only the strength of the metal surface.

Forged surfaces, machining marks, sharp notches, corroded areas, abrupt changes of section, and other discontinuities have long been known to detract from the strength of fatigue specimens. Obvious surface imperfections are now recognized as stress raisers; and many fatigue tests have been made to measure the extent of the damage caused by each major form of surface imperfection. The fatigue strength of specimens having "imperfect" surfaces is compared to the fatigue strength of specimens that are so carefully processed that all visible stress raisers are removed. These carefully finished specimens are erroneously assumed to yield true measures of the fatigue strength of the metals being tested.

The approved methods for determining the inherent fatigue strength of structural materials fail in their purpose because:

1. The processes applied in finishing the specimens introduce residual stresses of significant but unknown magnitude.

2. Under dynamic loads the elastic limit of ordinary structural metals is so low (Ref. 1) that plastic deformations, the extent of which varies with the manner of loading, often alter the stress continuously during a fatigue test.

3. The surfaces of structural materials are weaker in fatigue (Ref. 2) than sub-surface material.

Shot Peening Theories

Shot peening induces residual tensile stress in the unpeened sub-surface metal as well as residual compressive stress in a thin surface layer. The residual tensile stress in the "core" increases as the depth of the peened layer is increased. Also for constant depth of peening, the tensile stress in the core increases as the thickness of the specimen is decreased. The internal tensile stress must vary with the depth of peening and with the specimen thickness since, to satisfy equilibrium conditions, the compressive force in a surface layer that results from peening must be balanced by an equal tensile force in the core metal.

It will be shown that the residual tensile stresses in the cores of cylindrical shot peened specimens of various diameters are approximately the same magnitude as the presumed difference in stress between the surface and the metal immediately below the peened layer. And also, that the magnitude of the residual stress induced in the surface by the peening will be compressive, Fig. 2, and approximates one-half of the nominal yield stress of the peened metal.

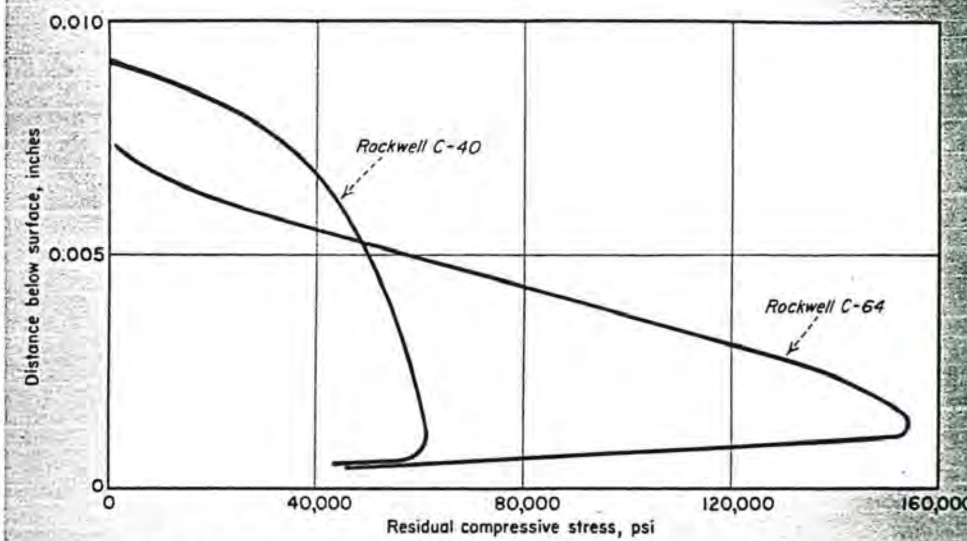


Fig. 2 — Magnitude and depth of the residual stress induced by shot peening varies with the yield stress of the peened metal.

Fig. 3 — Shot peened Belleville spring. Life of this spring and of many other parts is increased by production shot peening.

The increase in fatigue strength that follows shot peening is explained by two theories.

One theory holds that: (a) Surfaces are weaker under repeated loading than sub-surface material; and (b) Fatigue fractures can develop only from tensile stresses (Ref. 2). By this theory, the fatigue strength is increased because shot peening induces residual compressive stress in a thin surface layer (Ref. 3). As a result, the surface tensile stresses from external loads are reduced by an amount equal to the effective induced residual compressive stress. The observed gain in fatigue strength, therefore, results mainly from reducing the damaging tensile stress in the weaker surface metal with, perhaps, some increase in hardness.

The alternate theory assumes that cold working operations, such as shot peening, strengthen the surface layer by "work hardening" (Ref. 4). The resulting gain in fatigue strength, therefore, is a measure of the increase in strength that results from "work hardening," unless the fatigue fracture originates in the undisturbed metal immediately below the "work hardened" layer. The unpeened metal below this layer is assumed to withstand greater fatigue loads because, in beams subjected to bending loads, the stress in the sub-surface metal is less than the surface stress. The stress differences between the surface metal and the metal immediately below the peened layer must therefore be equal to or greater than the assumed gain in strength from "work hardening."

By the use of conventional assumptions, this stress difference can be calculated if the depth of the peened layer is known.

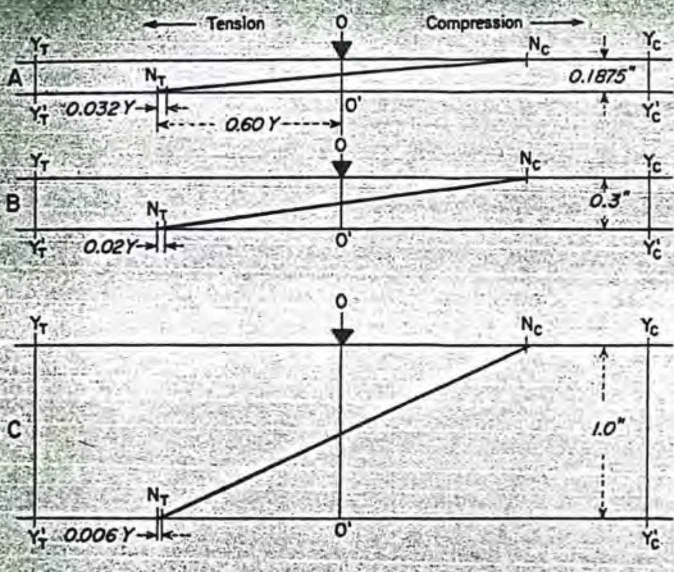


Fig. 4—Stress gradients and stress reduction at 0.005 in. depth in beams of different thicknesses when subjected to bending loads equal to 60 percent of yield stress.

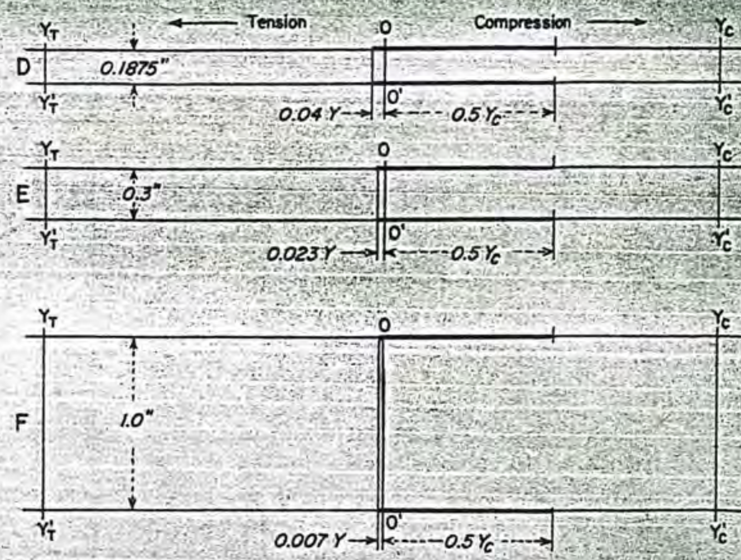


Fig. 5—Residual compressive stresses in the surfaces and residual tensile stresses in the cores of different cylindrical specimens that have been shot peened 0.005 in. deep.

Stress Gradient in Beams

Within the elastic range, the stresses produced in beams externally loaded in bending are assumed to increase linearly from zero at their neutral planes to a maximum in the outermost fibers. The relative magnitudes of the stresses in the sub-surface metal and the stress at the surface, are proportional to the distances from the neutral plane.

In Fig. 4 the diagrams *A*, *B* and *C* show the stress gradients from bending loads in three cylindrical beams. The diameters of the beams are 0.1875; 0.3; and 1.0 in. respectively. The bending loads, which act on the beams in a downward direction, stress the outermost fibers to 60 percent of the nominal yield stress *Y* of the metal. At any depth in each beam, the horizontal distance from the vertical line OO' to the diagonal line N_cN_t is the resulting nominal stress. The nominal yield stress of the specimens is the horizontal distance from the vertical line OO' to the vertical line Y_tY_t' for tensile yield, and to the line Y_cY_c' for compression yield.

In the smallest beam, diagram *A*, the distance from the zero stress plane to the surface is one-half the beam diameter or 0.094 in. The nominal stress at a fiber 0.005 in. below the surface is

$$\frac{0.60\,Y\,(0.094-0.005)}{0.094}=0.568\ Y$$

or 43.2 percent less than the nominal yield stress of the metal, and 3.2 percent of *Y* less than the nominal surface stress.

The nominal stress at a fiber 0.005 in. below the surface of the 0.3 in. specimen, diagram *B*, is 0.58 *Y*, or 42 percent less than the nominal yield stress of the metal, and 2 percent of *Y* less than the nominal surface stress. In the 1.0 in. beam, diagram *C*, the nominal stress at a fiber 0.005 in. below the surface is 0.594 *Y*, or 40.6 percent less than the metal nominal yield stress, and 0.6 percent of *Y* less than the nominal surface stress.

Equilibrium Conditions

The residual compressive stresses in the surfaces and the residual tensile stresses in the cores of shot peened cylindrical specimens that are required to satisfy equilibrium conditions are shown in Fig. 5. These specimens are of the same diameter as the bending fatigue specimens of Fig. 4, and assumed to be shot peened to a depth of 0.005 inch.

In the diagrams of Fig. 5, the nominal yield stress of the specimens is the horizontal distance from the vertical line OO' to the vertical line Y_tY_t' for tensile yield, and to line Y_cY_c' for compression yield. The distance $0.5Y_c$ is the maximum residual compressive stress induced by shot peening.

The resultant residual compressive force, which tends to lengthen the specimens, is exerted upon a hollow cylinder having an outer diameter equal to the diameter of the specimen and a radial thickness equal to the depth of peening.

Since the magnitude of the residual compressive stress from peening decreases with depth, the mean residual stress over the depth of the peened metal may be taken as two-thirds of the maximum residual stress induced by peening, or one-third of the nominal yield stress. From these values of the hollow cylinder area and mean stress acting upon that area, the force acting to lengthen the peened specimens may be calculated.

The resisting tensile force, which necessarily is equal to the lengthening force, may be assumed to act uniformly over the unpeened core area. From these data the magnitude of the resultant tensile stress in the core can be calculated.

By this procedure, the residual tensile stress in the unpeened core of the 0.187 in. dia specimen *D*, Fig. 5, is found to be approximately four percent of the nominal compressive yield stress. Similarly, the residual tensile stress in the cores of the specimens *E* and *F* are found to be 2.3 and 0.7 percent, respectively, of the nominal compressive yield stress.

Residual Core Stress Cancels Stress Gradient

When the peened specimens of Fig. 5 are subjected to the same bending loads as the specimens of Fig. 4, the maximum tensile stress in the core is the sum of the stress on a fiber 0.005 in. from the bottom surface of the beam, as calculated by the stress gradient, and the residual tensile stress in the unpeened core.

Thus, although the maximum stress in the core when calculated by the stress gradient is apparently less than the surface stress, the maximum core stress, resulting from the combined flexural stresses and residual stresses induced by peening, is greater than the surface stress. When specimens *D*, *E* and *F* are subjected to the bending loads of Fig. 4, the maximum core stress exceeds the surface stress by 1.33; 0.5; and 0.166 percent respectively.

Whether the depth of the peened layer is increased or decreased within the normal range of peening intensity, this relation between maximum core stress and surface stress in bending fatigue specimens is substantially the same.

Shot peening is only one of the cold working processes that induce residual compressive stresses in the surfaces of processed metals. The effects are much the same whether the stress is induced by honing, tumbling, or rolling, except that in honing the induced stress and the depth of the affected layer are considerably less than from ordinary shot peening, and in rolling (Ref. 35) the residual stress magnitude may approach the nominal yield stress of the metal.

Shot Peening More Effective on Hard Steel

Shot peening has been found to be more effective in increasing the fatigue strength of hard surface steel specimens than of softer specimens. By the alternate theory, this phenomenon would require more effective "work hardening" when shot peening steel of Rockwell C 62 than when peening steel of low hardness.

Little if any measurable increase in hardness, however, can be detected after peening very hard steel. Also, as is shown in Fig. 2, the depth of the peened layer in the harder steel is less than in the softer steel. For this reason, the fatigue strength should decrease instead of increase with hardness, since the nominal stress difference between the surface and the unpeened sub-surface metal would be reduced.

These data support the theory that shot peening is effective in increasing the fatigue strength because the residual surface compressive stress offsets, in part, the inherent weakness of surfaces that are subjected to repeated loads.

The theory of increased fatigue strength of surfaces by "work hardening" is further weakened by the relationship between indentor hardness measurements and surface stress shown in Fig. 6. The data recorded in this chart were obtained from steel disks that were deformed from a plane surface toward spherical shapes for the purpose of developing bi-axial stresses in the surfaces.

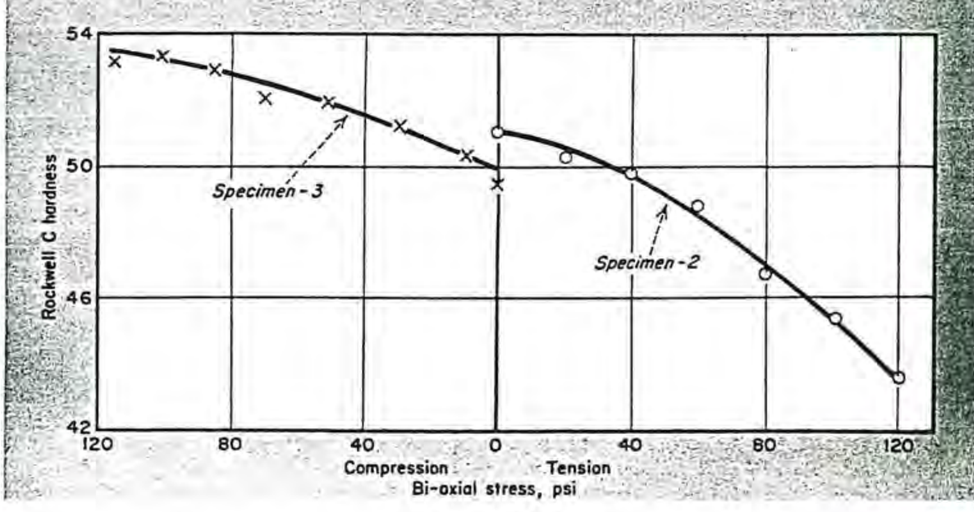
Five Knoop hardness readings were taken at equal angular intervals for each of several stress levels within the elastic range of the specimens. The plotted points are the average of the five readings converted to the Rockwell C scale. Note that compressively stressed surfaces appear to be harder than the unstressed specimens, and that tensile stressed surfaces appear to be softer.

