Residual Stress Effects on Fatigue of Surface Processed Steels


ABSTRACT: Procedures are presented for analyzing the cyclic stability and influence on fatigue resistance of residual stress patterns arising from mechanical and thermal surface processing treatments such as shot peening and induction hardening. Cyclic properties and behavioral trends developed using smooth, axial specimens of steels simulating the various microstructures found in surface processed componentry are used to develop criteria to predict cyclic stability, the rate of relaxation for prescribed straining levels, the failure initiation point (surface or subsurface), and expected fatigue lifetime. The validity of the approach is verified using experimental data from the literature. Finally, the incorporation of these procedures in modern computer-based fatigue analysis routines, and opportunities for further enhancements, are discussed.

KEY WORDS: fatigue (steels), induction hardening, life prediction, residual stress, shot peening, stress relaxation

Ground vehicle components such as springs, shafts, and gears are routinely subjected to surface processing treatments to improve mechanical durability. The influence of processes such as shot peening, induction hardening, and carburizing on fatigue performance depends, in a rather complex way, on local material properties, the service loading and, in particular, the magnitude, distribution, and stability of residual stresses. Furthermore, because of the continuing pressures to develop more efficient and lighter weight structures, there is considerable interest in maximizing the benefits of surface processing. These factors are considered in this paper in the context of the cyclic deformation behavior of steels and a procedure is presented for analyzing and optimizing the fatigue resistance of surface processed componentry.

The treatment employed is based on a previously reported fatigue analysis for carburized steel [1]. Specifically, cyclic properties determined using axial specimens of steels simulating the various microstructures found in surface treated members are used to characterize fatigue resistance and residual stress effects, including cycle dependent stress relaxation. A technique for maximizing fatigue resistance by making failure equally likely in case and core is presented and demonstrated with experimental results.

The current work emphasizes mechanically processed (shot peened, strain peened) and thermally processed (induction hardened) steels where residual stresses often exhibit larger effects than in carburized steels. In Fig. 1, typical residual stress profiles obtained with such treatments are shown. In the case of peening, strain peening—in which a part, such as a spring, is deformed during processing—imparts higher compressive residual stresses and a deeper pattern of penetration than conventional peening does. For induction hardening, the residual stress pattern depends upon the depth of hardening and, in general, relates to the hardness...
profile as indicated in the figure. In either instance, reasonable latitude exists to alter residual stress profiles through the control of processing variables.

A major goal of this effort is to develop analysis procedures compatible with modern cumulative damage programs for predicting component fatigue life under complex service loading conditions [2]. These computer-based techniques provide material modeling routines that simulate cyclic material responses during fatigue and thus are ideally suited to handle residual stress analysis. In the next section, approaches for incorporating residual stress effects in durability analysis procedures are presented. This is followed by the development and demonstration of analysis techniques for cyclic stress relaxation and fatigue life prediction.

**Durability Analysis**

Fatigue analysis routines, such as those described in Ref. 2, provide a systematic framework for coordinating and combining information concerning material properties, component geometry, and service loading to make estimates of service performance. These procedures are enjoying increased use in ground vehicle design with the trend towards greater reliance on analytical design studies in product development programs.

The flow chart in Fig. 2 suggests an approach for incorporating surface processing effects in such procedures. Identification of the steel and specific surface process dictate the appropriate
material properties. Additional information regarding residual stress and hardness profiles are required to characterize processing effects. Based on envisioned service stresses, judgements can then be made concerning the stability of residual stresses, that is, whether cyclic relaxation occurs. Finally a fatigue analysis reveals the probable failure location and lifetime. When properly implemented, such tools can aid the designer in optimizing product performance through judicious material and processing selection.

As suggested in the above, when predicting fatigue performance, it is important to consider the magnitude of residual stresses, both at the surface and below the surface of a component, as well as their stability under service loading. Cycle dependent stress relaxation may negate their potential benefits [3,4]. A procedure for characterizing and predicting these effects is presented in the next section.

