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Residual Stresses in Quenched and Tempered Plain Carbon Steels

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Abstract

An investigation was made of factors contributing to maximum compressive residual stress. Stresses from furnace hardening heat treatment were shown to be highest at high hardness, medium carbon content, large section size, and minimum hardenability over the range investigated. Shot peening was found to decrease high heat treatment stresses. An example showed very high fatigue strength in plain carbon steel at high hardness which was related to the very high compressive residual stress induced by severe water quenching during heat treatment.

OVER THE LAST SEVERAL YEARS, studies have been made in the Research Department of Caterpillar Tractor Co., concerning the effect of residual stress on fatigue performance of steels and on the factors contributing to high compressive residual stress. Results of some of these investigations were discussed in a recent paper[1]. Effects on residual stress of variations in composition of plain carbon and some alloy steels, furnace hardening heat treatment, and cold working by shot peening were investigated. The influence of residual stress in fatigue was analyzed according to the theory of Fuchs[2], in which long life performance is determined by resistance to crack initiation and/or propagation.

This is an excerpt of some of the highlights from that paper concerning production of high compressive residual stress. An example is included showing the marked effect of residual stress on fatigue performance.

Test Procedure

Specimens used for the residual stress investigations were cylinders, basically of about 2-in. diameter and 6-in. length, of plain carbon and some boron steels. Chemical compositions of these along with the steels used in the fatigue tests are recorded in Table 1. The 0.25-in. radius circumferential notch was the smallest in which residual stress in the longitudinal direction could be measured by x-ray diffraction. The applied stress concentration factor in the notch was 1.5. All specimens were furnace heated and water quenched except the SAE 86B45 specimens, which were oil quenched. Fatigue specimens were finish ground in the notch after heat treatment. Those to be used unpeened were electropolished in a bath of concentrated 60 per cent phosphoric plus 40 per cent sulfuric acids to remove the worked layer. Some cylindrical specimens were electropolished slightly to remove a decarburized or oxidized layer before surface stress measurement. Shot peening was done with 0.033-in. diameter shot for an intensity of about 0.024 in Almen A-2.

TABLE 1

Chemical Compositions of Steels (Weight Per Cent)

Element: SAE No.	C	Mn	B
Plain Carbon Steels			
1018	0.20	0.79	
1035	0.35	0.82	
1042	0.45	0.76	
1045	0.44-0.50	0.70-0.85	
1078	0.80	0.41	
1095	1.00	0.26	
Plain Carbon-Boron Steels			
10B35	0.32-0.36	0.74-0.85	0.0004-0.0007
10B39	0.43	1.09	0.0014
10B45	0.43	0.85	0.0011
10B45 elevated Mn	0.43	1.56	0.0009
Alloy Steel			
86B45*	0.42-0.46	0.78-0.94	0.0014-0.0016

* 0.45-0.54 Ni, 0.54-0.58 Cr, 0.20-0.22 Mo

Residual stresses were measured by x-ray diffraction according to the two-exposure method described in SAE Report TR-182[3]. Filtered chromium radiation was used with the 211 diffraction peak of iron. The stress factor was calculated using the stress equation and elastic constants of 30 10^6 psi for Young's modulus and 0.29 for Poisson's ration. Stresses were measured in the longitudinal direction at mid-length of the cylindrical specimens and in the critical section of the fatigue specimens. Longitudinal stress is most significant in bending fatigue. Measurements at depths achieved by grinding and electropolishing were corrected for the effect of stressed layers removed[4].

Fatigue tests were run with an alternating bending fatigue machine, which has provision for applying a mechanical mean load. Alternating, non-rotating bending stresses are applied utilizing the principle of inertia force compensation. The machine is tuned for resonance so stress in the notch is proportional to the centrifugal force of an out-of-balance weight driven by an electric motor. A unique feature of this machine is the provision for applying a mechanical mean stress. Stresses reported are actual longitudinal stresses in the notch, determined by calibrating with a specimen containing strain gages.