This apparent hardness change is to be expected from instruments that measure hardness by indentations, because such instruments are also crude measuring devices, as was noted by Crampton (Ref. 8) in testing the hardness of drawn brass tubes. Compressively stressed surfaces resist penetration by the indentor more than tensile stressed surfaces do. Since the depths of the indentations are taken as measurements of relative hardness, errors in real hardness in residually stressed metal are unavoidable.

Indentor measurements of "work hardening" must also reflect the magnitude of the residual stress in the metal being measured. It would be expected, therefore, that shot peened and other cold worked specimens would show increased hardness readings in the affected metal and decreased hardness readings in the metal immediately below the peened layer that is residually stressed in tension.

In Fig. 7 are shown the results of a series of hardness readings made on each of twelve shot peened specimens, which were ground and lapped to a 100 to one slope to depths sufficient to penetrate the cold worked metal (Ref. 9). Knoop hardness measurements were made

Fig. 6 — Indentor hardness measurements and surface stress in steel disks that were deformed from a plane surface toward vertical shapes.



at 0.039 in. intervals as measured on the inclined planes, which thus correspond to nominal depth intervals of 0.00039 in. These hardness readings, converted to Rockwell C scale, are averaged in Fig. 7, together with the average hardness readings of the same specimens as taken from non-peened areas.

The peened areas show greater hardness numbers near the surface, where the residual stress is compressive; and lower hardness numbers in the deeper metal, where the residual stress is tensile. The readings taken from non-peened areas show hardness intermediate between those for the peened areas, as would be expected since the residual stress in these areas was presumably zero.

The numerous hardness gradient measurements that are recorded for carburized, nitrided, and other residually stressed surfaces, including hardenability test specimens, give only the indentor readings. These readings are probably in error in regard to real hardness for the compressively stressed surface as well as for the tensile stressed core.

No data are known that attempt to differentiate between "real" hardness and stress hardness, therefore, the extent of real "work hardening" in any specimen is not known.

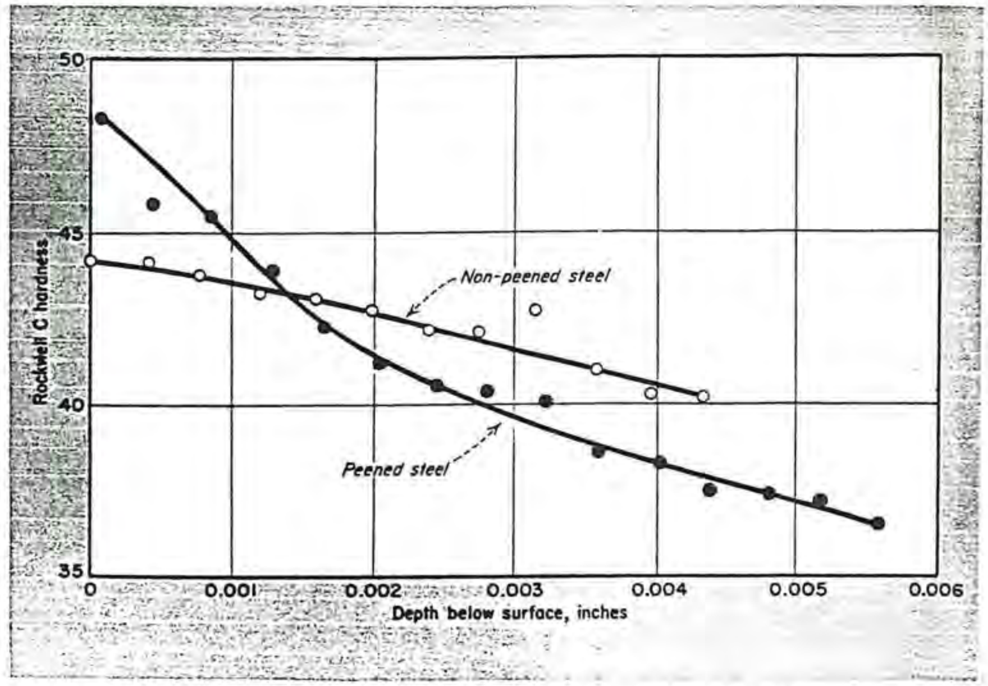


Fig. 7 — Hardness measurements on cross sections of peened and non-peened steel specimens that were ground and lapped to a 100 to one slope to depths sufficient to penetrate the cold worked metal.

Some work hardening change probably occurs similar to that which seems to follow the cold working of copper, as indicated by the apparent change in the elastic limit of tensile specimens when loaded above the proportional limit. With this increase of yield strength under tensile loading, however, there is also a decrease in the elastic limit under compressive loading.

Pull-Pull Fatigue Tests

Another fatigue strength comparison, and perhaps better for indicating surface weakness than specimens tested in bending, is one in which the bending stress gradient as shown in Fig. 4 does not occur, or, at least, is greatly reduced. Data for such a comparison were obtained from a series of fatigue tests in which only tensile loads were repeatedly applied on steel specimens of 0.187 in. dia. The tests were conducted by the Research Laboratories Division, General Motors Corporation. Fig. 8 shows the dimensions of the specimens and the results of the tests.

The specimens were made from new Allison engine connecting rod bolts, AEC 4340-X steel hardened and tempered to 33-36 Rockwell C hardness. Their surfaces were carefully ground and smooth finished in a manner intended to avoid the development of residual stresses of appreciable magnitude. All specimens were subjected to a calculated stress cycle of plus 32,500 psi to plus 150,000 psi. Several specimens were measured to certify that the maximum stress was less than the nominal yield stress of the steel.

The term "nominal yield stress" is used to identify the limit of proportionality, which is the static stress at which the tensile stress-strain curve deviates from a straight line. The term "nominal elastic limit" would serve as well, except that the symbol Y is easily recognizable as indicating yield. The word "nominal" indicates that the elastic limit or the yield stress as determined by static loads do not define the limit of proportionality when the specimen is subjected to often repeated loads.

To repeat a statement made earlier in this article, "...under dynamic loads the elastic limit of ordinary structural materials is so low that plastic deformations, on a macro scale, the extent of which vary with the manner of loading, often alter the stress continuously during a fatigue test."

In the series of tests on the specimens made from the rod bolts, it was desired to conduct the tests at high stress levels to cause early failure of the non-peened specimens. This precaution was necessary to assure that failure of the more durable peened specimens would also occur in reasonable time, since the fatigue strength comparison was to be made on a relative life basis.

At the left-hand side of Fig. 8, the results of tests on fifteen non-peened specimens are shown; each bar represents one specimen and its height represents the number of cycles that were applied before failure. These bars are arranged in ascending order for easy comparison.

In Fig. 8 are also shown the results obtained from tests of three groups of shot peened specimens, which differed from one another only in the intensity of the peening

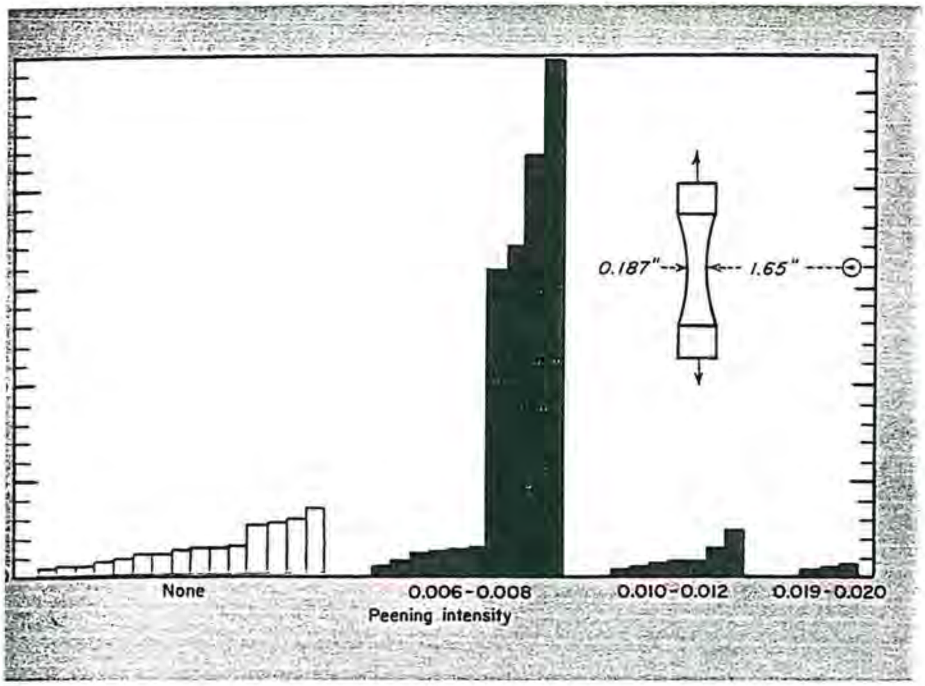


Fig. 8 — Relation between tension fatigue durability and shot peening intensity, as indicated by pull-pull fatigue tests on AEC 4340-X steel specimens hardened and tempered to 33-36 Rockwell C hardness.

that was applied. In arranging the tests it was assumed that light peening would prolong the life of the specimens, because the surface weakness would be overcome by a very thin layer of residual compressive stress without seriously increasing the sub-surface tensile stress. It was also believed that more intense peening could reduce the fatigue durability because of the greater internal tensile stress as well as the more severe bruising of the peened surface.

Light Peening Superior to Heavy Peening

From Fig. 8 it is seen that the durability of the lightly peened second group of ten specimens was greater than the non-peened specimens, and that the durability decreased as the peening intensity was increased. The data suggest that peening lighter than the 0.006 to 0.008 A2, which was used on the second group of specimens, would have given even better fatigue strength and perhaps reduced the variability of life among the specimens.

Since the diameters of these specimens were 0.187 in., the residual tensile stress in the unpeened core metal was relatively great, as is indicated in the diagram *D*, Fig. 5. The internal residual tensile stress was added to the nominal tensile stress from the external load. Varying the peening intensity does not greatly alter the magnitude of the residual compressive stress in the surfaces; the effect being mainly to alter the depth of the peened layer. It is to be expected, therefore, that peening pull-pull specimens to a greater depth than is necessary to counteract surface weakness reduces their fatigue durability by increasing the internal residual tensile stress, and thereby increases the maximum test stress.

It is probable that for the pull-pull specimen shown in Fig. 8, the depth of the peened layer could have been reduced to not more than 0.002 in. with actual increase in fatigue strength, as compared to the greater but unmeasured core residual tensile stress that resulted from the peening intensity that was applied. The loss of fatigue strength for the third and fourth groups is presumably chargeable to greater core residual tensile stress, together with the more severe bruising of the surfaces of the specimens that accompanied the greater peening intensity.

The results of these tests, particularly the qualitative fatigue strength comparisons of the non-peened and the lightly peened groups of specimens, favor the theory of surface weakness. Quantitative fatigue strength comparison cannot be obtained from such tests, even if the actual stresses at the surface and in the sub-surface metal were known, because so far as could be determined by visual inspection of the fractures, no failures originated in the sub-surface material.

To measure the relative strengths of surface and sub-surface metal it is, of course, necessary to know the stress causing fatigue fractures in each of the regions where fatigue strength is to be compared. It is also important to conduct the test in such manner that the fractures for each region to be compared develops in approximately the same number of stress applications, or that a sufficient number of specimens are tested to establish the fatigue endurance limit.

In the process of shot peening, the peened surfaces are severely bruised and notched by the shot impacts. When chilled iron shot are used many of the shot are fractured. Visual inspection will reveal numerous sharp cuts and an occasional instance in which fractured shot fragments are embedded in the peened surface.

Surface Imperfections Are Stress Raisers

All these added surface imperfections constitute stress raisers of the same severity as if they occurred in unpeened surfaces. They will augment the damaging tensile stress from the external load in the same manner that any form of surface imperfection raises the magnitude of the applied tensile stress. As long as the residual compressive stress, however, is greater than the local increase in tensile stress, as represented by the most severe stress raiser, the fatigue strength of the specimen will be increased by the peening.

Residual Stress Measurements

To discuss the effects of residual stresses on fatigue strength is useless, of course, unless it is first contrived to obtain reasonably accurate measurements of the magnitudes and arrangements of the principal stresses.

The residual stresses in planes of the principal stresses of a large variety of specimens have been measured by the General Motors Research Laboratories Division using the dissection method.

This process, which has been used since it was first reported by Heyn (Ref. 10), consists of removing successive layers of material from the specimen and measuring the deformation of the remainder of the specimen after each layer is removed. From these measurements, the original residual stress in the specimen is calculated.

The principal interest is in measuring, as accurately as possible, the residual stress in the plane of the principal stress as identified by the direction of the applied load and the direction of the fatigue fracture. Since the residual stress gradient is often very steep, it is important that the thickness of the successive layers removed be as thin as possible.

In the process of removing metal, it is easily possible to introduce new residual stresses as great or greater than the original stresses being measured. This danger increases as the thickness of the removed layer is decreased. Since the maximum thickness of successive layers near the surfaces and elsewhere, when the rate of stress change is large, must be of the order of 0.0005 in., each step in the process requires the utmost care and precision. For example, a layer of 0.0005 in. is removed in steps not greater than 0.0001 in. For a thicker layer, the final 0.001 in. of metal is also removed in not less than ten approximately equal steps.

Since the forces and force moments of the original residual stresses in the specimen were in equilibrium, a check upon the accuracy of the dissection stress measurements can be made by calculating the degree of unbalance of the forces and force moments from the reconstructed stresses. Errors are found to range up to plus or minus five percent.

It should not be understood that the errors in balance of forces and force moments indicate that the maximum errors in the reconstructed stresses are within five percent of their actual values. It is probable that, in regions of rapid stress changes, particularly near the surface, the errors in stress magnitude may be considerably greater because only a small portion of the original specimen is used for the measurements.

Since the stress in any specimen is probably never more simple than biaxial, losses of residual stress will inevitably occur when a small dissection specimen is removed from a large sample. Errors also arise from the fact that the effect of stresses in planes other than the one being measured are neglected. Although a high degree of accuracy in stress magnitude is desirable, it is often more important to know accurately the pattern or arrangement of the residual stresses within the specimens.

