Changes in Residual Stresses During Tension Fatigue of Normalized and Peened SAE 1040 Steel

by

M. McClinton and J. B. Cohen

ABSTRACT

Appreciable compressive stresses develop during tensile fatigue (R=0) or normalized SAE 1040 steel, but only in or near regions of stress localization. These stresses develop in stages. After shot peening, the resultant compressive stresses are rapidly eliminated by tension-tension fatigue above the endurance limit, and replaced by tensile stresses. At lower stress levels the induced stresses fade quickly.
INTRODUCTION

It is now well known (but often ignored!) that residual stresses develop during fatigue of well annealed specimens of most metals and alloys. Compressive or tensile stresses are formed, apparently depending on the mode of testing. For example, tensile stresses occur in impact fatigue, but compressive stresses arise in reverse bending. In fact, in low-cycle fatigue, the sign of the stress is opposite to the sign of the load before this load is released, and reverses every half cycle in fully reversed axial loading. For stresses below the endurance limit, stress concentrators, such as second-phase particles or grain junctions can cause such changes; the residual stress forms early in the test and subsequently is constant. At higher applied stresses, the residual stresses increase and then decrease well before failure. These induced stresses can develop without any appreciable slip band formation.

Surface treatment is often employed to produce compressive residual stresses, as such stresses are thought to improve fatigue life. But the results are not completely clear. For soft steels, plastic deformation in the near-surface regions appears to be the primary cause of this increase (not the residual stresses), whereas for hardened steels, the residual stress is the main factor. In axial loading of Al alloys, this improvement is primarily in the low cycle regime, with no effect (or decreased life) in the high cycle regime. These induced stresses are altered during fatigue. It is generally accepted that the stress "fades", the more rapidly the higher the applied stress, and the less steep is the stress gradient. All detailed studies of fading have so far been carried out in a bending mode.

(Tests in uniaxial loading under strain control were used to simulate residual stresses, in ref. 18, by altering the strain limits. Under such conditions the "residual stress" will obviously vanish as the specimen lengthens. Also, in such simulations, the induced stress is uniform across the cross-section, but this is not the case with actual residual stresses.)

The rate of fading sometimes depends on the sign of the residual stress, but sometimes does not. Stress relief should depend on the sum of applied and residual shear stresses; if the residual stress is isotropic in the surface,
it cannot contribute. Unfortunately, whether or not the stress was isotropic was not checked in most studies. There is also one case (316 stainless steel, tension-tension fatigue) in which initial compressive stresses (the source was not reported) were quickly replaced by tensile stresses.

Surface treatments like peening lead to subsurface cracking in fatigue and the maximum compressive stress (which is below the surface) gradually moves into the specimen during fading.

It is the purpose of this paper to examine the changes in residual stress during fatigue of both a normalized and normalized and peened plain carbon steel, in tension-tension fatigue. This is the first stage of a study of fading in steels.

EXPERIMENTAL PROCEDURES

Specimens

Hot rolled SAE 1040 steel plate was normalized by heating at \(1145^\circ K\) for 30 min. and air cooling. Flat fatigue specimens were cut from this plate, 6.4 mm thick 90 mm long (in the rolling direction) and 25 mm wide. The gage section was 9 mm long, 6 mm wide, with a 6.35 mm radius joining to the grip sections. These specimens were milled to remove oxide and the decarburized zone, then polished through 600 grit paper. The resultant surface residual stress was -372 MPa (-54 ksi). A subsequent anneal for 1 hr. at \(973^\circ K\) in Argon followed by furnace cooling, resulted in a near zero value of stress. Some of these specimens were shot peened for 45 seconds (on both sides) with 230 grit steel shot; the nozzle was 100 mm from a specimen and the air pressure was 90 Psi. The Almen value was 0.0343. The resultant profile of residual stress is shown in Fig. 1. The mechanical properties of both types of specimen are given in Table I.

The endurance limit for this steel is available only for fully reversed loading. For the tension-tension fatigue employed in this study the limit was estimated from Table I by Goodman's method. Gerber's approach yields values ~ 20 pct higher, while Soderberg's results in values ~ 30 pct lower. Results will be reported in terms of the load as a fraction of the static yield stress, with this estimate of the fraction of the endurance limit in parentheses.
Fatigue Equipment

Cyclic loading was carried out on an MTS servo-hydraulic machine, in load control at 50 Hz. The wave form was sinusoidal, with \( R = 0 \), and a maximum stress ranging from 263 to 414 MPa. In some cases, hysteresis loops were recorded, to establish the onset of permanent strain.