Variables Affecting Residual Stress

Heat Treatment - The basic effect on residual stress of tempering for hardness variation was shown with a series of plain carbon steel cylinders, water quenched. Carbon content ranged from 0.20 to 1.00 per cent. As shown in Fig. 1, substantial surface residual stresses of 95 to 160 ksi compression were obtained as quenched. In the high carbon level steels these stresses were considerably decreased by tempering at low temperatures. At the medium and low carbon levels, however, little stress change resulted. This is evidently an auto-tempering effect due to the high M_S temperature of these lower carbon level materials. Tempering above 400° F caused a rapid decrease in compressive stresses, complete relaxation being obtained at about 800° F.

Hardness was measured after each of these tempers. The residual stress data was plotted versus hardness in Fig. 2 for the various carbon levels. The first point on each curve corresponds to the as-quenched condition. Compressive stresses are seen to decrease considerably with small decreases in hardness. The curves lie in order of increasing carbon content toward higher hardness. This is because the higher carbon level materials are harder as quenched.

The effect of tempering at the various carbon levels is shown by the superimposed isotemper curves in Fig. 2. A 300° F temper, which is often given to reduce cracking tendency, is seen to have relatively small effect on residual stress. Also seen is an apparent optimum carbon content for maximum residual stress at a given temper. It corresponds to the intermediate carbon level of 0.35 to 0.45 per cent of all tempers. This effect could be due to a maximum difference between case and core hardness at this intermediate carbon level, or the influence of M_S temperature along with retained austenite at the higher carbon levels.

Production parts are usually designed for a given strength, which calls for a given hardness. The previous data are replotted in Fig. 3 as surface residual stress versus carbon content for various hardnesses. It is seen that compressive residual stress increases with decreasing carbon content at a given hardness. At Rc 55 hardness, for example, the 0.35 per cent carbon level gave the highest compressive stress. These data indicate that, to achieve the maximum residual stress in a part that is to be of a given hardness, the lowest carbon level material which will just provide this hardness with little or no tempering should be used.

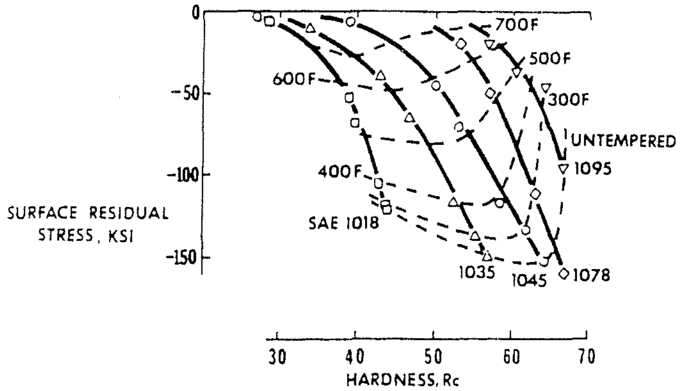

Fig. 2. Variation of residual stresses with hardness. Dotted lines are temper isothermal curves, showing a maximum compressive stress at an intermediate carbon level for a given temper.

The above data have been for shallow-hardening, plain carbon steels. Residual stress also varies with hardenability; an example of this is shown in Fig. 4. Residual stress is compared for two, 2.75 in. diameter cylinders, water quenched. A shallow-hardening, plain carbon steel is compared with a deeper-hardening boron steel of approximately the same carbon content and hardness. Residual stress is plotted as a function of depth below the surface. Surface compressive stress was low in both specimens because of a decaburizing furnace atmosphere. However, a maximum compressive stress was seen at 0.10 to 0.20 in. below the surface. This stress was the most significant in fatigue, as shown in this paper and Ref. 5. The plain carbon steel contained a much higher maximum stress of 185 ksi compared to 125 ksi in the boron steel.