By dissection processes, the residual compressive stress that is induced by shot peening has been found to approximate one-half of the nominal yield stress of the peened metal (Ref. 11), as is indicated in the chart Fig. 2. Dissection stress measurements, however, are not capable of detecting highly localized stress variations. It is probable that the stress induced by each shot impact is not uniform in all parts of any single indentation, therefore, it is to be expected that the minimum residual stress in a shot peened surface will be less than the measured average. Added to this uncertainty is the probability of micro stresses originally in the metal, and the unknown magnitude of the individual stress raisers that are formed by the peening.

Greater gains in fatigue strength result when the peening is performed with whole shot, which are substantially spherical, than when the peening material is contaminated with broken and deformed shot (Ref. 12). This gain presumably results from the avoidance of cuts and abrasions, and the consequent reduced severity of the peening stress raisers with, perhaps, more uniform intensity and coverage because of the uniformity of particle size.

Stress From Shot Peening Controllable

For the foregoing and other reasons, the increased fatigue strength that is obtained by ordinary shot peening can be used only as a qualitative measure of surface weakness. A somewhat better appreciation of the magnitude of surface weakness can be had by increasing the mechanically induced surface residual compressive stress sufficiently to cause fatigue fractures to originate in sub-surface metal. Such an increase in surface stress can be accomplished by "Strain Peening," a process that was first used by the author (Ref. 13) to prevent stress corrosion cracking.

When shot peening has been applied to attain adequate coverage, regardless of the state of residual stress that prevailed in the surface before peening, the average induced stress is not greatly increased with increased time of exposure of the surface to the impacting shot, or with the size, or the velocity of the shot. The effect of these variables is mainly to vary the depth of the residually stressed layer.

If before peening the surface is residually stressed in tension, as it will be if finished by grinding, the magnitude of the compressive stress induced by peening will be the same as that which would be induced if the surface had been initially stressed in compression, or if it had been entirely free from stress.

By applying shot peening, or an equivalent operation, however, while the surface is in a suitable state of strain, the magnitude of the final residual stress after peening can be controlled to equal any value within the range from the nominal compressive elastic limit to approximately one-half of the nominal tensile elastic limit.

Strain Peening

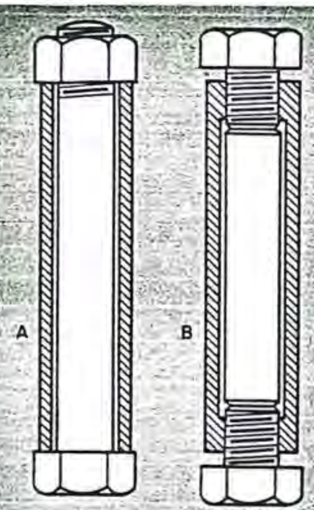


Fig. 9 — Tubular specimens adapted for strain peening. — (A) Tube pre-loaded in compression.— (B) Tube pre-loaded in tension.

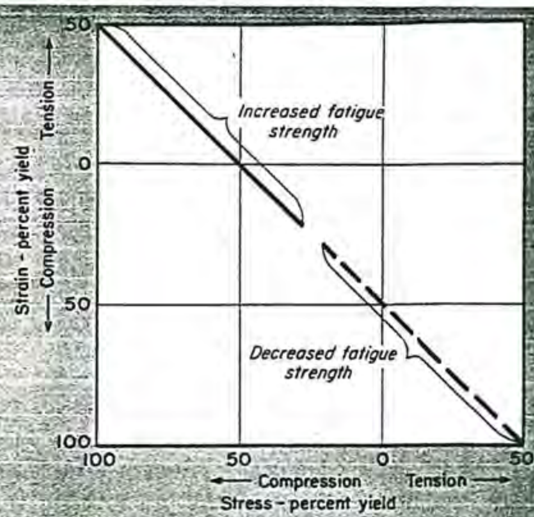


Fig. 10—Approximate residual stress resulting from strain peening in percent of nominal yield stress. Possible residual stress ranges from a yield stress of 50 percent in tension to 100 percent in compression.

If the tubes shown in Fig. 9 are shot peened while the bolt and tap bolts are slack the tube surfaces will, as in all peening operations, be residually stressed in compression to approximately one-half of their nominal yield stress. Since the specimens are cylindrical, the residual stress will be longitudinal, tangential, and radial; not biaxial as in plane surfaces. The longitudinal and tangential stresses will approximate one-half of the nominal yield stress of the metal.

Suppose the bolt, Fig. 9 (*A*), is tightened to stress compressively the tube to one-half of its nominal yield stress. (The stress from the load applied by the bolt acting in the tangential and radial directions will here be neglected.) If the tube is shot peened while loaded, its surface while loaded after peening will be residually stressed to the same extent as if no external load was present, that is, the longitudinal and tangential stress will be one half of the nominal yield.

Residual Peening Stress Lost. Removal of the axial load by releasing the bolt will permit the tube to lengthen elastically to nearly its original dimension. As the tube lengthens, the residual peening stress acting in the axial direction will be dissipated and only the tangential residual stress will be retained.

If the service or test loads applied to the tubular specimen are to act principally in the longitudinal direction, the retained tangential stress will have little effect on the fatigue strength of the specimen. The peening, however, will seriously diminish the fatigue strength of the tube against repeated loads acting in the axial direction. The surface will be cold worked to approximately the same degree as in normal peening, and stress raisers of similar severity will be formed, but these effects serve only to increase the weakness of the surface. The immunizing effect of shot peening is lost with the loss of the residual compressive stress.

The extent of damage from shot peening will increase as magnitude of the compressive bolt load, at time of peening, is increased.

For example, if the applied bolt load is increased to stress the tube to its nominal compressive yield strength and the specimen is then shot peened, the residual stress at the conclusion of peening will as before be equal to one-half the nominal compressive yield stress. During peening the surface compressive stress is decreased from the 100 percent stress imposed by the bolt to the 50 percent yield stress of normal peening.

Upon release of the bolt the tube will elastically recover nearly its original length, whereby the surface will be extended to alter the stress from one-half nominal compressive yield to nearly one-half nominal tensile yield. The loss in fatigue strength will now be greater because not only is the surface vulnerability increased by stress raisers, but the damaging tensile stress from the service load is increased by the surface residual tensile stress.

Peening Stress Doubled. Beneficial strain peening results when suitable specimens are shot peened while stressed in tension. In Fig. 9 (*B*) is shown a tubular specimen with a tap bolt fitted in each end. When tightened the tap bolts bear upon a strut within the tube. By tightening the tap bolts against the strut, the tube can be loaded in tension to any desired stress.

If the tube is stressed to one-half its nominal tensile yield stress by tightening the screws and then shot peened, the peening will change the surface stress from tension to compression. The residual stress magnitude, as in ordinary peening, will be one-half nominal compressive yield stress.

Upon release of the tap bolts the tube will contract to nearly its original length. The contraction will not greatly alter the tangential residual stress, but will increase the longitudinal residual compressive stress from one-half nominal yield stress to double that amount. As a result of the increased residual compressive stress, greater protection will be available against surface weakness, and the fatigue strength of the specimen under repeated longitudinal tensile stresses will be greatly enhanced in any test that does not dissipate the residual surface stress.

Peening Stress Variable Over Wide Range. The range of residual stress, in terms of nominal yield stress, that can be induced in the surface of shot peened specimens by strain peening is shown in Fig. 10; the possible residual peening stress ranges from 50 percent yield stress in tension to 100 percent yield stress in compression.

For increasing fatigue strength, practical peening is limited to the solid line, Fig. 10. The broken line is of value in providing specimens, whereby the relative effectiveness of "work-hardening" and residual stress may be measured.

Idealized Strain Peening Diagrams

Diagram Fig. 11 (A) shows a beam loaded in bending by a downward acting load at O. The resulting stress magnitude at any depth within the beam is represented by the horizontal distance from the vertical line OO' to the diagonal line N_cN_t. The externally applied stress ON_c on the upper surface is one-half the nominal compressive elastic limit* OY_c; and the tensile stress $O'N_t$ on the lower surface is one-half the nominal tensile elastic limit $O'Y'_t$.

When both of the strained surfaces of the loaded beam, Fig. 11 (A), are shot peened, the usual compressive residual stress is induced in the transverse direction; but the peening does not alter the longitudinal stress on the upper surface, since this stress is already compressive and is approximately equal to the stress that would otherwise be induced by peening.

Since shot peening always induces bi-axial stresses, and transverse stress is relatively unimportant in the bending specimens being discussed, hereafter reference to stress will relate to longitudinal stress.

The stress in a thin layer on the lower surface, Fig. 11 (A), which is stressed in tension by the applied load, becomes compressive after peening by the amount $O'M$, which is equal to one-half the compressive elastic limit $O'Y'_c$.

When the external bending load is removed, elastic recovery of the beam removes all except the stress change that was induced in the beam by the peening, as shown in Fig. 11 (B). This stress change is equal to the distance N_tM, Fig. 11 (A), measured from the vertical line OO' of Fig. 11 (B). That is, the residual compressive stress on the lower surface of the beam is now equal to the distance $O'M'$, which is also the nominal elastic limit of the metal. There will be a permanent set in the free beam because of the residual compressive stress on the lower surface.

In resisting repeated loads applied in a downward direction, the fatigue strength of this strain peened beam will be greater than is obtainable from simple peening. The greater residual compressive stress on the lower side of the beam will reduce the magnitude of the surface tensile stress from the downward acting loads. However, the fatigue strength of this strain peened beam against repeated loads acting in an upward direction will be decreased, since there is no residual compressive stress to offset the stress raisers that were formed on the upper surface by the peening.

If at the time of peening, the specimen is strained in compression substantially greater than one-half the nominal yield strength, for example such that the applied stress equals the elastic limit as shown in Fig. 12 (A), the compressive stress on the upper surface will be reduced by the peening to the distance OJ, which is approximately one-half the nominal yield stress.

The resultant residual stress on the upper surface immediately upon removing the external load will be tensile, Fig. 12 (B), by the distance OJ', which is equal to approximately one-half the tensile yield stress. The tensile stress on this surface from upward acting loads will then be the sum of the residual stress and the stress from the externally applied load. Since all fatigue fractures are caused by tensile stresses, the result will be extensive loss in fatigue strength because of the combined tensile stresses from the external load, and from the residual tensile stress that was induced by the peening.

PRESTRESSING MAY BE OVERDONE. On the lower surface of the diagram, Fig. 12 (A), the sum of the tensile stress from the external load and the residual compressive stress from peening is indicated by the distance Y'_tM. Upon removal of the external load, the tensile stress from the load is removed from the sum and the residual compressive stress equals the distance $O'M''$, as shown on the lower surface of the diagram Fig. 12 (B). However, this sum exceeds the nominal yield strength of the metal by the distance $M'M''$, and this portion is therefore immediately dissipated by plastic yielding. The final residual compressive stress will therefore be equal to the yield strength of the metal, exactly as occurred in Fig. 11, which was peened at one-half of the strain that was applied in the Fig. 12 specimen.

The yielding represented by $M'M''$ can be detrimental to the fatigue strength of the specimen, since this stress is first induced by peening, and then lost by compressive yielding. It is possible damage will result by exhausting the capacity of the metal for plastic adjustment through excessive cold working.

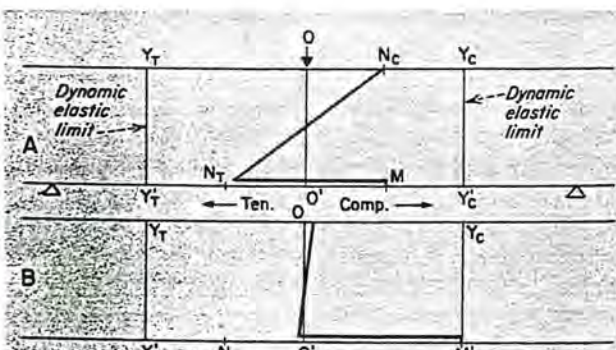


Fig. 11 — (A) Stress magnitude at any depth within a beam loaded in bending by a downward acting load. — (B) Stress change, when external bending load is removed, that was induced by peening.

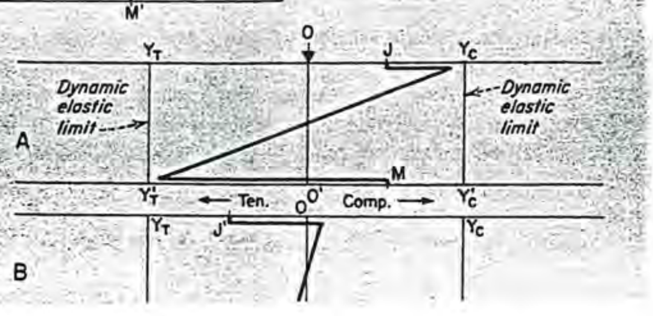


Fig. 12 — (A) Stresses in peened beam with applied stress equal to the elastic limit. — (B) Resultant residual stress when external load is removed.

*The magnitude of plastic yielding under repeated stresses, particularly when the load is applied only in one direction, is greater than the plastic yielding measured by static loads. Measurements indicate (Ref. 1) that plastic yielding continues at a decreasing rate throughout uni-directional fatigue tests. The stress indicated by the dynamic elastic limit is therefore lower than the conventional yield stress but it does not identify a limit of plastic yielding.

Measurements of Residual Stress

The ability to control the magnitude of the residual compressive stress, by performing the peening while the specimen is strained in tension, supplies a method for estimating, with reasonable accuracy, the relative fatigue strength of surface and sub-surface material. By varying the magnitude of the residual stress, fatigue fractures can be made to originate at the surface or in sub-surface metal with substantially equal frequency and after approximately the same number of load applications. Since it is necessary to avoid any loss of protective stress, the surface that is residually stressed in compression must be loaded only in tension.

In experimental work, this condition is most conveniently accomplished by the use of specimens subjected to repeated bending loads acting only in one direction. Dissection stress measurements may then be made to establish the magnitudes of surface and sub-surface residual stresses. These measured residual stresses are added to nominal calculated stress from the external load to give a reasonable measure of the actual stress distribution at the time of fracture.

Such residual stress measurements have been made on specimens, similar to Figs. 11 and 12, except that the specimens had been shot peened on the tension surface only while strained in bending. Fig. 13 shows the residual stress, as measured by the dissection method, developed by strain peening the surface of a leaf spring specimen made from SAE 5150 steel heat-treated to a hardness of Rockwell C 47. The peening was applied on the lower surface while this surface was loaded in bending to a specified tensile strain of 0.00586 in. per in. In terms of stress, this strain is equal to approximately 170,000 psi.

