Influence of shot peening intensity on fatigue design reliability of 65Si7 spring steel

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A lot of research has been done to improve the fatigue strength of metallic materials by creating compressive residual stress field (CRSF) in their surface regions through shot peening. In this paper, the axial fatigue strength of 65Si7 spring steel is evaluated experimentally as a function of shot peening intensity for the application in the automotive vehicles. Fatigue life at various shot peening conditions is determined with S/N curves and optimum shot peening intensity is also determined. The effect of Almen intensity on compressive residual stress and relaxation of compressive residual stress have been discussed for fatigue life extension. Shot peening of leaf springs is illustrated to cause improvement in fatigue strength, reduction in weight and reliability. A flow chart has been developed for improvement in fatigue design of components for economy.

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Various methods have been employed in order to improve the fatigue strength include optimization of geometric design, stronger materials and surface processing such as shot peening. Among them, shot peening has long been widely used as a low cost and simple method for increasing the fatigue strength. Fatigue design or designing against fatigue failure, may have the objective of infinite life, zero weight, infinite strength or 100% reliability – or perhaps all four simultaneously1. These objective when viewed realistically, certainly make the better goal.

The increased fatigue life of a component by means of peening raises other issues like component design, size and material, which should be modified for economy and efficiencies2. Torres et al.3 observed experimentally the improvement in fatigue strength by shot peening and selection of most effective shot peening condition. Accurate fatigue predictions for actual component, which designers prefer, are still subjected to uncertainties. With the present knowledge, the relevance of full-scale testing can be well judged4. Compressive residual stress field and relaxed compressive residual stress field enabled better fatigue life estimation5,6. During a survey it was found that average life of leaf springs is 4-7 years in trucks due to fretting-fatigue failure7.

Through several attempts were made to evaluate modification in design and material due to shot peening, but very few studies to estimate the improvement in fatigue design at various shot peening intensities were hardly reported. The present study attempts to investigate the influence of shot peening intensity on fatigue design reliability of 65Si7 spring steel leaf springs.

Experimental Procedure

The chemical composition of 65 Si7 spring steel used was 0.65C-1.65Si-80Mn-0.014S-0.020P (weight %). The mechanical properties are: yield strength: 1158 MPa, ultimate tensile: 1272 MPa and fatigue limit: 602 MPa and elongation: 10%. The test material was first heat treated at 1195 K, and oil-quenched. Rockwell hardness attained was $H_{RC}$: 45. It was tempered at 796 K, for 2 h. This gave a Rockwell hardness $H_{RC}$: 38. For the purpose of comparing the peening effect on shot peened specimens, an A-type Almen strip, $76 \times 19 \times 1.3$ mm thick was used. The intensity was expressed as arc height of an Almen test strip. 0.1 mm arc height was designated 4A. Shot peening material was cast steel of ball diameter 1.0 mm. Shot peening was done using centrifugal wheel system: diameter of wheel 495 mm, operating speed 2250 rpm. Shot flow rate was varied to obtain various shot peening intensities. The

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material was treated with four Almen intensities: 6A, 12A, 18A and 22A. In all tests, a stress ratio \( R \) equal to 0.5 was used. Specimens were prepared according to ASTM E 466 and tested in axial fatigue testing machine MTS Model 810, at a frequency 30 Hz, at room temperature.

Actual testing of leaf springs was carried out in an electro-hydraulic fatigue component testing system. The laminated leaf springs were placed in a fixture simulating the conditions of vehicle. A hydraulic pressure of 20.6 MPa with a flow rate of 210 L/min was applied to hydraulic actuator to operate it at a frequency of 0.3 Hz with a displacement specified by the alternating load.

The residual stress induced by shot peening was measured by X-ray diffraction method. A Cr tube operating at 30 kV with current of 8 mA was used for projecting K\( \alpha \) 1 X-rays. The diffractive angle 2\( \theta \) without strain was 135.4°.

**Fatigue design**

Information flow diagram for improvement in fatigue design of a component is shown in Fig. 1. Essential surface characteristics to be known for fatigue design are (i) S/N curve, (ii) compressive residual stress field and (iii) relaxed compressive residual stress field.

**Full-scale testing**

Schijve\(^4\) recommended that the prediction model should be used for the estimation of fatigue life of a structure. This is especially true for prediction models that employ basic material data obtained on simple specimens. As a consequence, safety factors on predictions are required, and these factors have to be judiciously chosen, based on information on data and spectra, knowledge of governing conditions, statistical variations, and consequences of fatigue failures. The limited accuracy of predictions emphasizes the significance of full-scale testing.

In industries, full-scale finite life laboratory testing of components is done on a test rig. The simplification for laboratory test is to apply maximum load and minimum load at a given operating frequency to ascertain whether the component will sustain finite number of cycles. Almen\(^8\) suggested that most fatigue test should concentrate on finite life region about 1,00,000 cycle in a particular case – rather than endurance limit.