X-ray Measurements

An automated Picker X-ray diffractometer was employed, with (line focussed) CoK\(_\alpha\) radiation and the 310 peak. The divergence was 0.4 - 1°, and a stationary receiving slit was employed, 0.5 mm wide. Stresses were obtained via an on-line minicomputer control system, employing a five point parabolic fit to the top 15 pct of a peak, and six \( \psi \) tilts (to 45°). The stress was obtained parallel to the long direction.

There was only slight curvature in the interplanar spacing \( d \) vs \( \sin^2 \psi \), which indicates there were no appreciable changes in stress over the penetration depth of the x-ray beam. The correlation coefficient for a least-squares line \( d \) vs \( \sin^2 \psi \) was typically 0.99 or better. Repeated measurements showed that the stress was measured with a reproducibility of 3 - 10 pct.

RESULTS

As normalized

Plastic strain \( \sim 3 \times 10^{-8} \) was detected after \( 10^6 \) cycles at or above a maximum stress of 296 MPa, 0.7 (0.92) of the yield. No significant stresses developed below 0.61 (0.77) yield, even after \( 5 \times 10^5 \) cycles. Fig. 2 gives results on the changes in residual stress vs number of cycles at increasing stress levels. In fig. 3, results are given on changes in the shape of the x-ray peaks. For both shape and stresses there are stages in the changes, but these occur at different numbers of cycles. (Such stages for the breadth, but not the stresses, have been reported previously (28).)

Up to and including loads of 0.73 (0.92) of the yield, the specimen's surface is identical to an untested piece under the optical microscope, and only small compressive stresses develop. At 0.92 \( \sigma_y \) (1.16), Fig. 3b, between 0 and 5000 cycles, a specimen is still smooth. But beyond this point, regions
of strain localization develop, and there is a sharp increase in the residual stress, but only in or near such regions. The deformation markings are spread over the entire specimen near the plateau in residual stress at this load. A fourth stage occurs at $\sigma = 1.01 \sigma_y (1.28)$, with no additional unusual changes in the surface appearance, and just prior to failure at $1.8 \times 10^3$ cycles.

Etching revealed that these compressive stresses extended (unchanged) to at least 0.8 mm below the surface.

Shot Peened Condition

The results for residual stress are given in Fig. 4. There is some slight fading even well below the endurance limit, Fig. 4a, which is very much more pronounced near the limit, Fig. 4b. At $\sigma = 0.96 \sigma_y (1.16)$, the compressive stress is eliminated quite early in the life and replaced by a tensile residual stress. Failure occurs at $\approx 115,000$ cycles. The stress profile in this regime is illustrated in Fig. 5. Comparing this figure to Fig. 1, it is clear that the original profile has been completely changed; tensile stresses now extend to $\approx 0.1$ mm.

The x-ray peak's width decreases linearly (from $\sim 3.6^\circ$) with cycles, with a slope which increases with load. However, even at the highest loads examined in this study, the breadth near failure is $\sim 2.8^\circ 2\theta$, compared to an annealed value of $0.6^\circ$ and $0.9^\circ$ after fatigue of annealed specimens (Fig. 3c).

DISCUSSION

The principal results of this study are:

1) In annealed (soft) steel, appreciable compressive stresses develop in tension-tension fatigue, but only in regions of strain localization.

2) This stress (as well as line broadening) develops in stages.

3) In shot peened steel, the surface compressive stress is replaced by tensile stresses very early in fatigue, at stress levels just above the endurance limit.

4) This stress reversion occurs over appreciable depths.

5) Appreciable fading occurs at lower stress levels.
We consider first the unpeened steel. Weissmann and Kramer\(^{(29)}\) have demonstrated that the surface of many materials exhibits considerably more x-ray line broadening than the interior, implying that there is considerably more deformation in this region. This greater strain under a fixed load could be due to a lower yield stress (due to the biaxial nature of the strains in this region) or due to greater work hardening. In either case, the stress-strain curve in a local region under stress controlled fatigue can be illustrated schematically as in Fig. 6a. When the load is released, the near-surface regions are more extended than the bulk and are put into compression. After shot peening, the stress strain curves of a local region are reversed, as shown in Fig. 6b, and the surface is placed in tension, as observed here. This simple model appears to provide a suitable rationalization of the results. It should be kept in mind that these stress strain curves are for local regions. The fact that there are regions of strain localization, and x-ray line broadening implies that strains vary from point to point, so that it is possible for there to be a difference in total displacement from one region to another.

The drastic decrease in fatigue life in tension due to peening reported here may be in part due to the tensile stresses, but there is undoubtedly a contribution due to the roughened surface.