**Cycle-Dependent Stress Relaxation**

**Analysis**

It is common to assess residual stress effects on fatigue by treating them as mean stresses [4,5]. A material's resistance to stress relaxation can then be assessed by subjecting axial specimens to biased strain cycling and observing the cyclic change in mean stress. This technique is demonstrated by the stress-strain response in Fig. 3. Residual (mean) stresses would be expected to relax whenever the applied loading resulted in reversed plastic straining in the steel. Because of the tendency of many steels to exhibit cycle-dependent softening, this may occur at lower stresses than would be anticipated based upon monotonic yield strengths.

The cyclic stress relaxation behavior of a SAE 1045 steel at three hardness levels is shown in
RESIDUAL STRESS EFFECTS IN FATIGUE

FIG. 3—Procedure for determining cyclic stress relaxation rates.

\[ \sigma_{0N} = \sigma_{01}(N)^r \]

Mean stress, 1\textsuperscript{st} cycle

Mean stress, N\textsuperscript{th} cycle

\[ r = f(HB, \Delta\varepsilon) \]

Fig. 3. Using a representation suggested by Jhansale and Topper [6], the ratio of instantaneous mean stress to first cycle mean stress is plotted against cycles on logarithmic coordinates. The relaxation rate can thus be characterized by the slope of the line \( r \) yielding the relationship shown in the figure.

The relaxation behavior is little affected by the magnitude of the mean stress, but depends primarily on material hardness and applied strain amplitude. A threshold strain amplitude below which relaxation would not be expected to occur can be obtained by extrapolating the data for a particular hardness to a zero relaxation rate. This relaxation threshold can, in turn, be related to steel hardness as indicated by the relation at the bottom of Fig. 4. In this figure, the relaxation exponents for the SAE 1045 steel are plotted as a function of the ratio of applied strain amplitude to threshold strain amplitude resulting in the relationship shown. This suggests that the relaxation exponent \( r \) for a particular steel can be estimated from hardness and strain amplitude information.

Applications

The validity of the foregoing analysis was checked by comparing predicted results with experimental data from the literature. Mattson and Coleman [6] measured, by X-ray techniques, the change in surface residual stresses in a shot peened SAE 5160 bending member as a result of fatigue cycling. Their results, in terms of residual stress profiles before and after cycling, are shown in Fig. 5. Also shown in this figure are the strain threshold and relaxation exponent calculated for this steel, as well as the expected change in residual stress. The agreement with experimental results is excellent.

Bergstrom and Ericsson [8] have reported detailed X-ray measurements of the stress relax-
Where: \( \Delta \varepsilon = \) applied strain range

\( \Delta \varepsilon_{th} = \) strain threshold-relaxation

And \( \Delta \varepsilon_{th}/2 = \exp \left[ -8.41 + 5.36 \times 10^{-3} \times (HB) \right] \)

where: HB = Brinell Hardness

**FIG. 4—Procedure for predicting relaxation rates from hardness and applied strain range.**

**SAE 5160 (485 HB) — Shot peened**
Max. stress: 240 ksi (R=0)

**FIG. 5—Comparison of experimental and predicted stress relaxation in a shot peened spring steel [7].**
ation during fatigue of shot peened, notched, axial specimens. Their data for three different stress amplitudes \( R = -1 \) are plotted in Fig. 6. The lines represent the expected relaxation behavior based on analysis. Agreement for the highest stress level is again excellent; however, at the lower two levels, the predicted rates are too high. This can be explained by noting that the highest level exceeded the material yield strength, thus leading to the rapid cyclic softening characteristic of such medium carbon steels. At the intermediate stress level, softening is delayed for the first 100 cycles, after which the relaxation rate is closer to the predicted one. At the lowest level, softening is not likely to occur. Since the data used in developing the analysis are based on cyclically stabilized specimens, this apparent lack of agreement can be rationalized.

These results suggest that a complete relaxation analysis would require that cyclic softening be accounted for and relaxation data obtained at various degrees of stabilization. While this is certainly an achievable task, it is worth noting that, under the spectrum loading conditions often found in service, a relatively few, high stress levels can trigger cyclic softening, thus resulting in behavioral patterns closer to those envisioned in the analysis. In this regard, the proposed analysis tends to give "worst case" predictions of residual stress relaxation, hence providing useful design information.