The nominal yield stress of this steel was not measured, but to conform to the expected characteristics of steel of 47 R C hardness it will be assumed to be 200,000 psi, from which the average residual compressive stress induced by shot peening alone may be assumed to be 100,000 pounds per square inch.

From the reconstructed stress diagram, Fig. 13, it is seen that the residual compressive stress on the lower surface is 215,000 psi. This value is the sum of the stress induced by shot peening and the stress caused by the elastic recovery of the specimen after removal of the bending load, which was applied during strain peening. Since the elastic recovery was not complete, the residual stress added by the elastic recovery was less than the 170,000 psi that represented the strain peening load. Because of the plastic changes that occurred during the peening and during the subsequent fatigue test, a permanent set remained in the specimen similar to that indicated by the inclined lines in the unloaded specimens shown in the Figs. 11 (*B*) and 12 (*B*) diagrams.

Permanent Set in Prestressed Specimens

The magnitude of the permanent set remaining in the spring specimen of Fig. 13 is shown in Fig. 14. In this diagram the portion of the line representing residual stress, which lies between the points *C* and *D*, represents metal that experienced no plastic yielding during peening.

Before peening, the line *CD* was coincident with a portion of the vertical line *OO′*. The extent of its failure to return to its original position after peening, and after release of the external load, provides a measure of the permanent set of the specimen. Extending the line *CD* to the upper surface at *A*, and to the lower surface at *B*, permits measurement of the permanent set at both surfaces. On the lower surface this permanent set is represented by *BO′*, a distance equivalent to 85,000 psi tensile stress.

The residual compressive stress that was added to the shot peening stress was therefore 170,000 minus 85,000 or 85,000 psi. The assumed 100,000 psi residual stress from peening plus 85,000 from elastic recovery, equals a total surface residual compressive stress of 185,000 psi. But this value is 30,000 psi less than the residual stress that was measured by the dissection process, which it will be recalled was found to be 215,000 psi as shown in Fig. 13. The greater part of this discrepancy is probably in the assumed magnitude of the elastic limit of the peened metal.

The elastic limit of the surface metal was presumably increased by the plastic yielding that is seen to occur during strain peening in any stress-strain diagram. Through a considerable range of strain, yield strength increases with each of a succession of static tensile tests in which the applied stress exceeds the limit of proportionality.

Strain Peening Stress Increased by Subsequent Cold Work

Dissection measurements were made after the specimens had been subjected to 140,000 cycles of bending

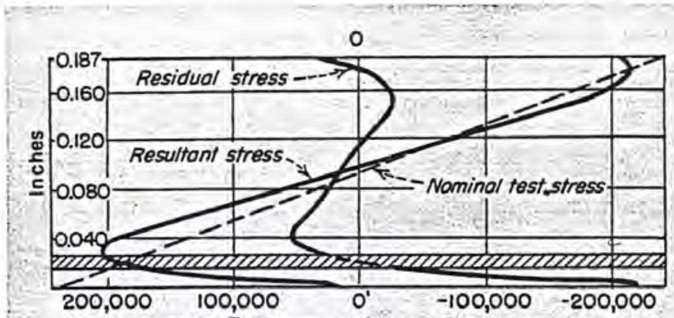
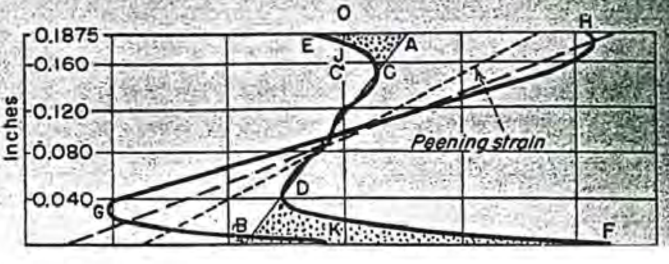


Fig. 13 — Measured residual stresses in a strain peened steel specimen after 140,000 stress cycles; specimen was shot peened only on the tension surface while strained in bending.

Fig. 14—Increase in fatigue strength by plastic yielding in specimens under unidirectional loads.



stress by downward acting loads. The dotted line Fig. 14 indicates the strain that was applied to the specimen during the peening. Since the fatigue test loads applied nominal stresses ranging from plus 25,000 to plus 240,000 psi, additional local plastic adjustment of the metal occurred in the most highly stressed regions during the test.

The elastic limit indicated by the dissection measurements is presumably a close approach to the dynamic elastic limit of the metal. Since the static elastic limit exceeds the dynamic elastic limit, and since the maximum measured residual compressive stress near both surfaces is 215,000 psi, it appears that the assumed nominal yield stress and the assumed residual stress induced by peening should be revised upward.

In Fig. 14 it is seen that extensive plastic yielding occurred to considerable depths from both surfaces. The extension of the line *CD* to the upper surface at *A* encloses the triangular darkened area *AECA*, which represents plastically deformed metal. The extent of yielding at any depth is, of course, the horizontal distance over the darkened area. The maximum yielding occurred at the surface, and approximates 83,000 psi. The horizontal distance from the vertical line between the points *C'* and *O* to the resultant stress line *HGK* is a measure of the compressive dynamic elastic limit of the steel near the upper surface of the specimen. This limit is seen to vary from 215,000 to 180,000 psi, the latter value presumably being a close approach to the dynamic elastic limit of that part of the specimen metal that had not been "cold worked."

Residual Stress Increased by Dynamic Yielding

Similar measurements can be made of the plastic movements of the metal near the tensile stressed under side of the specimen in the darkened area *BDFB*. The yielding in this area is complicated by the plastic movements that occurred during the strain peening. It is probable that all of the plastic movement in the metal near the surface is a direct result of strain peening but most of the plastic movement of the metal at depths greater than 0.020 in. was probably caused by dynamic yielding.

It may be, however, that some deep yielding ocurred during the strain peening. Although the surface stress was presumably less than the static elastic limit, it is nevertheless possible that yielding occurred because of the severe vibrations from the impacts of the shot. Since plastic yielding also occurred at depths of 0.025 in., where the stress during peening approximated 125,000 psi, most of the deep yielding probably occurred during the early part of the fatigue test with slow plastic movements (creep) continuing for the duration of the test. The resultant test stress at the limiting depth of plastic yielding is seen to be 190,000 psi approximately.

Prestress May be Lost

As a result of the yielding shown in Fig. 14, the fatigue strength of this specimen is greatly increased in any repeated load test that does not dissipate a substantial portion of the residual stress. When the residual compressive stress is made equal to the dynamic elastic limit of the metal, any additional compressive stress from external sources will necessarily cause compressive yielding, and thereby reduce the protection that is bestowed to the weak surface by the residual compressive stress.

For example, any upward acting bending load on the specimen Fig. 12 (*B*) will cause compressive stress on the lower surface. Since the compressive stress on this surface is already equal to the elastic limit, any additional stress in the same direction will necessarily result in plastic yielding, and thus dissipate residual stress in an amount equal to the stress from the upward acting load.

The maximum gain in fatigue strength that may be obtained by mechanical prestressing processes, therefore, is limited to specimens that are compressively prestressed to the elastic limit of the metal, as shown in Figs. 11 (*B*), 12 (*B*), and 13, providing they are repeatedly loaded in bending in a downward direction only. Any reversal of load will reduce the residual compressive stress that protects the weak surface against fatigue fractures.

The specimen shown in Fig. 13 was repeatedly loaded by a downward acting load applied as indicated by the arrow. This load exerted a maximum nominal surface stress at each load application of 240,000 psi, as shown by the broken diagonal line. The actual stress, shown as "Resultant Stress," is the sum of the nominal stress and the dissection measured residual stress. Under the nominal applied stress of 240,000 psi, the maximum compressive stress of 215,000 psi occurs about 0.010 in. below the upper surface, and the maximum tensile stress of 205,000 psi occurs at 0.030 in. from the lower surface.

Dynamic Yielding Increases Fatigue Strength

The dynamic yielding, which occurs during fatigue testing under unidirectional bending loads and unidirectional twisting loads, develops residual stresses that reduce the actual stresses in the specimens. As seen in Fig. 14, the sub-surface yielding reduced the stress magnitude. It is well-known that the fatigue strength of conventional nonprestressed specimens is greater when they are repeatedly loaded in one direction only than when they are subjected to reversed loads.

The measured residual stress on the non-peened upper surface of the beam, Fig. 13, which is nominally stressed only in compression, is actually a tensile stress. The measured tensile stress on this surface is greater than the maximum tensile stress on the peened lower surface, which is nominally stressed only in tension. The residual stress on the non-peened upper surface as has been described, is the result of compressive plastic yielding of this surface.

Fatigue failures frequently develop on the "compressively" stressed side of fatigue specimens. In specimens that are presumed to be free from residual stresses, such "compressive" failures are always caused by tensile stresses that are developed from compressive yielding. In the absence of adequate residual stress measurements, however, they are erroneously believed to be cohesive failures that result from compacting stresses.

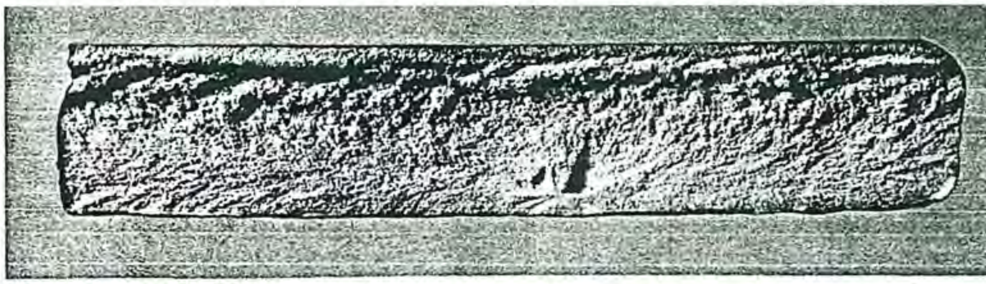


Fig. 15 — Sub-surface fatigue nucleus close to the tension surface of a prestressed spring specimen.

Prestressing for Efficient Use of Material

In specimens that are correctly prestressed for the most efficient use of material to support repeated bending loads in one direction only, such as is approached by the specimens Figs. 13 and 14, fatigue failures may originate in any of three locations. In the discussion of these three possible sources of fracture, it will be assumed that the residual stress measurements are exact.

1. The fracture could originate on the upper surface from the tensile stress *OE*. Fractures in this region would not develop to complete failure because the crack would propagate only to the depth *OJ*, which is the limiting depth of the tensile stress. The sub-surface compressive stress would form an impassable barrier to further progress of cracks. However, in the specimen illustrated, fractures could not originate on the upper surface because the stress *OE* can exist only when the external bending load is completely removed. Since the nominal downward acting bending stress during the fatigue test ranged from 25,000 to 240,000 psi, and since the measured tensile stress *OE* is 28,000 psi, the maximum tensile stress on the upper surface could not exceed 28,000 minus 25,000 or 3,000 pounds per square inch.

2. Fatigue fractures could and did originate on the lower surface from the tensile stress *O'K*, which is equal to 20,000 psi. The effective stress was greater than the dissection measured value because of the many severe stress raisers that were formed by the shot during peening.

3. Fatigue fractures could and did originate in sub-surface metal at the depth *G* from the tensile stress *O'G*, which is equal to 200,000 pounds per square inch.

In Fig. 15 is shown a fatigue fracture of sub-surface origin that developed in another of the group, not the one represented in Figs. 13 and 14, of prestressed spring specimens that were fatigue tested.

Sub-Surface Fractures in Efficient Specimens

Sub-surface fractures from tensile stresses of 200,000 psi occurred with approximately the same frequency as the surface fractures from tensile stresses of 20,000 psi. The fatigue strength of the surface was therefore one tenth of the fatigue strength of sub-surface metal. This strength ratio exaggerates the weakness of the surface because of the presence of stress raisers. Also the dissection stress measurements, particularly the surface stresses, are not sufficiently reliable to warrant the use of precise numerical comparisons.

Tests are contemplated on other specimens identical with the specimen shown in Fig. 13, except that the surface will be polished. The polishing will be applied to strain peened specimens and to specimens that have not been prestressed. After polishing, one group of non-prestressed specimens will be tempered in a vacuum or in a neutral atmosphere to reduce the residual compressive stresses that are induced by the polishing-operations. The results of such tests should provide a better measure of surface weakness than the data given in Fig. 13, because removal of the obvious stress raisers will remove most of the extra surface hazards introduced by the peening.

Dissection Measurements Require Great Accuracy

The cross-sectioned band near the lower surface of the beam, Fig. 13, indicates the portion of the specimen that remained when the dissection measurements were completed. Its thickness is 0.0105 in. During the dissection twenty layers were removed from the upper side of the beam and thirteen layers were removed from the under side. The dissection proceeded from the upper side to within 0.026 in. of the opposite surface before any metal was removed from the lower surface. In this manner, the accuracy of the measurements of stress near the critical tensile stressed surface was increased. Calculations of the moments from the measured residual stress show that the error in the reconstructed stress diagram is 3.4 percent.

Effect of Removal of Stress Raisers

A few tests have been made in which shot peened specimens were polished after peening. The magnitude of the residual stress was presumably not altered, but the polishing served to remove most of the obvious stress raisers that were left by the peening.

A series of tests conducted by Wright Field, and reported by the Office of Scientific Research and Development (Ref. 7), compared the fatigue strength of shot peened specimens with specimens that had been polished after peening. The latter showed an increase in fatigue strength of 20 percent at the endurance limit. It is improbable that the polishing added beneficial residual stresses, since the surface prestressing from peening was still effective. The gain probably results from the greater effectiveness of the peening stress because of the removal of obvious stress raisers.

Similar results were obtained from an earlier series of tests by Wright Field, which also are reported (Ref. 14) by the Office of Scientific Research and Development.