The effect was investigated further as shown in Fig. 5 over a greater range of hardenability using 1.75-in. diameter cylinders given the same heat treatment as in the previous

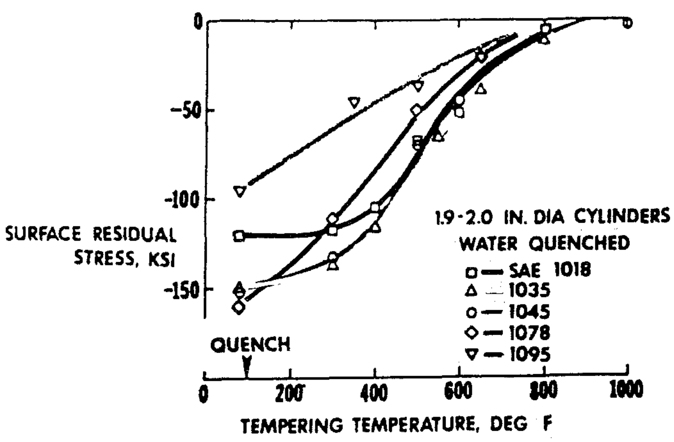

Fig. 1. Effect of tempering temperature on surface residual stresses in hardened plain carbon steel specimens of various carbon levels.

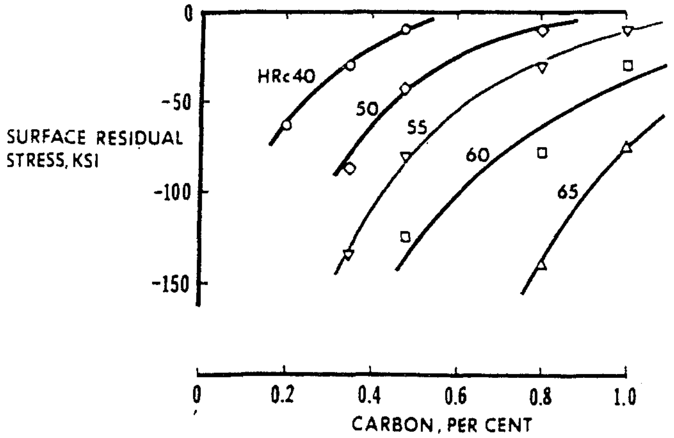

Fig. 3. Residual stress data of Fig. 2 as a function of carbon content for various hardnesses. Residual stress is a maximum in compression at the minimum carbon level for a given hardness.

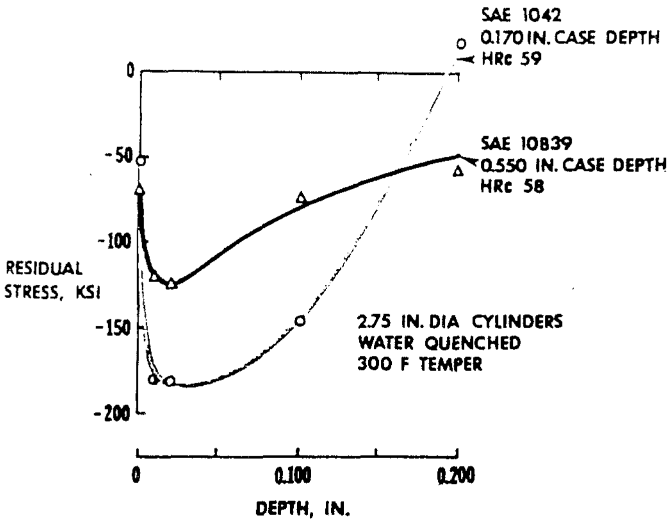

Fig. 4. Comparison of residual stresses in depth in furnace hardened steels of different hardenability.

example. Case depths in these medium carbon steels, defined as the depth corresponding to mean hardness between that of case and core, ranged from about 0.160 in. in plain carbon steel to through-hardening at this diameter in boron, elevated manganese steel. Peak residual compressive stress below the surface is plotted versus case depth. Again it is seen that compressive residual stress increases with decreasing case depth. This may be due to a decreasing case-to-core volume ratio or an increasing hardness gradient between case and core with decreasing case depth. These data show that plain carbon steel would be a good choice in fatigue applications at long lives near the fatigue limit. However, this high residual stress is obtained at some sacrifice in case depth. A deeper-hardening material may be a better choice for low cycle, high stress applications where some residual stress relaxation would be expected.