Before proceeding to fatigue life prediction, we consider the response of an induction hardened shaft subjected to a torsional loading spectrum as portrayed in Fig. 7. At the top of the

FIG. 6—Comparison of experimental and predicted (solid line) relaxation rates for shot peened notched specimens [8].
Surface: no residual

Surface: -100 ksi residual

\( \sigma - \varepsilon \) Response

FIG. 7—Surface and subsurface stress-strain simulation of an induction hardened shaft undergoing a torsional loading spectrum.

The computer simulations of the surface stress-strain response: (1) with no residual stress and (2) with an initial \(-690\) MPa \((-100\) ksi\) residual stress. The observed compressive bias observed in the latter case would be expected to increase fatigue life by perhaps a factor of three to four if no relaxation were to occur. To complete the analysis, however, it is necessary to consider the subsurface behavior in the unhardened core. This response is shown in the lower part of the figure and is typified by large plastic strain levels that result in surface residual stress relaxation. In fact, in this instance, failure initiates below the surface, thus making surface conditions inconsequential. An analysis dealing with such situations is presented in the next section.
Fatigue Life Prediction

Analysis

The induction hardened shaft example serves to emphasize the importance of considering both surface and subsurface phenomena when analyzing surface processed componentry. Using the previously established analogy between mean and residual stresses, this is conveniently accomplished using the following stress-life relation (after Morrow [5]):

\[
\frac{\sigma_a}{(\sigma'_f - \sigma_o - \sigma_r)} = (2N_f)^b
\]  

where

- \(\sigma'_f, b\) = material properties,
- \(\sigma_a\) = stress amplitude,
- \(\sigma_o\) = mean stress,
- \(\sigma_r\) = residual stress, and
- \(2N_f\) = life in reversals.

The application of this relation is illustrated for a bending member in Fig. 8. The individual stress gradients caused by processing and applied loading are plotted across the section from surface to center line. These are then combined and plotted as a damage parameter profile as indicated. Equation 1 indicates that the higher the magnitude of this parameter is, the shorter the fatigue life. In the figure, the parameter goes through a maximum below the surface, thus predicting subsurface crack initiation. This is often observed in surface processed members and, in this instance, is the result of the shallow case and subsurface residual tension field. Improvements can be realized by deepening the hardening or the compressive residual stress pattern.

FIG. 8—Stress and damage parameter profiles for a surface processed bending member.
Applications

The utility of this analysis has been verified using fatigue results from a series of mechanically processed SAE 5160 bending specimens [9]. In Fig. 9, residual stress profiles obtained by peening, strain peening, and strain peening followed by presetting are shown. Also shown are the fatigue lives obtained in four-point bending tests under the indicated stressing conditions. Predictions obtained using the above analysis agree closely with the experimental results. With the exception of the unpeened control specimens, all failures initiated subsurface, nominally where the residual stress profile became tensile. While displaying a lowered peak compressive stress, the preset specimen has a deeper pattern of penetration, hence resulting in the improved fatigue resistance observed under these testing conditions.

Further support for the validity of this technique is supplied using data from Starker et al. [10] on a shot peened, hard steel. Results from bending tests of specimens treated with two different shot sizes are reproduced in Fig. 10. Of interest are the two stress levels at which both surface and subsurface failure origins are observed. Analysis results, shown at the bottom of the figure, confirm that such behavior is expected: compare the damage parameter for location 1 with locations 2 and 3, and location 4 with location 5. Furthermore, calculated fatigue lifetimes of 1 to 2 million reversals agree favorably with experimental results.