ACKNOWLEDGEMENTS

Mr. W. P. Evans, Caterpillar Tractor Co. graciously performed the shot peening. This research was supported by the Office of Naval Research. The X-ray measurements were carried out in the X-ray Facility at Northwestern University, supported in part by the NSF-MRL program under grant No. DMR-76-80847. Portions of this study were presented (by M. M.) in partial fulfillment of the requirements for the M. S. degree in the Materials Science and Engineering Department, Northwestern University.
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FIGURE CAPTIONS

Fig. 1 Stress profile of shot peened 1040 steel. Layers were removed by chemical etching (100 pts 30% H₂O₂, 10 pts 48% HF).

Fig. 2a Residual stress vs. cycles at \( \sigma_{\text{max}} = 0.73 \) (0.92) of the static yield stress, normalized 1040 steel.

b Residual stress vs. cycles at \( \sigma_{\text{max}} = 0.92 \) (1.16) of the static yield stress, normalized 1040 steel. The two symbols represent two different specimens cycled under identical conditions. Points with a horizontal cross mark indicate repeated residual stress measurements at different locations on the same specimen.

c Residual stress vs. cycles at \( \sigma_{\text{max}} = 1.01 \) (1.28) of the static yield stress, normalized 1040 steel. Points with a vertical cross indicate repeated residual stress measurements.

Fig. 3a Peak width vs. cycles at 0.92 (1.16) of the static yield stress, normalized 1040 steel.

b Peak width vs. cycles at 1.01 (1.28) of the static yield stress, normalized 1040 steel.

Fig. 4a Residual stress vs. cycles for shot peened specimen, \( \sigma_{\text{max}} = 0.62 \) (0.75) of the yield stress.

b Residual stress vs. cycles for shot peened specimen, \( \sigma_{\text{max}} = 0.79 \) (0.95) of the yield stress.

c Residual stress vs. cycles for shot peened specimen, \( \sigma_{\text{max}} = 0.96 \) (1.16) of the yield stress.

Fig. 5 Stress profile of shot peened specimen after 800 cycles at 0.96 (1.16) of the yield stress.

Fig. 6a A hypothetical stress vs. strain curve, comparing the response of the surface and interior of an annealed steel.

b A hypothetical stress vs. strain curve, comparing the response of the surface and interior of a shot peened steel.
FIG. 2a

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FIG. 2c

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Number of Cycles

Peak Half Width, ($\Delta 2\theta^\circ$)

$10^3$ $10^4$ $10^5$ $10^6$

50 60 70 80 90 100 110

FIG. 3a

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FIG. 3b

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FIG. 4a

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Residual Stress, (MPa)

Number of Cycles

FIG. 4b  M. McClintoon and J. B. Cohen
FIG. 4c

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FIG. 6b

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The Experimentally Determined Mechanical Properties of the Normalized and Shot Peened 1040 Steel* 

<table>
<thead>
<tr>
<th>1040 Steel</th>
<th>$\sigma_y$ (.2%) (MPa)</th>
<th>UTS (MPa)</th>
<th>% elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized</td>
<td>407.72</td>
<td>613.74</td>
<td>.270</td>
</tr>
<tr>
<td>Shot peened</td>
<td>425.98</td>
<td>596.37</td>
<td>.266</td>
</tr>
</tbody>
</table>

*Experiments were performed using an Instron Tensile testing machine.
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Changes in Residual Stress during the Tension Fatigue of Normalized and Peened SAE 1040 Steel

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SUMMARY

During the tension-tension fatigue of normalized SAE 1040 steel under applied stress control, compressive residual stresses develop, but only in or near deformation markings. However, if this steel is shot peened prior to fatigue, the compressive residual stresses produced by peening are eliminated during fatigue and replaced by tensile residual stresses, when the applied (fatigue) stress is above the endurance limit.

I. INTRODUCTION

The mechanical working of the near-surface regions of a manufactured item is often carried out, e.g. by shot peening, because it is commonly accepted that this processing increases the fatigue limit [1]. One result of this deformation is the formation of a compressive residual stress in the surface, because the material in this vicinity is restrained by the interior of the part. For soft steels the plastic deformation due to peening, and not the residual stresses, appears to produce most of this improvement in fatigue limit, whereas for hardened steels the residual stresses are most important [2]. Nearly all the research on this topic has been carried out by fatigue in bending or torsion. The type of loading may be important in assessing the effect of a surface treatment. Furthermore, stresses can fade during fatigue [3-8].

It is also established that residual stresses develop during the high cycle fatigue of annealed metals and alloys. These stresses are reported to be tensile (+) after impact fatigue [9], but compressive (−) stresses develop in reverse bending [10, 11].