Another point bought out in Fig. 5 is that even the through-hardened specimen contained a substantial residual stress of 90 ksi compression. Residual stress from heat treatment is a combination of two components, a thermal stress and a transformation stress. The thermal stress is a result of the plastic deformation accompanying the high thermal gradient during the quench. The transformation stress is due to volume misfit between case and core. Thermal stress increases with quench severity. Therefore, although this specimen contained little transformation residual stress, high thermal stress was obtained because of severe water quenching. An oil quench would have resulted in lower residual stress for this reason.

The previous results have been for 2- to 3-in. diameter cylinders. An investigation was also made of the effect of section size on residual stress using a series of SAE 1045 steel cylinders of various diameters, water quenched. Surface residual stress is shown versus the diameter, which ranged from 0.12 to 3.75 in., in Fig. 6. Stress increased rapidly with increasing diameter to about 1 in. and continued to increase over the range of diameters investigated. The same trend was seen after tempering to a lower hardness. At small diameters, this increase was possibly due to an increasing thermal gradient with increasing diameter. At larger diameters, it may have been due to a decreasing case-to-core volume ratio. These data show that large heat treated parts, which are common in the automotive, earthmoving, and farm equipment industries, will contain substantial residual stresses which in turn will have a significant effect on fatigue performance. If the performance of these parts is to be evaluated in a fatigue test, specimens should be used which are of a size near that of the part. If small fatigue specimens containing little residual stress are used, they must be loaded in a manner in which the effect of the residual stress in the part can be produced with an equivalent mechanical mean stress in the specimen. This is why the relatively large fatigue specimens were used in the present investigation.

Shot Peening - The present results indicate that there are instances when heat treatment alone may not produce compressive residual stress of sufficient magnitude; e.g. small, thin sections or high hardenability steels. Other means are sometimes used to supplement the low heat treatment stress. This is conveniently done by cold working after heat treatment; e.g. rolling or shot peening. Surface residual stresses due to peening are shown for two materials in Fig. 7. Plain carbon steel specimens, water quenched, are compared to oil quenched alloy steel specimens. Data are shown over a range of hardnesses. The plain carbon steel specimens contained a substantial residual stress of 150 ksi

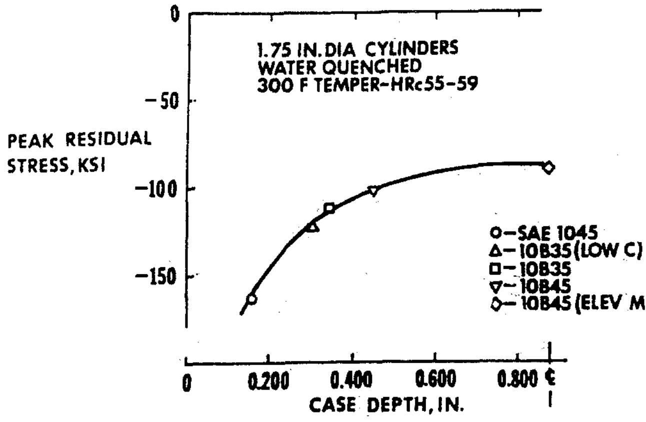

Fig. 5. Variation of peak residual stress with hardenability. Residual stress increases in compression with decreasing case depth.

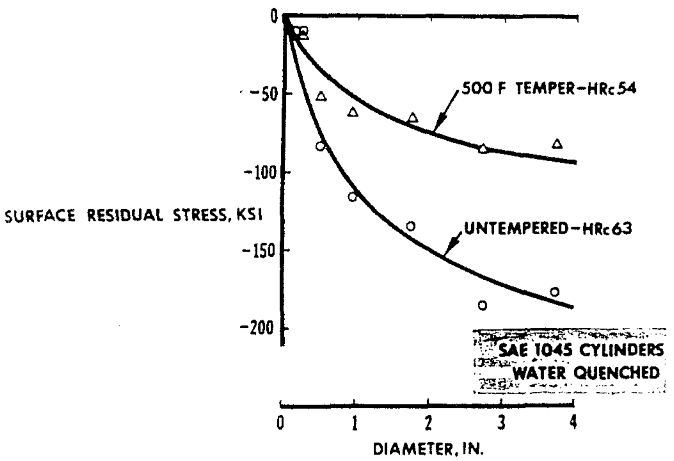

Fig. 6. Surface residual stress as a function of specimen diameter for two hardness levels. Residual stress increases in compression with increasing section size.