The results of an interesting se-

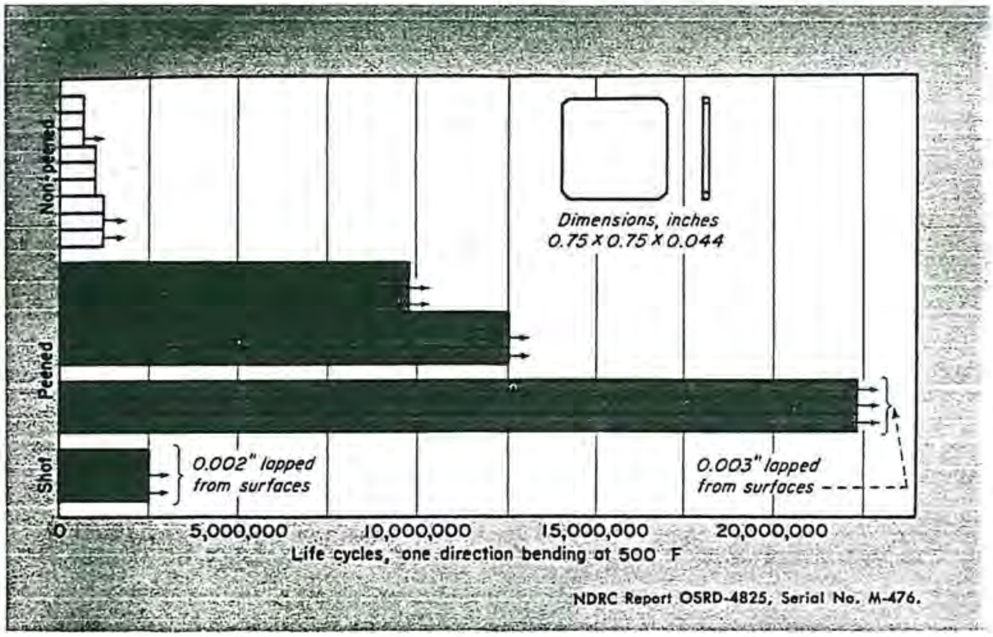


Fig. 16—Fatigue durability of non-peened and shot peened air compressor discharge valves that were surface finished by several methods.

ries of tests, also reported by the Office of Scientific Research and Development (Ref. 15), that included honing after peening are shown in the bar chart, Fig. 16, which is replotted from the original report. The chart compares the fatigue durability of non-peened and shot peened air compressor discharge valves, made of SAE 1080 steel heat-treated to Rockwell C hardness of 46-52, that were surface finished by several methods. Dimensions of the valves are shown in the chart. Shot peening was done by the General Motors Research Laboratories Division to an intensity of 0.007A2. The test valves were installed in air compressors and life tested, by Bendix Westinghouse Automotive Air Brake Company, with the results shown in the chart.

Excessive Honing Destroys Peening Effect

The increased durabiilty resulting from shot peening, as seen in Fig. 16, was further enhanced by lapping 0.002 in. from the peened surfaces. This amount of lapping was sufficient to remove the peening stress raisers. Because of the low intensity peening applied to these hard specimens, and the consequent rapid diminution of residual stress with depth, it is probable that the magnitude of the residual stress was also reduced by the relatively deep honing.

The beneficial effect of removing the peening stress raisers more than offset any loss of residual stress, since no failures of the peened and honed specimens occurred in the test, which was stopped after more than 20,000,000 stress cycles. Note, however, that when 0.003 in. was lapped from the valves, the compressively stressed layer from peening was penetrated; in consequence of which the fatigue weakness of the surface reappeared and the fatigue durability dropped to only slightly better than honed, but non-peened valves.

Residual compressive stress can be induced by other mechanical processes such as tumbling, hammering (Ref. 16), burnishing, and superficial rolling (Ref. 17). Rolling presents several advantages because: (a) The depth of the induced stress is controllable and reproducible, (b) excessive local cold working can be avoided, (c) the operation does not introduce severe stress raisers, and (d) the induced residual compressive stress is more uniform and of greater magnitude than can be induced by individual impacts such as shot peening. The presumed superiority of rolling, however, has not been proved since adequate comparative fatigue strength measurements have not been made.

Rolling is not so versatile as shot peening or tumbling, since it cannot be applied to irregular shapes, but by the use of suitable tools rolling may be applied to symmetrical shapes such as plane surfaces, cylindrical shafts and bores, and other surfaces of revolution.

In many of these, strain rolling can be used to increase the residual compressive stress in the same manner as that described for shot peening. For example, a shaft or tube such as the strained specimen shown in Fig. 9 can be burnished, tumbled, hammered, or superficially rolled while stressed in tension. The tensile strain can be obtained by axial loading; or the rolling or other prestressing tool can be applied on the tension side of a shaft that is strained by a bending load, such as is applied to a rotating beam fatigue specimen.

Strain peening, strain rolling, or strain prestressing by other operations including polishing, can be advantageously applied to torsion bars that are to be repeatedly twisted in one direction only. The bar being prestressed is strained in the direction of the normal load while the rolling or peening is applied. Something less than the maximum prestress can be retained when low magnitude twisting loads on torsion bars, or bending loads on leaf springs, occur in the opposite direction to the normal working load. Reversed loads at relatively low stress often occur in vehicle suspension springs from rebound.

Polishing Fatigue Specimen Defeats Purpose

As a part of his investigation of the effect of specimen size on fatigue strength, H. F. Moore tested three groups of rotating beam specimens made from SAE 1035 steel finished by different processes (Ref. 18 and 19). The first group of specimens was tested in the as rolled and polished state. The second group was the same as the first except that the specimens were bright annealed in vacuum after polishing. The third group was the same as the second except for repolishing after being vacuum annealed. These tests did not supply important data for size effect studies. But when interpreted in terms of surface weakness and the effect of residual stress on fatigue strength, these data become very important.

Specimens of three different diameters were tested in the first and second groups, but only one diameter of specimen was tested in the third group. Annealing was accomplished by holding the specimens at 1500 F for two hours followed by slow controlled rate cooling. The annealing did not alter the surface finish, but it presumably removed any residual compressive stress that was induced by the polishing operation. The comparison shown in Table I is the fatigue strength in pounds per square inch at the endurance limit and the percent gain in fatigue strength that was caused by the residual compressive stress induced by polishing.

The specimens in group 2, which were annealed after polishing, are definitely weaker than the specimens shown in group 1 that were not annealed. The specimen in group 3, which was repolished after annealing, has recovered the same endurance limit strength as the original "as rolled and polished" specimens although the surface smoothness was not altered.

Residual Stress Induced by Various Operations

The greater strength of the specimens in group 1 and 3, Table I, results from the surface residual stress that was induced in a very shallow layer of the specimens by the polishing operation. That the residual stress from polishing is compressive is shown by the three plates of Fig. 17, the upper surfaces of which were finished by the processes indicated.

Each of the three plate specimens was straight and relatively free from residual stress before the upper surface finishing operation was applied. The curvatures shown, therefore, result from the stress developed in the upper surface of each strip during the finishing. Note that specimen *A* is curved concave on the upper surface in response to the tensile stress developed by grinding. Specimens *B* and *C* are curved convex on their upper surfaces, showing that honing and filing develop residual compressive stresses. Dissection stress measurements (Ref. 11) indicate that the initial residual compressive stress from polishing may exceed 20,000 pounds per square inch.

A file finish must not be assumed to be as effective as finishing by honing, even if the residual compressive stresses should be of the same depth and magnitude. The surface scratches produced by filing constitute stress raisers, and the effect of the compressive residual stress is reduced by the augmented tensile stress from these stress raisers.

It is probable that grinding induces residual compressive stress by the plastic "smearing" of the metal, similar to that which occurs in honing and filing. However, since the rate at which metal is removed generates heat, and since highly localized heat develops residual tensile stress, the net effect of ordinary grinding is tensile stress.

Experiments by General Motors Research Laboratories have shown that thin stress free plates ground on one side may indicate compressive stress or tensile stress depending upon the grinding wheel characteristics and the rate at which metal is removed. Compressive stress is indicated when the specimen is ground on one side using a soft, sharp, coarse grit wheel and removing shallow cuts of 0.0001 in. or less per pass. In practical grinding operations the residual stress is always tensile, and ground surfaces are therefore always weaker in fatigue than compressively stressed surfaces of equally smooth finish. High speed polishing by abrasive covered felt wheels is similar to grinding and therefore often produces inferior parts.

Fatigue Test Data May Be Misleading

From the H. F. Moore tests, it may be concluded that the practice of low speed polishing of fatigue specimens not only removes obvious stress raisers, but it also imparts additional strength by virtue of inducing residual compressive stress.

This increased strength destroys the accuracy of the test in so far as the test reflects the fatigue strength of the specimen material. For this reason few if any fatigue tests of "ideal" highly polished specimens, one favorite form of which is shown in Fig. 18; have fulfilled their purpose. The standard fatigue specimen, Fig. 18, is included here to emphasize that standard procedure merely perpetuates the errors that are inherent in

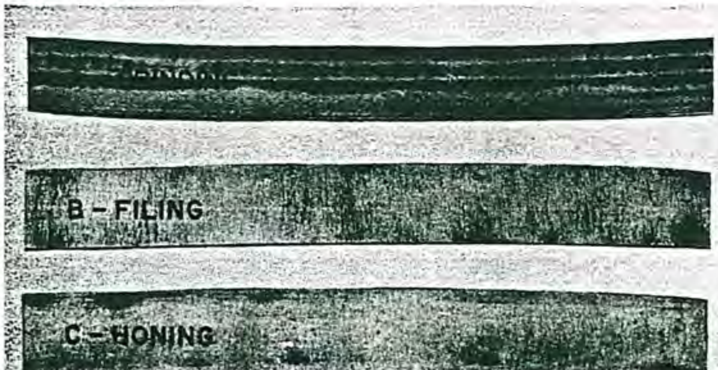


Fig. 17 Above — Curvature of specimens shows stress induced by various treatments. (A) Tension. (B) and (C) Compression. Fig. 18 Below — Standard rotating beam fatigue specimen gives misleading results.

Table I — Fatigue Strength at the Endurance Limit Of SAE 1035 Steel Rotating Beam Specimens

Group	Condition of Specimen	Specimen Dia, In. 0.125	0.250	0.500
1	As rolled and polished	39,000	39,000	35,000
2	As rolled-polished-vacuum annealed	35,000	34,000	31,500
3	As rolled-polished-vacuum annealed-repolished	.....	39,000	.....
	Percent fatigue strength increase resulting from residual compressive stress	11	15	11

the specimen preparation and in the manner of loading. The magnitude of the errors no doubt vary considerably depending upon the manner in which the specimens are tested, and the initial magnitude of the compressive stress that was induced. For the H. F. Moore specimens the polishing residual stress, given in Table I, accounts for 11 to 15 percent of the observed strength.

Residual Stress From Thermal Treatments

Fatigue specimens in which surface residual compressive stresses are developed by several common thermal treatments are perhaps the best available sources of data for evaluating surface weakness.

Nitriding and carburizing are among the most effective treatments for increasing the fatigue strength of steel. These treatments develop residual compressive stresses in the surfaces of case hardened parts. In Fig. 19 are shown the depths and magnitudes, as measured by the dissection method (Ref. 11), of the residual stresses developed in nitrided and carburized specimens by the expansion of the hard case during the hardening transformations.

Although the residual stresses from these treatments are less than was obtained by shot peening very hard steel, Fig. 2, they are more effective than the residual stress from shot peening would be when applied to the same steel without the hardened case. The greater surface yield strength, which is provided by the hardened case, prevents the loss of surface residual compressive stress during fatigue testing particularly in rotating beam, reversed bending, and reversed torsional tests. The surface protective stress in case hardened parts, therefore, remains fully effective under externally applied loads that would dissipate much or all of the protective stress induced by shot peening specimens having the same core hardness.

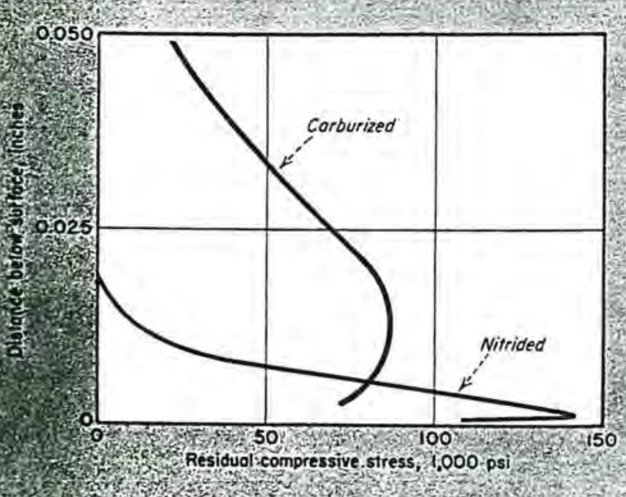
In reversed load testing, the manner in which residual stress is lost is shown in Figs. 20 (*A*) and (*B*), which represent a beam that is shot peened on both upper and lower surfaces. The magnitude of the peening stress on the respective surfaces is indicated by the distances *OJ* and *O'M*, each of which is equal to one half the elastic limit.

A downward acting load at *O* Fig. 20 (*A*), stresses the beam as indicated by the diagonal line $N_C N_T$. The line $J_2 N_C N_T M'$ represents the sum of the residual stress and the externally applied bending stress. Since the stress represented by the distance $Y_C J_2$ exceeds the elastic limit of the metal, this portion of the residual stress on the upper surface is immediately lost, and only the portion $N_C Y_C$ remains. The fatigue strength of the specimen under repeated downward acting loads is not reduced by this loss, because it occurs on the side of the beam that is stressed only in compression. This loss, therefore, does not appreciably alter the tensile stress on the under surface, which determines the fatigue strength of the beam.

If the beam is now loaded from the opposite side by an upward acting load, Fig. 20 (*B*), a similar portion $Y'_C M_2$ of the residual compressive stress will be lost from the lower side of the specimen.

During the first downward acting load, Fig. 20 (*A*), the maximum tensile stress on the lower surface is represented by the distance *M'O'*. But when the load is reversed, Fig. 20 (*B*), the maximum tensile stress on the upper surface is represented by the greater distance K_2O. The increase in tensile stress is equal to the distance $Y_C J_2$ that was lost by the compressive yielding of this surface from the initial downward acting load.

After one complete reversed load cycle, the magnitude of the protective residual compressive stress on both surfaces is diminished, and the fatigue strength of the specimen may actually be reduced by the shot peening. The remaining protective stress may not be sufficient to offset the damage caused by the peening stress raisers. The same reduction of the residual compressive stress that is induced by low speed polishing of "ideal" rotating beam fatigue specimens also occurs. The polishing operation, however, does not add stress raisers, therefore, any remaining stress is effective in overcoming surface weakness.