The foregoing examples illustrate that this rather straightforward analysis can provide a useful approach to help designers understand and optimize fatigue performance through surface processing.
Starker et al (1979)

Analysis of Shot Peened Bending Specimens

<table>
<thead>
<tr>
<th>Location</th>
<th>$\sigma_a$</th>
<th>$\sigma_r$</th>
<th>$\frac{\sigma_a}{\sigma_f - \sigma_r}$</th>
</tr>
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<tbody>
<tr>
<td>1 (surf)</td>
<td>1100</td>
<td>-800</td>
<td>0.31</td>
</tr>
<tr>
<td>2 (sub)</td>
<td>875</td>
<td>+100</td>
<td>0.33</td>
</tr>
<tr>
<td>3</td>
<td>820</td>
<td>+100</td>
<td>0.31</td>
</tr>
<tr>
<td>4 (surf)</td>
<td>1050</td>
<td>-800</td>
<td>0.29</td>
</tr>
<tr>
<td>5 (sub)</td>
<td>750</td>
<td>+100</td>
<td>0.28</td>
</tr>
</tbody>
</table>

FIG. 10—Analysis of shot peened bending members exhibiting both surface and subsurface failure initiation [10]. (NOTE: Straight lines indicate applied bending stress distributions; curved lines indicate fatigue strength profiles.)
processing. In the following section, some additional implications of the analysis are discussed and suggestions for future improvements presented.

Discussion

To gain additional insight into material characteristics conducive to surface processing response, it is informative to consider the variation of certain properties with hardness. In Fig. 11, trends indicative of a range of medium to high carbon steels are shown. Fatigue strength, as indicated by $\sigma_f'$, increases linearly with hardness, attains a maximum at about 600 HB, and decreases slightly thereafter. This final decrease is due, in part, to inclusion effects. With regard to residual stresses, it is noteworthy that the cyclic yield strength, $S_y'$, falls below the monotonic value, $S_y$, at hardnesses up to 550 HB. Such cycle dependent softening promotes rapid residual stress relaxation.

Not surprisingly, the stress amplitude threshold for relaxation shows a trend similar to that of the cyclic yield strength. Furthermore, at hardnesses less than 550 HB, stress relaxation can be expected at lives of $10^6$ reversals or longer. Finally, the influence of compressive residual stresses on fatigue resistance at $10^6$ is largest at the highest hardnesses and diminishes rather rapidly with decreasing hardness. Material requirements promoting strong residual stress effects are (1) a high monotonic yield strength to achieve a significant initial residual stress and (2) cyclic stability to preclude relaxation. These trends suggest that approximately a factor-of-three improvement in long-life fatigue strength is attainable through hardening, with another factor-of-two improvement possible through residual stress effects.

![Fig. 11—Cyclic properties of medium carbon steels as a function of hardness.](image-url)
A number of future developments can be envisioned to further extend the utility of these concepts. More detailed cyclic deformation models incorporating both cyclic softening and stress relaxation are needed to improve predictive accuracy. The inclusion of models to account for stress-strain state effects would also prove helpful in this regard. Finally, improved crack growth models to account for residual stress effects, as well as conditions for nonpropagating cracks \([11,12]\), are needed to extend analysis capabilities. As such improvements become available, they can be readily incorporated into existing durability analysis routines, thus helping to assure their timely implementation in design practice.

This methodology can provide a quantitative basis for designers to more effectively use surface processing to achieve desired component performance objectives. Guidelines are also established for performance improvement through judicious material and process selection. This capability provides a basis for developing the necessary links between design and manufacturing functions leading to process control strategies related to component service performance.

**Summary**

Cyclic properties and behavioral trends developed using axial specimens of steels simulating the various microstructures found in surface treated members have been used to develop a comprehensive procedure for analyzing residual stress effects on fatigue. Mean stress relaxation tests provide criteria for determining relaxation strain thresholds and rates of relaxation when the thresholds are exceeded. A stress-based life relation, incorporating mean and residual stress effects, is used to identify the probable failure location, surface or subsurface, and expected fatigue lifetime. Predictions based on this analysis compare favorably with a variety of experimental results taken from the literature. The incorporation of this methodology in modern, computer-based fatigue analysis procedures can provide a useful tool for designers to use more effectively surface processing techniques to achieve performance objectives.

**References**