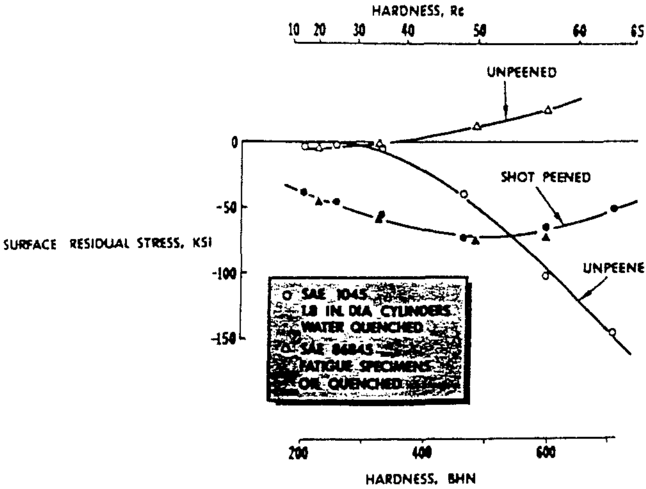

Fig. 7. Surface residual stress produced by shot peening for two prior heat treatment stress states over a range of hardnesses. Peening stress is independent of prior stress.

compression as quenched. This stress was completely relieved by tempering to a hardness of Rc 30 to 40. But the alloy steel specimens, which were oil quenched and through-hardened, contained zero or slightly tensile residual stresses from heat treatment. Sets of both types of specimens were shot peened. The graph shows that the surface residual stresses resulting from peening the two types can be represented by a single curve of surface residual stress versus hardness, even in the high hardness region where the prior heat treatment stresses were entirely different. This shows the leveling or equalizing effect of shot peening on surface residual stress and indicates an independency of peening stress on prior stressed condition. Stress increased to a maximum of about 75 ksi compression at a hardness of RC 45 to 50, corresponding to the approximate shot hardness. At higher hardnesses the compressive stress decreased slightly. At low hardnesses shot peening was beneficial, producing a uniform compressive residual stress. At high hardnesses where there was little heat treatment stress, shot peening produced a beneficial compressive stress. However, a high stress due to heat treatment was actually decreased by shot peening. This was evidently accompanied by some softening as indicated by a sharpening of the x-ray diffraction peak. These data show that although shot peening is often beneficial, it cannot be used indiscriminately, especially at high hardnesses.

Effect of Residual Stress of Fatigue Performance

The effect of residual stress on fatigue is shown for high hardness steel by the S-N plots in Fig. 8. Curves are shown for two levels of net mean stress. The upper one corresponds to a mean stress being provided by the high compressive residual stress from heat treatment of 240 ksi. Because of the very high heat treatment stress, a very high alternating fatigue strength of 220 ksi was seen for a life of 5 million cycles. When part of this high heat treatment stress was cancelled with a tensile mechanical mean stress for a net mean stress of 75 ksi compression, the fatigue strength was considerably decreased.

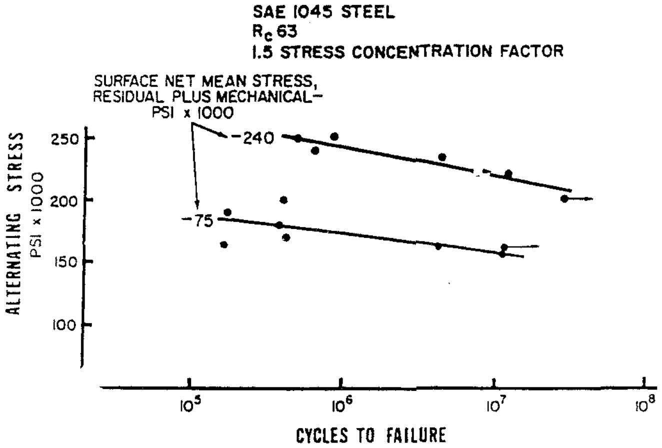

Fig. 8. S-N curves for hardened steel at different mean stress levels, showing the effect of high compressive residual stress on fatigue performance.