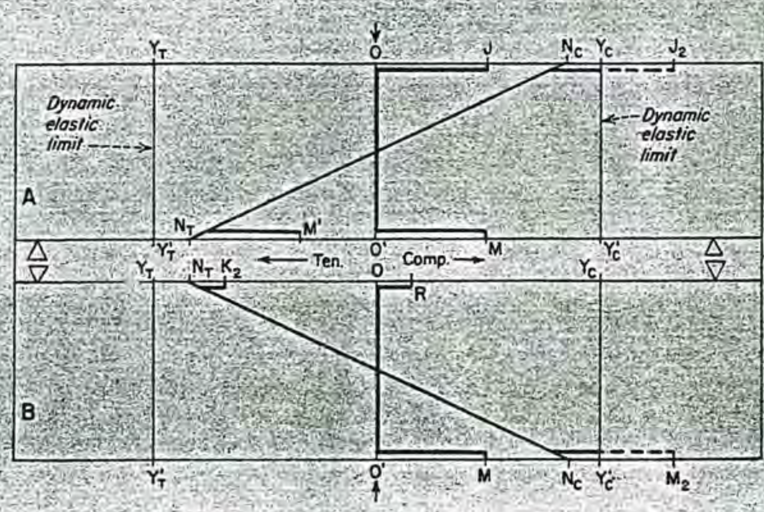


Fig. 19 Left — Residual stresses developed in nitrided and carburized specimens by the expansion of the hard case during

Fig. 20 Right — Manner in which residual stress is lost in a

Measurements of Residual Stress Loss

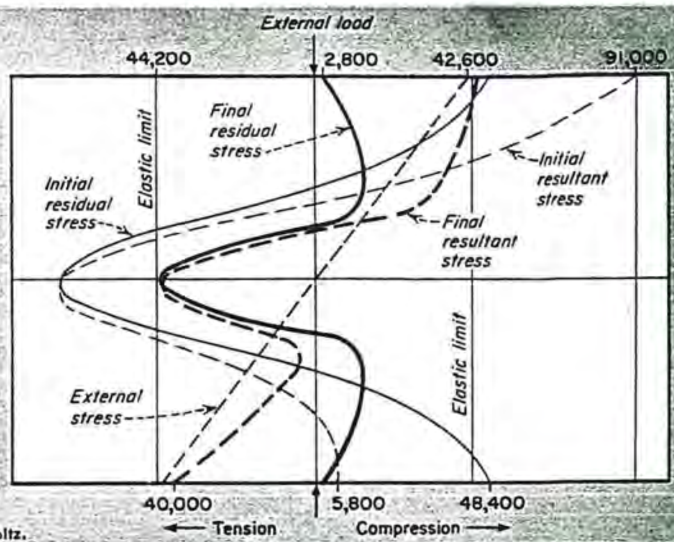


Fig. 21 — Residual stresses in annealed steel specimens that were quenched in ice water from a tempering temperature of 1100 F.

Replot from Buehler and Buchholtz.

Buehler and Buchholtz (Ref. 20) reported experiments with annealed steel specimens in which residual stresses were developed by quenching in ice water from a tempering temperature of 1100 F. The yield stress of the steel is given as 44,200 psi. The residual stresses in one specimen were measured by the dissection method, which resulted in the internal stress pattern shown in Fig. 21 by the fine unbroken line labeled "Initial Residual Stress." The measured surface residual stress of 48,400 psi is not compatible with the estimated yield strength, but this discrepancy is not important to the results of the test as will appear.

A second specimen was dissected for stress measurements after it had been fatigue tested in reverse bending for 8,000,000 stress cycles at a nominal stress of 42,600 psi in either direction. The residual stress in this specimen is shown in Fig. 21 by the unbroken line labeled "Final Residual Stress." It will be seen that all of the surface residual stress except 2800 psi was lost during the test.

The reason for the loss is, of course, the same as was observed for the specimens Fig. 20. The sum of the initial surface residual stress and the surface stress from the external load is equal to 91,000 psi, as shown by the broken line labeled "Initial Resultant Stress." Since this stress exceeds the elastic limit of the steel by 47,000 psi, almost all of the residual stress was immediately dissipated.

The numerical values of stresses given in Fig. 21 cannot be expected to be of a high order of accuracy because, in addition to the usual errors, the results of the measurements from two specimens had to be used. However, the probable errors are small in comparison to the magnitude of the stress that was lost.

Residual Stress Retained by Case Hardened Specimens

The surface residual compressive stresses developed by case hardening processes such as nitriding, cyaniding, carburizing, and in some instances by induction and flame hardening, remain fully effective under external loads that completely dissipate the stresses induced by mechanical treatments such as polishing, shot peening, and rolling. The yield strength of the hardened case from each of the thermal treatments mentioned greatly exceeds the yield strength of the core of all ordinary fatigue specimens. For this reason, under the conditions of loading shown in Fig. 20, no loss of surface residual stress occurs in case hardened steel.

Since the residual compressive stress in the surfaces of nitrided specimens is great, and since this stress is not appreciably diminished by yielding, fatigue fractures originate in the non-nitrided sub-surface metal.

In non-nitrided specimens of identical sound steel, fatigue fractures invariably originate at the surface. Comparisons of the fatigue strength of nitrided and non-nitrided specimens, both of which are substantially alike in physical properties, therefore, may be used to indicate the magnitude of surface weakness. Since in both kinds of specimens the fracture originates in substantially identical material, it is only necessary to know the actual stress at the point of fracture origin in the nitrided and in the non-nitrided specimens.

The fatigue tests should be made under load conditions that will cause failure of both kinds of specimens in approximately the same number of stress applications or the endurance limit for both types should be established.

Surface Weakness Estimated From Nitrided Specimens

Dissection stress measurements from identical non-nitrided and nitrided specimens that have been fatigue tested to failure are not available. Rough estimates of the relative strength of surface and subsurface steel, however, may be made from published fatigue data obtained from suitable specimens. Among the test data that may be used for this purpose are the results of tests reported by Johnson and Oberg (Ref. 21) of Wright Field. This report is selected principally because of the availability of the photographs Fig. 22, which show the sub-surface origin of the failure in the nitrided specimens as compared to the surface origin of the fractures in the non-nitrided specimens.

The relative fatigue strength of the two groups of rotating beam specimens is shown in the SN chart

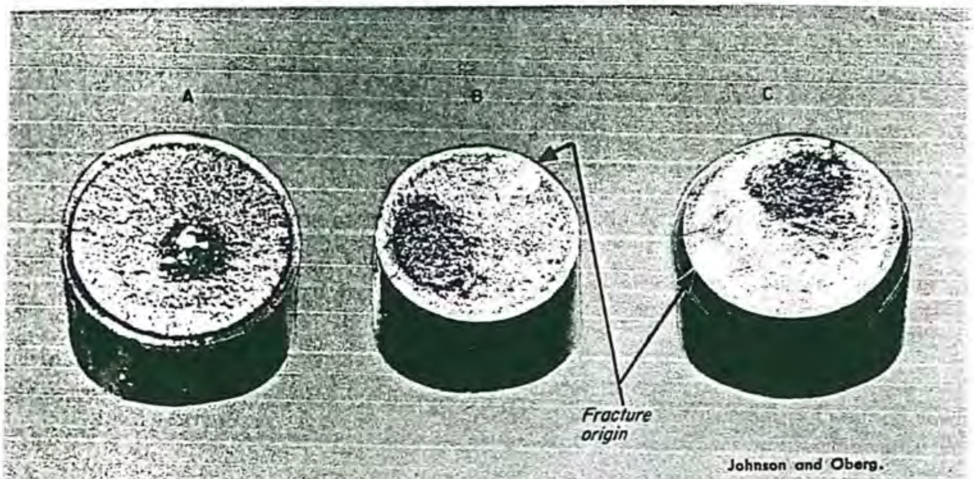


Fig. 22—Origin of failures in Johnson and Oberg specimens. Fatigue fracture in nitrided specimens B and C originated in core. Fatigue fracture in non-nitrided specimen A originated at surface.

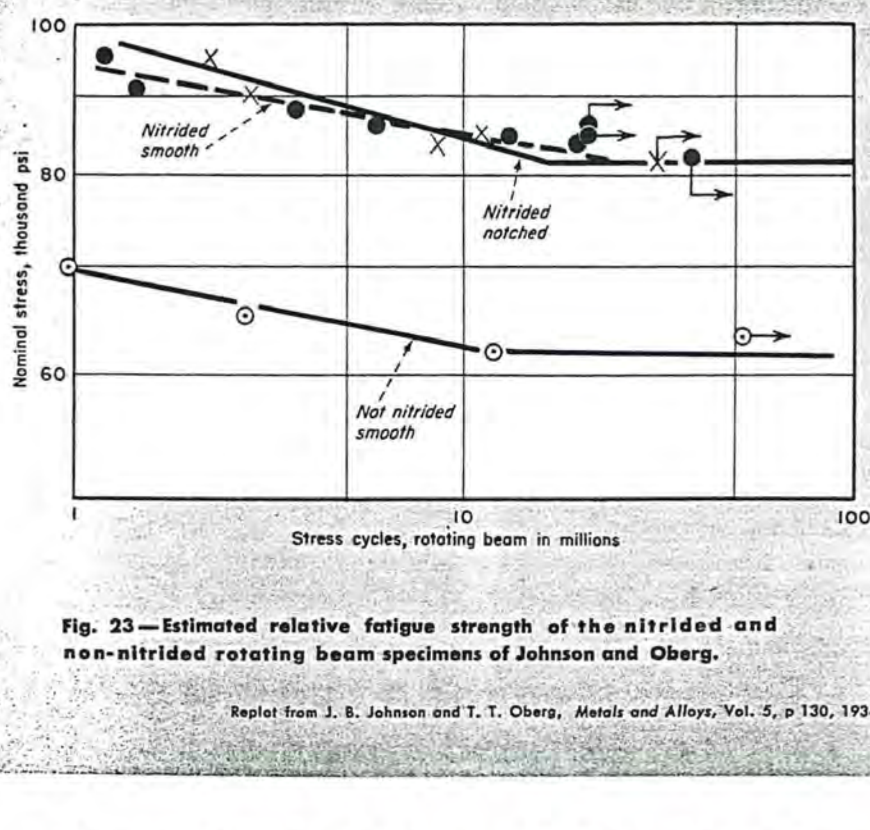


Fig. 23—Estimated relative fatigue strength of the nitrided and non-nitrided rotating beam specimens of Johnson and Oberg.

Replot from J. B. Johnson and T. T. Oberg, *Metals and Alloys*, Vol. 5, p 130, 1934.

Fig. 23, which is a replot of the original data. From these graphs, it is seen that the nominal fatigue endurance limit of the non-nitrided specimens, in which the fracture originated at the surface, is 62,000 psi as compared to the nominal endurance limit of 82,000 psi for the nitrided specimens, in which the fracture originated in the sub-surface metal. The reported stresses are presumably the calculated values at the surfaces of the 0.3 in. dia specimens. The actual stresses are not known for either kind of specimen because of the presence of residual stresses in both types.

In the non-nitrided specimens, the stress causing fractures was probably less than the value shown in the chart because, in the process of polishing, residual compressive stresses are induced in the surface by the polishing. The effective stress at the surface of these specimens is, therefore, the stress recorded in the chart minus the retained residual compressive stress from the polishing. Polishing stress measurements indicate that residual compressive stress from this source may exceed 20,000 psi (Ref. 11). But if compressive stress of this magnitude was induced during polishing, as indicated in Fig. 20, it is possible that a part was dissipated by yielding during the reversed bending fatigue tests.

Probably the best estimate of the discount that should be applied to the fatigue strength of the Johnson and Oberg non-nitrided specimens, because of the residual stress from polishing, are the data from the H. F. Moore specimens given in Table I. If eleven percent of the observed 62,000 psi fatigue strength is attributed to polishing residual stress, the actual fatigue strength of the polished surfaces was approximately 56,000 pounds per square inch.

Reconstructed Stress in Nitrided Specimens

The actual stress in the sub-surface metal of nitrided specimens, at the points of origin of the fractures, would be greater than was indicated for this portion of the beam by the calculations. To convey an idea of the stress pattern in the nitrided specimens shown in Fig. 22, the diagram Fig. 24 has been constructed from Johnson and Oberg test data.

This diagram assumes that the magnitude and depth of the measured residual stress shown in Fig. 19 applied also to the 0.3 in. specimens used by Johnson and Oberg. The axial compressive force from the residual stress in the nitrided case of this composite specimen must be balanced by a tensile force of equal magnitude acting on the core. Since the area of the core is greater than the area of the case, the maximum residual tensile stress in the core would be approximately one-tenth of the residual compressive stress in the case.

Measurements of the photographs, Fig. 22, indicate that the failures originated approximately at 0.025 to 0.030 in. below the surface, which serves to indicate the depth of the maximum resultant tensile stress. It is seen that the sum of the stress from the external load and the residual tensile stress in the core at the point of maximum stress is 78,000 psi, which is 95 percent of the nominal surface stress. By comparison, the stress as calculated from the nominal stress gradient at a depth of 0.027 in. is 82 percent of the surface stress. However, the stress as indicated in the SN diagram, Fig. 23, is presumably the nominal surface stress and not the nominal stress at the depth of the fracture origin.

Because of the many uncertainties in the foregoing estimates of the actual stress, the present purpose will be better served by using the reported nominal test stresses for comparing the relative fatigue strength of the surface and sub-surface metal. From the SN chart, Fig. 23, the ratio of surface strength to sub-surface strength at the endurance limit is 62,000 to 82,000 psi, that is, based on the uncorrected stresses the fatigue strength of the surface is about 75 percent of the fatigue strength of submerged metal.

Nitrided Surface Stresses Always Compressive

The maximum nominal stress that was applied to these nitrided specimens during the reversed bending test, it is interesting to note, was less than 100,000 psi. Since the residual compressive stress in a nitrided case, as shown in Fig. 19, approximates 140,000 psi, it is apparent that the stress from the reversed bending load in much of the nitrided case was not tension at any time. This deduction accounts for the fact that the hard surfaces of case hardened specimens are not "brittle," and that Johnson and Oberg found that sharp notches could be ground through 70 percent of the nitrided case before the fatigue strength of the specimen was adversely affected. Fatigue fractures can only develop and propagate in regions that are stressed in tension.

Incidentally, the maximum compressive stress in the case was, of course, equal to the sum of the residual compressive stress and the stress from the test load, which on the basis of the nitriding stress shown in Fig. 19 approximated 230,000 psi, as shown in Fig. 23 near the upper surface.

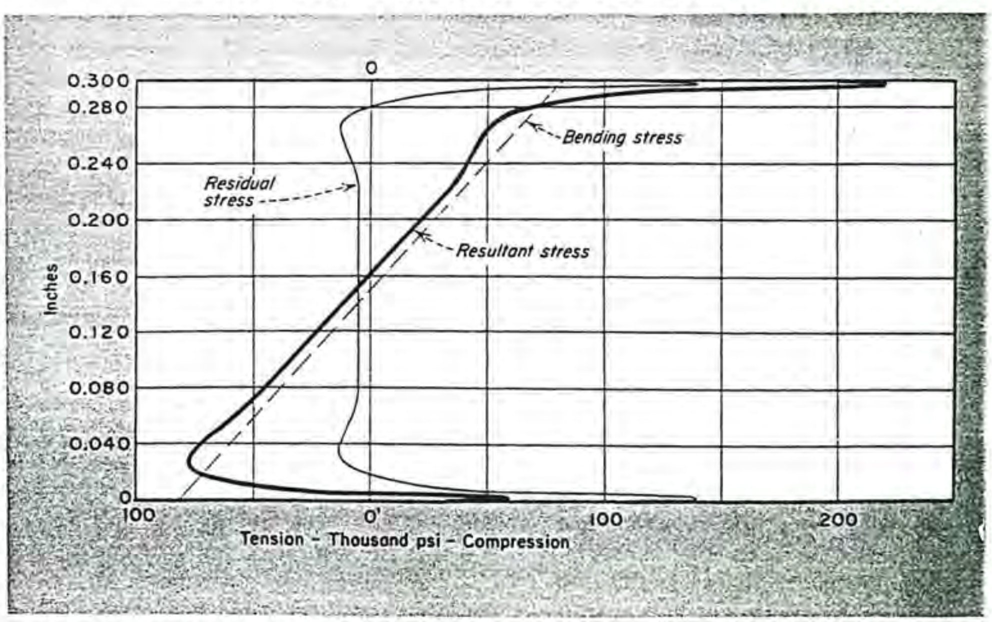
Other reports relating to fatigue strength comparisons of nitrided and non-nitrided specimens are suitable for indicating the relative strength of surface and sub-surface metal. In all the references, which will be cited, care was used to develop the same physical properties in the non-nitrided steel of both kinds of specimens. The fatigue strength of the surface will be given in percent of the core fatigue strength based upon the uncorrected stress values given in the several reports.