More information is needed concerning changes in residual stresses during fatigue, particularly under modes of loading other than bending, for high cycles, and in annealed and shot-peened conditions. In this paper, preliminary information is presented on the high cycle tension-tension fatigue of both normalized and peened plain carbon steel.

2. EXPERIMENTAL PROCEDURES

2.1. Specimens

Hot-rolled SAE 1040 steel plate was normalized by heating at 1145 K for 30 min and air cooling. Strips were cut with the length in the rolling direction of the original plate. Fatigue specimens were then machined with a gauge section 9 mm long, 6 mm wide and 6.43 mm thick, with an arc of 6.35 mm radius between the grip and gauge sections. All specimens were milled to remove oxide and the decarburized zone (detected metallographically) and were subsequently ground through 600 grit paper. After an anneal for 1 h at 973 K in argon, followed by furnace cooling, the stress was typically 20-30 MPa. This small value is similar to the reproducibility of the X-ray measurements used to obtain the stresses (this method will be described below). Therefore it was assumed that this anneal was sufficient to provide essentially stress-free specimens.

Some of these specimens were shot peened for 45 s (on both faces and on the edges) with 230 grit steel shot, yielding an Almen A intensity (the middle Almen range with center deflections of the Almen test strip of 0.1 -
Fig. 1. Stress profile or shot-peened SAE 1040 steel: ——, uncorrected; ——, corrected for layer removal (the layers were removed by chemical etching (the etchant consisted of 100 parts 30% H₂O₂ and 10 parts 48% HF)) and stress gradients.

0.5 mm) of 0.343 mm. The profile of residual stress from the surface to the interior is shown in Fig. 1, as determined by X-ray diffraction. Because the corrections [12] for layer removal and the stress gradient were small, no corrections were made to all subsequent measurements of a profile. It should be noted that there is no indication of tensile stresses just below the surface as might occur because of overpeening.* The mechanical properties of the specimens are summarized in Table 1. Shot peening causes only small changes in these mechanical properties.

The endurance limit is available only for fully reversed loading (216 MPa [13]). For the tension–tension fatigue employed in this study, this limit was estimated to be approximately twice this value.

2.2. Fatigue testing
Cyclic loading was performed on an MTS servohydraulic machine, in load control, at 50 Hz. The waveform was sinusoidal, with \( R = 0 \), and a maximum stress ranging from 207 to 412 MPa. Observations of the surface were made at 100x in white light, with a travelling microscope. Specimens were removed from the machine from time to time

*The stresses were measured in only the ferrite and are balanced through the cross section by stresses in the carbides, and by a small tensile stress at depths greater than those examined here.

<table>
<thead>
<tr>
<th>SAE 1040 steel</th>
<th>( \sigma_y(0.2%) ) (MPa)</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized</td>
<td>408</td>
<td>614</td>
<td>27</td>
</tr>
<tr>
<td>Shot peened</td>
<td>426</td>
<td>596</td>
<td>27</td>
</tr>
</tbody>
</table>

*Experiments were performed using an Instron tensile-testing machine. The specimens were of the same shape and size as those used for the fatigue tests.

to measure the residual stress at various numbers of cycles and then reinserted in the grips. (A test was not carried to failure, except where indicated in the text.)

2.3. X-ray measurements
An automated Picker X-ray diffractometer was employed with (line-focused) Co K radiation. The position of the 310 diffraction peak was used to determine residual stresses. The beam divergence was 0.4°(2θ) for the annealed specimens, and the beam was masked to provide an irradiated area on the specimen of 2.3 mm². For the shot-peened specimens, a divergence of 1° was employed. The irradiated area was 14.8 mm². The halfwidth was 3.3° compared with a value of 0.6° for the annealed specimens. This broader less intense peak necessitated the wider divergence. (The receiving slit was 0.2° wide in all cases.) Stresses were obtained via an on-line mini-computer control system [14] with the so-called stationary slit method. A five-point parabolic fit was employed to the top 15% of a peak, to establish its 20 position, typical of modern practice in the U.S.A. In stress measurements using X-ray diffraction the stress is obtained from the slope of interplanar spacing \( d \) (calculated from the peak position) versus \( \sin^2 \psi \) where \( \psi \) is the tilt of the specimen surface normal from its usual position (in which position the normal to the surface bisects the incident and diffracted beams). Six \( \psi \) tilts to 45° were employed, approximately equally spaced. The surface residual stress was obtained in the direction of the load, i.e. along the long direction of a specimen’s sur-
face. There was only slight curvature in $d \sin^2 \psi$, which indicates that there was no appreciable change in stress over the penetration depth of the X-ray beam [15]. (The correlation coefficient for a least-squares fit of such data to a straight line was typically 0.99 or better.) Measurements were repeated on several specimens, and the results indicated a precision of 20 - 30 MPa or less (3% - 10% of the stress value), as was indicated above.