The effect of shot peening at high hardness was shown with a similar set of specimens. One specimen was run for several million cycles at lower stresses and then at a completely reversed stress of 220 ksi. After 1 million cycles, cracks were noticed in the surface. The test was continued for a total of 8 million cycles at this stress level as shown by the open symbol in Fig. 8, after which the test was stopped so the specimen could be examined. Many superficial cracks were seen at the position of maximum stress. Evidence of spalling and fretting corrosion was also seen. In order to determine how deep the cracks had propagated after these many cycles at high stress, the specimen was broken open in static bending. As shown by the fretting corrosion discoloration on the fracture surface, the cracks had propagated to approximately 0.050 in. compared to the case depth of approximately 0.150 in.

It is believed that the low crack propagation rate is explained by the residual stress-depth profile in these specimens. As shown in Fig. 9, a very high average compressive stress of 240 to 250 ksi was present in the unpeened specimens. This is higher than previous results on uniform cylinders of the same material, hardness, and diameter because any decarburized material at the surface was removed by electropolishing, and also because of an apparent residual stress concentration effect in the

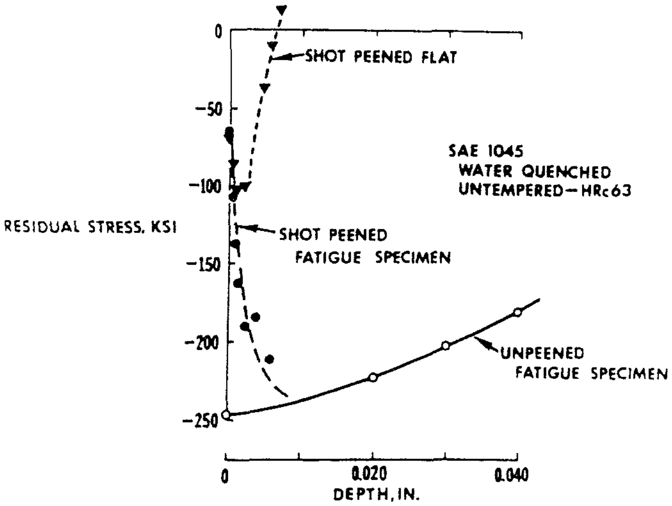

Fig. 9. Residual stress-depth curves showing the high compressive heat treatment stresses in the shallow-hardened fatigue specimens and the effect of shot peening with and without a prior heat treatment stress.

notch. But even this very high surface compressive residual stress was decreased to the characteristic value of about 60 ksi at this hardness by shot peening; this is the same effect as shown in Fig. 7. The stress increased below the surface, reaching the unpeened stress at about the depth affected by peening as indicated by a peened flat having no prior heat treat stress.

Because of the decrease in surface stress due to peening, reversed bending imposed a high tensile component of stress. As a result of this and of crack-like defects seen at the surface due to peening (discussed in the earlier paper [1]), fatigue cracks initiated relatively easily. But after they propagated into the region of high compressive residual stress, they were progressively slowed and/or effectively stopped. This shows the benefit in reversed bending fatigue of a high compressive residual stress from heat-treatment. The effect of the weakened surface due to peening was overcome by the subsurface high compressive stress field; the resulting fatigue strengths of peened specimens were as high as those of unpeened specimens. This is explained by the Fuchs theory (2), where resistance to crack propagation is believed high in the presence of a high compressive stress. With a tensile mechanical mean stress, however, performance of peened specimens was much poorer than that of unpeened specimens. According to the theory, resistance to crack propagation decreases rapidly with decreasing compressive net mean stress, while resistance to crack initiation is much less affected.

Summary

The results indicate that maximum compressive residual stress is obtained in steel by using:

a. High hardness parts given little or no temper.
b. An optimum carbon content of 0.35 - 0.45 per cent at a given tempering temperature.
c. Minimum carbon content when considering a given hardness.
d. Minimum hardenability over the range investigated.
e. A severe water quench as opposed to oil quenching.
f. Shot peening in cases where there is little or no residual stress from heat treatment.

High compressive stress, when combined with high hardness, results in maximum long life fatigue strength.

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