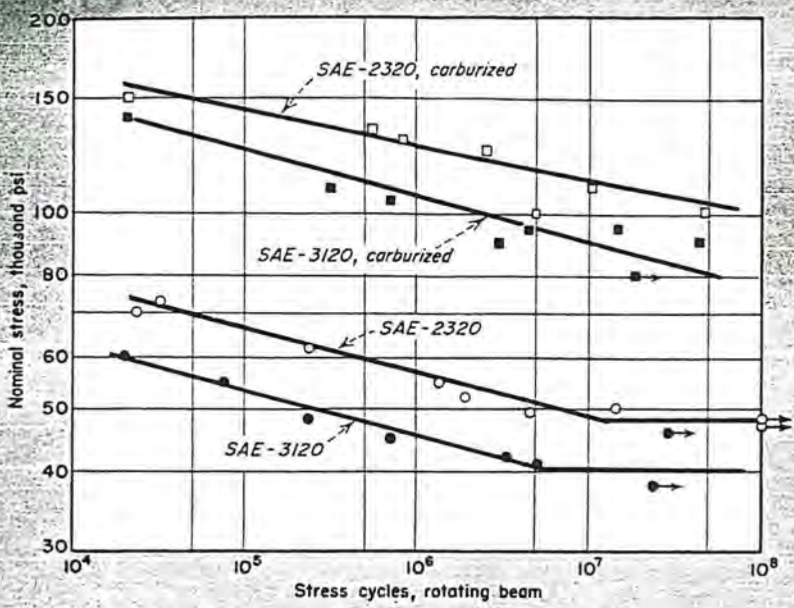
Von O. Hengstenberg and Mailaender (Ref. 22) tested three groups of specimens made from different kinds of steel. Subsurface fractures were reported to have occurred in the nitrided specimens. The surface fatigue strength is shown as 69 percent, 73 percent, and 78 percent of the fatigue strength of sub-surface metal for the respective steels.

Mailaender (Ref. 23) reported fatigue tests that indicate the fatigue strength of the surface to be 71 percent of the fatigue strength of sub-surface metal.

Sutton (Ref. 24) compared nitrided and non-nitrided specimens by repeated axial loads as well as by rotating beam loaded in bending. This comparison is an interesting variation because, as is evident from inspection of Fig. 24, the tensile stress in the nitrided specimens is proportionately greater under axial loads than under bending loads. Sutton's uncorrected stress data give the surface fatigue strength of rotating beam specimens as 82 percent, and the axial stressed specimens as 97 percent, of the fatigue strength of sub-surface metal. Presumably these values would approach one another, and they would also become smaller, if corrected stresses were available.

Fig. 24 — Constructed stress pattern in the nitrided specimens shown in Fig. 22 used by Johnson and Oberg.





Replot from H. F. Moore and N. J. Alleman; A.S.S.T. Trans., Vol. 13, 1928.

Fig. 25 — Fatigue strength of carburized and non-carburized SAE 3120 and SAE 2320 steel rotating beam specimens.

Surface Weakness Estimated From Carburized Specimens

Tests that have been made to measure the relative fatigue strength of carburized specimens can also be used for estimating surface weakness. Among the fatigue data, which are suitable for this purpose, are the results of two series of tests conducted by H. F. Moore and N. J. Alleman (Ref. 25) on carburized and non-carburized SAE 3120 and SAE 2320 steel.

These data are shown in the replotted SN chart Fig. 25. From this chart it is seen that the fatigue strength of the surfaces of non-carburized specimens is, in terms of uncorrected stress, only one-half as great as the fatigue strength of the equivalent material in the core of the carburized specimens.

The data reported by Moore and Alleman do not mention sub-surface fractures. But properly performed carburizing and quenching develop residual compressive stress in the hardened layer somewhat as is indicated by the measured stress shown in Fig. 19. Also, since the diameter of the specimens was the standard 0.3 in., probably many or all of the fractures in the carburized specimens originated in the core.

Through correspondence, it has been learned that Professors Moore and Alleman recalled that many sub-surface fractures did occur. At the time when these tests were made the effects of residual stresses were not appreciated, and since the point of origin of the fractures was not important to the purpose of the tests, no record was made of their frequency.

Only Nominal Stress Available

As in the nitrided specimens, the stresses that are recorded in the SN chart, Fig. 25, are nominal only and the actual stresses at the point of fracture origin can only be approximated by dissection measurements of the residual stresses in the carburized and the uncarburized specimens. Polishing stresses were probably induced and may have been retained on the surfaces of the uncarburized specimens, in which event the stress for these specimens will have to be revised downward.

Carburizing would have developed residual compressive stresses in the case during the hardening transformation, but it is hazardous to judge the magnitude of these stresses by the measured values shown in Fig. 19. These stress measurements were made on a specimen carburized to a depth of approximately 0.055 in., whereas, the carburizing depth of the Moore and Alleman specimens is given as 0.025 in. for the SAE 2320 steel and 0.032 in. for the SAE 3120 steel.

Both series of specimens were quenched in oil directly from the carburizing box without subsequent treatment. The surface hardness is recorded as Rockwell C 64-65. The tests are disappointing in that the non-carburized specimens were tested in the as rolled condition, therefore, the physical properties of the surface of these specimens may differ from the physical properties of the core of the carburized specimens.

Surface Only one Half as Strong as Sub-Surface

There can be no doubt that the cores of the carburized specimens were residually stressed in tension. It is, therefore, reasonable to assume that the actual differences in the stresses at the points of origin of the fractures were greater than the difference in the nominal stresses shown in the SN chart. In the absence of more precise data, the comparisons will be made on the uncorrected stresses as reported, from which it is found that the surface fatigue strength for both steels is approximately 50 percent of the strength of the sub-surface metal.

Although the Moore and Alleman report does not recognize residual stresses, it does comment on the test results as follows: "... where the core and case meet, it will be found . . . that at the endurance limit (the) computed stress is . . . usually 50 percent higher than the endurance limit of the virgin metal. This would indicate that at the outer edge of the core the strength of the material is at least as great as that of the virgin metal."

Woodvine (Ref. 26) fatigue tested three kinds of steel in the carburized and non-carburized condition. In preparing the specimens, Woodvine reports that the non-carburized specimens were given the same heat-treatment as the carburizing specimens, except that they were heated in sand instead of in a carburizing environment. Sub-surface fractures were found in the carburized specimens. The surface fatigue strengths of the three steels based on uncorrected stresses as reported were 51, 55, and 62 percent of the strengths of the sub-surface steel in their respective groups.

CYANIDING DEVELOPS RESIDUAL STRESS. Residual stresses that are developed by cyaniding have not yet been measured by the General Motors Research Laboratory, but the measurements made by Becker and Phillips (Ref. 27) will serve as qualitative if not quantitative evidence. The residual stresses in the hardened case are shown to be compressive.

The fatigue strength of cyanided and non-cyanided specimens of 0.16 carbon steel as reported by Lea (Ref. 28), indicate that in terms of uncorrected stresses, the non-cyanided surface of his test specimens was 55 percent as strong as the non-cyanided sub-surface steel.

Ductile and Brittle Materials

The ratio of surface fatigue strength to sub-surface fatigue strength is probably not the same for all structural materials. It is also probable that in any material this ratio varies with such properties as hardness and ductility.

The surface of a specimen of very hard steel, in which the hardness is uniform throughout, does not have the surface protection of residual compressive stresses that occurs in case hardened surfaces. Through-hardened steel specimens will therefore be more susceptible to surface fatigue failure, because the low ductility of the hard metal reduces the ability of the surface to relieve local tensile stresses by plastic adjustment. Such specimens are said to be "notch sensitive" or "brittle."

Effect of Surface Stress Raisers in Statically Loaded Ductile Metals

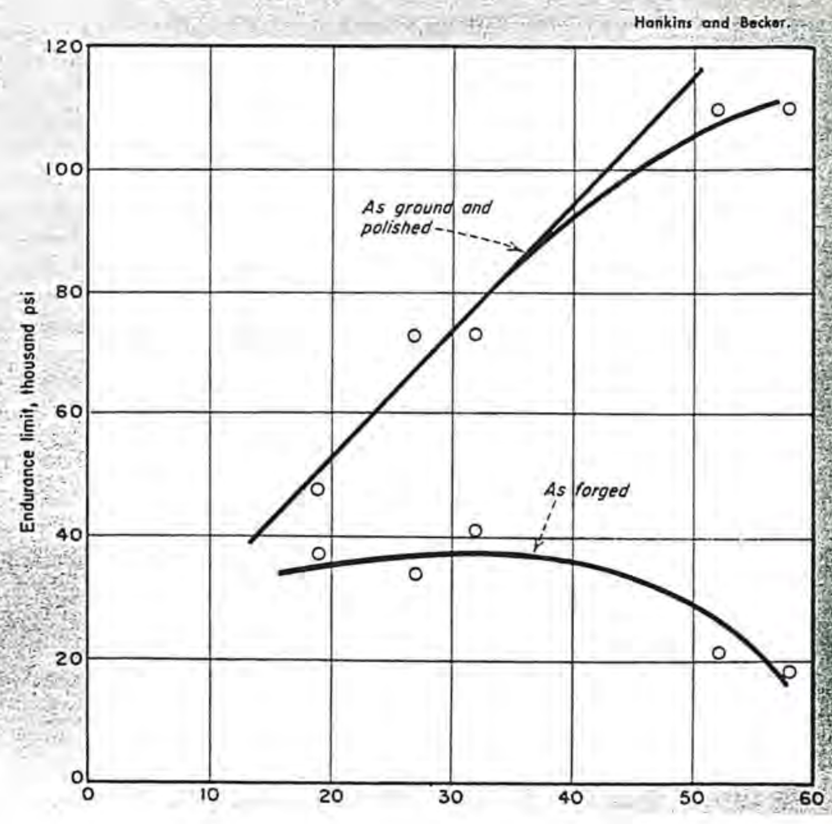
In ductile metals under static loading, the effect of surface stress raisers is negligible. Any local increase of stress in a stress raiser, for example a scratch, is dissipated by plastic flow of the metal affected by the stress raiser. Such localized plastic adjustments may be said to occur on a micro scale. The result is that the surface stress becomes quite uniform in spite of surface imperfections. Also in statically loaded ductile specimens, the effect of the inherent weakness of surfaces is also reduced by general plastic yielding of the surface at nominal stresses less than the yield strength of the core.

Plastic flow of surface metal has been shown by Norton (Ref. 29), who measured the residual stress in a tensile specimen after it had been statically loaded slightly above the nominal elastic limit. He found that a surface layer of measurable depth was residually stressed in compression, presumably because of the greater plastic extension of the surface than of the sub-surface metal. Such surface extension probably occurs, but on a greatly reduced scale, when ductile metals are subjected to repeated loads at lower stresses, as in fatigue tests. Fatigue fractures therefore are brittle in appearance in metals that will show extensive necking under static tests.

Plastic relief of local stresses becomes increasingly difficult as ductility is reduced until, as in a material such as glass, local stress raisers and general surface weakness are equally effective whether the specimen is loaded statically or by repeated loads. For this reason, the strength of glass under repeated loads is identical with its static strength. In terms of the relative magnitudes of static and fatigue strength of metals, this fact means that because of surface weakness the static strength of glass is reduced to equal its strength under repeated loads.

A suggestion of this increased surface vulnerability with decreased ductility is seen in the experiments of Hankins and Becker (Ref. 30). As shown in the plot of the data they obtained from ground and polished steel specimens, Fig. 26, the endurance limit increases linearly with hardness until Rockwell C 40 is reached. At higher hardness levels, the reduced ductility does not permit adequate plastic relief of the tensile stress in local stress raisers. The rate of fatigue strength increase is therefore sharply reduced,

Fig. 26—Increase of surface vulnerability with hardness in ground and polished steel specimens.



although the strength of the sub-surface steel presumably continues to increase at high hardness levels.

Improving Static and Impact Strength

Surface weakness affects the strength of materials under load conditions other than repeated stresses.

Materials of low ductility fail at low stress by brittle fractures under static and impact loads, because they are not capable of yielding to relieve local high stresses whether from surface imperfections, residual micro stresses or just plain undefined surface weakness. Brittle materials will therefore suffer from surface imperfections whether the applied load is static, impact, or repeated fatigue loads. The imperfections may or may not be in the form of recognizable stress raisers but, regardless of smoothness, the surfaces are weaker than sub-surface material.

Since completely brittle materials fail only by tensile stresses (Ref. 31) their strength, under various kinds of loading, is increased by inducing residual compressive stresses in the fracture sensitive surface layer. Steel having the hardness of the case of carburized and nitrided specimens would be notch sensitive and therefore brittle, except as shown in Fig. 19 that the hard layers are residually stressed in compression.

Prestressing by mechanical means can only be accomplished in materials having some ductility. Fig. 2 shows that steel of Rockwell C 64 hardness is sufficiently ductile to respond to shot peening. The peening, which was not of high intensity, is seen to have developed a residual compressive stress that extended to a depth of 0.009 in. and a magnitude of 150,000 psi. Mechanical prestressing can, therefore, be expected to increase the static, the impact, and the fatigue strength of many hard metals.

Mechanical prestressing should also be effective in reducing the "brittleness" acquired by hardened steel that is uniformly hard throughout. Such prestressing should also reduce the hazard of fractures that often occur because of reduced ductility at low temperature. In fact, the effectiveness of surface residual compressive stress should increase as the "brittleness" increases.