3. RESULTS

3.1. As-normalized specimens

After $10^6$ cycles, a plastic strain of $3 \times 10^{-5}$ was detected at an applied stress of 296 MPa (from the cyclic stress-strain hysteresis loop). This value increased to $5 \times 10^{-5}$ at the highest stress. No plastic strain was detected below 296 MPa, and the changes in residual stress were within experimental error, even after $10^6$ cycles (at or below this applied stress).

At 376 MPa and between 0 and 5000 cycles, a specimen remained smooth in appearance under the optical microscope. At a higher number of cycles, deformation bands were noticed in some areas, similar to Lüder's bands. These increased in size and frequency with further cycling, covering the entire gauge length at approximately 20,000 cycles. Up to this range, significant changes in residual stress were detected (Fig. 2(a)) but only when the X-ray beam was placed over the deformation bands. (This is why the X-ray beam was masked, to reduce its area to a size near that of the bands.) After the bands covered the entire specimen, further changes in stress occurred, and the value was independent of the location of the X-ray beam.

A similar sequence was observed at a higher applied stress, 412 MPa (Fig. 2(b)), but with deformation bands first occurring at a much smaller number of cycles (600 cycles). This specimen failed at $1.8 \times 10^8$ cycles.

After cycling so that the residual stress was uniform across the gauge length, and the deformation bands were throughout the gauge area, layers were removed by etching and it was found that the compressive stresses extended to at least 0.8 mm below the surface (at which point the etching was stopped).

Fig. 2. (a) Residual stress vs. number of cycles for normalized SAE 1040 steel at an applied stress of 376 MPa. The two symbols (*) represent two different specimens cycled under identical conditions. Points with a horizontal line indicate a repeated residual stress measurement at a different location on the same specimen, whereas points with a vertical line represent the range of repeated measurements at the same location. (b) Residual stress vs. number of cycles for normalized SAE 1040 steel at an applied stress of 412 MPa. Points with a vertical line indicate the range of repeated measurements of residual stress at the same location.

3.2. Shot-peened condition

In this case the residual stress was the same from region to region in the gauge area and, because of the surface roughening caused by the peening, no deformation bands due to fatigue were apparent. The changes in residual stress during fatigue at various loads are
shown in Fig. 3. There was some fading even well below the estimated endurance limit, i.e. at an applied stress of 263 MPa. Significant hysteresis (plastic strain) was detected even at this stress. Fading was more pronounced at 336 MPa. At an applied stress of 408 MPa, close to the static yield stress, the compressive residual stress induced by peening was replaced by a tensile residual stress between 0 and 100 cycles. This specimen had a life of only 115,000 cycles. The profile of residual stress was obtained on a second specimen, after 800 cycles at this last applied stress, and is shown in Fig. 4, which should be compared with the profile just after peening (Fig. 1). It is clear that the original profile has been completely altered by fatigue; tensile residual stresses extend to a depth of about 0.1 mm.
4. DISCUSSION

We consider first the unpeened steel, in which compressive stress develops in the deformation bands. Elongated grains in such bands would be restrained by the surrounding material and this is most like the cause of the compressive stress in the bands. Such stresses would impede fatigue crack propagation.

After shot peening, the near-surface regions are severely cold worked. In tension–tension fatigue, the observed change of sign in the residual stress near the surface (from compressive to tensile) implies that the bulk is deforming (elongating) more than the surface regions and putting the near-surface regions into tension. (The fact that plastic deformation occurred in this case is indicated by the open hysteresis loops.)

It is clear from these results that the shot peening of steels is not always beneficial for fatigue life. Under tension–tension fatigue, or if the fatigue history is largely tensile, and if the applied stresses are near the fatigue limit, deleterious stresses may develop subsequent to peening, but not in the absence of peening.

ACKNOWLEDGMENTS

Mr. W. P. Evans, Caterpillar Tractor Company, graciously performed the shot peening. This research was supported by the Office of Naval Research. The X-ray measurements were carried out in the X-ray Facility at Northwestern University, supported in part by the National Science Foundation–Materials Research Laboratory Program under Grant DMR-76-80847. Portions of this study were presented (by M. M.) in partial fulfillment of the requirements for the M.S. degree in the Materials Science and Engineering Department, Northwestern University.

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