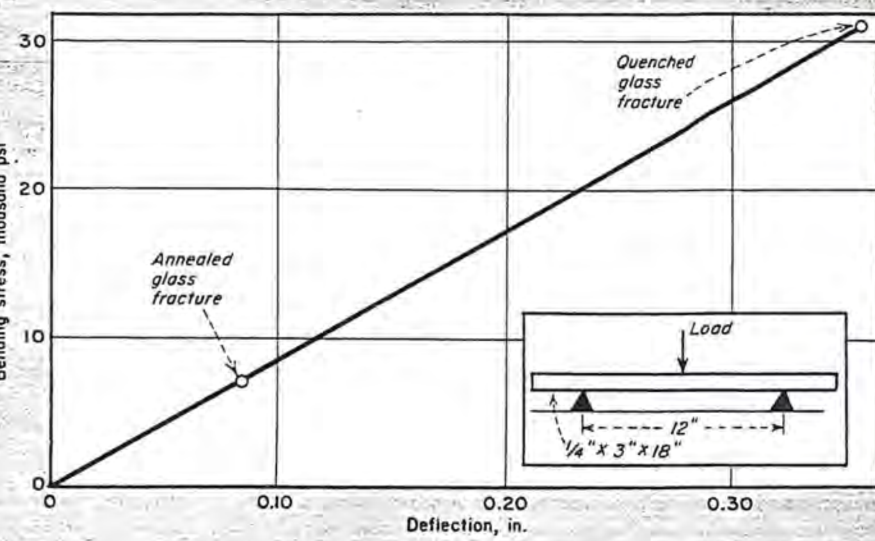


Fig. 27 — Stress-strain curves in annealed and in quenched glass. Insert shows specimen dimensions and loading method.

Strength Increases As Ductility Decreases

Materials, such as glass, in which measurable plastic flow cannot occur at ordinary temperatures may have their static strength and impact strength increased by an amount equal to the magnitude of residual compressive stress that can be developed in the surface of the specimen. Thus the static, impact, and fatigue strength of glass (Ref. 32) can be increased several hundred percent by quenching from a temperature at which the glass is plastic.

When a glass plate or rod is quenched from the plastic range, the surfaces cool and contract while the core deforms plastically to conform to the altered surface dimensions. Subsequent cooling and contracting of the core develop a tensile stress in the sub-surface glass and a corresponding compressive stress in the surfaces. The residual surface stress that is trapped by this process is three or more times as great as the tensile strength of ordinary annealed glass.

The increase in static strength obtained by prestressing is shown by the experiment recorded in Fig. 27. Static bending loads were applied on annealed and on quenched glass beams as shown at the lower right of the chart. The annealed glass failed at a stress of 7,000 psi, whereas the prestressed glass failed at a nominal stress of 32,000 pounds per square inch.

Residual Stress Measurements in Glass

Residual stresses in quenched glass have been measured by Littleton (Ref. 32), by means of photo-elastic strain patterns. He found that the static strength of quenched glass exceeds that of annealed glass by an amount equal to the magnitude of the residual compressive stress that is developed during quenching. This observation means that the static strength of the quenched glass beam, Fig. 27, was increased from a nominal stress of 7,000 psi to nominal stress of 32,000 psi by a surface residual compressive stress of 25,000 psi.

Based upon the residual stress experiments of Littleton and the static strength comparisons of Fig. 27, the stress diagrams of the latter specimens are reconstructed in Fig. 28. Since the annealed glass plate was presumably free from residual stresses of significant magnitude, the stress in this specimen at the instant of fracture is repre-

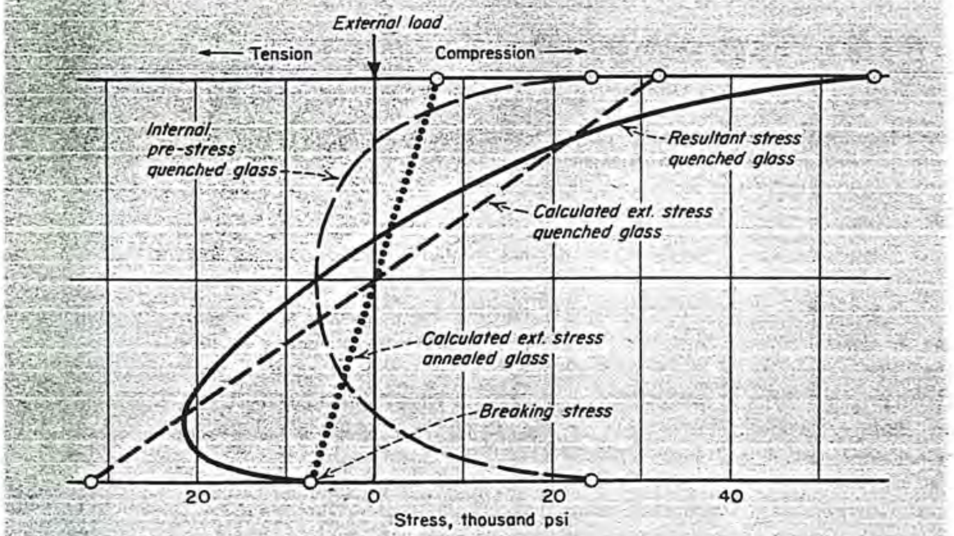


Fig. 28—Reconstructed diagrams to show stress distribution in glass beam specimens when they were loaded to failure.

sented by the diagonal dotted line labeled "Calculated Ext. Stress Annealed Glass." This line is drawn to conform to the static strength test, by which the fracture was found to occur on the lower surface at 7,000 psi tensile stress.

The nominal stress from the external load on the quenched glass at the instant of fracture is represented by the dashed diagonal line labeled "Calculated Ext. Stress Quenched Glass." The surface stresses are shown as 32,000 psi to conform with the Fig. 27 nominal test stress.

The distribution of the residual stress that was developed by the quenching operation is shown by the symmetrical curved line labeled "Internal Prestress Quenched Glass," which is proportioned in accordance with Littleton's photoelastic measurements. The residual compressive stress on both surfaces is shown as 25,000 psi for the reason stated previously.

The resultant stress shown in Fig. 28 is the algebraic sum of the residual stress and the nominal stress from the external load. It is represented by the unbroken curved line labeled "Resultant Stress Quenched Glass," which extends from 57,000 psi compression to 7,000 psi tension. It will be seen that the maximum tensile stress occurs in sub-surface glass, and reaches a value of approximately 21,000 psi but, because of surface weakness, the fracture presumably originated at the surface from a tensile stress of only 7,000 pounds per square inch.

Strength Increased Four Hundred Percent

Although the quenched glass beam, Fig. 27, was more than 400 percent stronger than the annealed glass beam, the surface fracture strength was the same for both specimens. By these tests, the surface of polished plate glass is found to be less than 33 percent as strong as subsurface glass. Many years ago Littleton said, "We never test the strength of glass; all we test is the weakness of its surface." It now appears that this statement applies equally well to repeatedly loaded metals and perhaps to many other materials.

Available test data (Ref. 33) show that the fatigue strength of glass subjected to repeated bending loads is substantially the same as its static strength. Its impact strength may be somewhat greater because of the short duration of loading. Since there is no change in stress by plastic flow, the strength of glass is not affected by the manner of loading, except for the well-known loss of strength (Ref. 31-34) as the duration of loading is increased.

It is to be expected that the behavior of metals will approach the behavior of glass as their ductility is decreased. Very hard steel tested at a very low temperature should be relatively insensitive to the manner of loading, and surface weakness should increase. Its fatigue strength should approach its static and impact strengths, and surface prestressing should remain effective regardless of loading method.

EDITOR'S NOTE: In the near future PRODUCT ENGINEERING will publish a sequel article "Fatigue Failures Are Tensile Failures" by J. O. Almen, in which he will discuss how unexpected improvement in fatigue strength is often obtained from processes that are applied for other purposes.

ACKNOWLEDGMENTS

Valuable assistance was given by many co-workers in the General Motors Corporation in the preparation of this article. Particularly appreciated is the help given by: William E. Miller and Carmin Guerrera, who performed the delicate dissection operations and the precise measurements by which the residual stresses in many specimens were reconstructed. Mary Elizabeth Kerr performed the calculations and prepared the many charts that are used as illustrations. Robert Schilling, R. L. Mattson, and Maurice Olley offered many helpful criticisms and suggestions.

BIBLIOGRAPHY

1. Unpublished data General Motors Research Laboratories.

2. J. O. Almen, Shot Blasting to Increase Fatigue Resistance, *S. A. E. Journal*, v. 51, No. 7, 1943, p. 248.

3. A. Thum and W. Bautz, Ursachen der Steigerung der Dauerhaltbarkeit gedruckter Staebe, *Forschung des Ingenieurwesens*, v. 6, No. 3, May/June, 1935, p. 121-8.

4. O. Foeppl and A. Thum, Steigerung der Dauerhaltbarkeit durch Oberflaechen-druecken, *Zeitschrift des Vereines Deutscher Ingenieure*, v. 77, No. 50, 1933, pp. 1335-1337.

5. O. J. Horger and H. R. Neifert, improving Fatigue Resistance by Shot Peening, *Experimental Stress Analysis*, v. II, No. 1, May, 1944, p. 178.

6. O. J. Horger and C. H. Lipson, Automotive Rear Axles and Means of Improving their Fatigue Resistance, *A.S.T.M. Technical Publication*, No. 72, presented June, 1946.

7. R. L. Mattson and J. O. Almen, Effect of Shot Peening on the Physical Properties of Steel, Final Report, Part II, O.S.R.D. No. 4825, published by National Defense Committee of the Office of Scientific Research and Development, War Metallurgy Division, 1945, pp. 65-66.

8. D. K. Crampton, Effects of Internal Stresses on Properties of Drawn Brass Tubes, *Trans. Amer. Mining and Metallurgical Engineers*, v. 104, 1933, p. 210.

9. R. L. Mattson and J. O. Almen, Effect of Shot Peening on the Physical Properties of Steel, Final Report, Part II, O.S.R.D. No. 4825, published by National Defense Committee of the Office of Scientific Research and Development, War Metallurgy Division, 1945, pp. 98-99.

10. E. Heyn, Internal Strain in Cold Wrought Metals and Some Troubles Caused Thereby, *Journal of the Inst. of Metals*, v. 12, 1914, p. 137.

11. J. O. Almen, Peened Surfaces Improve Endurance of Machine Parts, *Metal Progress*, Feb., 1943, p. 215.

12. H. H. Miller, New Cut Wire Shot Big Boon to Peening, *S.A.E. Journal*, v. 57, No. 8, Aug., 1949, p.44.

13. R. L. Mattson and J. O. Almen, Effect of Shot Peening on the Physical Properties of Steel, Final Report, Part 1, O.S.R.D. No. 3274, published by the National Defense Committee of the Office of Scientific Research and Development, War Metallurgy Division, 1944, p. 81.

14. R. L. Mattson and J. O. Almen, Effect of Shot Peening on the Physical Properties of Steel, Final Report, Part 1, O.S.R.D. No. 3274, published by the National Defense Committee of the Office of Scientific Research and Development, War Metallurgy Division, 1944, pp. 56 and 57.

15. R. L. Mattson and J. O. Almen, Effect of Shot Peening on the Physical Properties of Steel, Final Report, Part II, O.S.R.D. No. 4825, published by National Defense Committee of the Office of Scientific Research and Development, War Metallurgy Division, 1945, pp. 43 and 44.

16. R. L. Mattson and J. O. Almen, Effect of Shot Peening on the Physical Properties of Steel, Final Report, Part III, O.S.R.D. No. 6647, published by National Defense Committee of the Office of Scientific Research and Development, War Metallurgy Division, 1946, p. 110.

17. O. J. Horger, Increasing Fatigue Strength of Press Fitted Axle Assemblies by Surface Rolling, A.S.M.E. Trans., v. 58, 1936, pp. A91-A98.

18. H. F. Moore, Size Effect and Notch Sensitivity in Fatigue Tests of Steel, *A.S.T.M. Proceedings*, v. 45, 1945, pp. 516-519.

19. D. Markoven and H. F. Moore, Effect of Size of Specimen on Fatigue Strength, *A.S.T.M. Proceedings*, v. 44, 1944, pp. 143 and 144.

20. H. Buehler and H. Buchholtz, Die Wirkung von Eigenspannungen aus die Biegeschwingungsfestigkeit, *Stahl u. Eisen*, v. 53, 1933, pp. 1330-1331.

21. J. B. Johnson and T. T. Oberg, Effect of Notches on Nitrided Steel, *Metals and Alloys*, v. 5, 1934, pp. 129 and 130.

22. O. Hengstenberg and R. Mailaender, Bending Fatigue of Nitrided Steels, *Kruppsche-Monatschefts*, v. 11, Sept.-Oct. 1930, p. 252.

23. R. Mailaender, Ueber die Dauerfestigkeit von nitrierten Proben, *Tech. Mitt. Krupp*, Hft 2, July, 1933, pp. 53-58, also *Z. Ver. deut. Ing.*, v. 77, 1933, pp. 271-274.

24. H. Sutton, Fatigue Properties of Nitrided Steel, *Metal Treatment*, v. 2, 1936, pp. 89-92.

25. H. F. Moore and N. J. Alleman, Fatigue Tests of Carburized Steel, *Trans. Amer. Soc. Steel Treat.*, v. 13, 1928, pp. 405-419.

26. J. G. R. Woodvine, Behavior of Case-Hardened Parts Under Fatigue Stresses, Carnegie Schol. Mem., *Iron Steel Inst.*, v. 13, 1924, pp. 197-237.

27. M. L. Becker and C. E. Phillips, Internal Stresses and Their Effect on the Fatigue Resistance of Spring Steel, *The Jour. of Iron and Steel Inst.*, v. 133, No. 1, 1936, pp. 427-442.

28. F. C. Lea, Effect of Discontinuities and Surface Conditions on Failure Under Repeated Stress, *Engineering*, v. 144, 1937, pp. 87-90, 140-144.

29. J. T. Norton, X-ray Methods in the Field of Residual Stresses, *Experimental Stress Analysis*, v. 11, No. 1, pp. 157-160.

30. G. A. Hankins and M. L. Becker, The Fatigue Resistance of Unmachined Forged Steels, *The Jour of the Iron and Steel Inst.*, v. 127, No. 2, 1932, p. 205.

31. F. W. Preston, The Mechanical Properties of Glass, *Journal of Applied Physics*, v. 13, Oct., 1942, pp. 623-634.

32. J. L. Littleton, Jr., A New Method for Measuring the Tensile Strength of Glass, *Physical Review*, v. 22, 1923, pp. 510-516.

33. Unpublished data General Motors Research Laboratories.

34. A. A. Griffith, The Phenomena of Rupture and Flow in Solids, *Transactions Royal Society*, A, v. 221, 1920, p. 162.

35. Hayo Foppl, Messung der Spannungen und der Plastischen Verformungen an Oberflachengedruckten Probekorpern, Mitteilungen des Wohler-*Institute Braunschweig*, Heft 41, Friedr. Vieweg & Sohn, Braunschweig, 1948.