**Reduction in weight**

The compressive residual stress generated on upper surface due to shot peening reduces the effectiveness of tensile service load. Note that the sign of residual stress is important because if the part were reverse loaded in service to the point of yielding, it would relieve beneficial compressive stress and compromise the part life. Permissible stress after shot peening \((S_{sp})\) for static load is given as follows:

\[
S_{sp} = \frac{S_y + CRSF}{FOS} 
\]

where FOS is factor of safety and \( S_y \) is yield point stress. FOS has been applied on CRSF because of measurement error, wear of surface and variation in shot size.

Compressive residual stress induced by shot peening varies with cyclic loading due to relaxation of CRSF. Relaxation of CRSF is due to micro yielding and depends upon ductility of the material, number of cycles and stress applied\(^1\). Therefore, the permissible stress \((S_{sp}')\) taking into account the relaxation of CRSF is stated as:

\[
S_{sp}' = \frac{S_y + RCRSF}{FOS} 
\]

where \( S_{sp}' \) is permissible stress after shot peening. The savings obtained by the use of shot peening are quite appreciable and hence designer must include its effect in calculation.

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Fig. 1—Information flow diagram for improvement in fatigue design.
For a dynamic load, it is obvious from S/N curves that fatigue strength increases from $S_f$ to $S'_f$ for a shot peened component. This reduces weight of the component and increases reliability at higher alternating load. In a conventional nominal stress approach, the equivalent life curve is first used to transfer the asymmetrical stress cycle into a symmetrical stress cycle; then the symmetrical cycle S/N curves used to calculate the fatigue damage. There are many empirical equivalent life equations:

- Modified-Goodman equation:
  \[ S_a = S_f \left[ 1 - \frac{S_m}{S_{st}} \right] \]  
  \[ \text{... (3)} \]

- Gerber equation:
  \[ S_a = S_t \left[ 1 - \frac{S_m^2}{S_{st}^2} \right] \]  
  \[ \text{... (4)} \]

- Soderberg equation:
  \[ S_a = S_t \left[ 1 - \frac{S_m}{S_y} \right] \]  
  \[ \text{... (5)} \]

After shot peening, fatigue limit increases from $S_f$ to $S'_f$ and hence there is increase in alternating stress amplitude ($S'_a$) for a given mean stress $S_m$. Therefore, equivalent life equations for a shot peened component are as follows:

- Modified-Goodman equation:
  \[ S'_a = S'_t \left[ 1 - \frac{S_m}{S_{st}} \right] \]  
  \[ \text{... (6)} \]

- Gerber equation:
  \[ S'_a = S'_t \left[ 1 - \frac{S_m^2}{S_{st}^2} \right] \]  
  \[ \text{... (7)} \]

- Soderberg equation:
  \[ S'_a = S'_t \left[ 1 - \frac{S_m}{S_y} \right] \]  
  \[ \text{... (8)} \]

**Results and Discussion**

Fatigue design of shot peened leaf springs has been illustrated with an example for improvement in fatigue life, fatigue strength, reduction in weight and reliability.

**S/N curves of leaf springs**

Full-scale finite life laboratory testing of leaf springs is done on a test rig, (Fig. 2). Drawing of full-scale leaf springs (12 mm x 70 mm) is given in Fig. 3 and specifications are given in Eq. (7). The static load in applied by giving deflection to leaf springs by hydraulic ram. Hydraulic actuators are set according to alternating load. Bending stress for leaf springs ($\sigma_b$) was calculated using the relation:

\[ \sigma_b = \frac{6PL}{nbt^2} \]  
\[ \text{... (9)} \]

where $P$ is the force applied at the end of the spring, $L$ is the half of the total length of the span, $n$ is the total
number of leaves, \( b \) is the width of each leaf and \( t \) is the thickness of each leaf. Finite life S/N curves at various shot peening intensities are shown in Fig. 4.

**Residual stress**

Fig. 5 shows the variation of compressive residual stress field (CRSF) with the depth of deformed layer for all the peening conditions. It was found that the CRSF is approximately same for zero depth of deformed layer. It was noticed that surface stresses are more related to mechanical characteristics such as hardness and surface roughness. Increase in hardness and surface roughness was observed at various shot peening conditions. As the distance from surface increases, compressive residual stress is different at various shot peening intensity. The improvement in fatigue life is a consequence of the compressive residual stress field induced by shot peening. It is expected to find an increase in fatigue life with greater CRSF\(^ {12,13} \). However, the correlation between fatigue life and CRSF parameter was not clear. This is due to fact that fatigue life is lesser when shot peening intensity is 22A instead of 18A (Fig. 4).

Additional tests were performed to examine the possible variation of the residual stresses induced by shot peening under cyclic loading. Relaxation of stress was measured on specimens by X-ray diffraction technique after 1,10,000 cycles when alternating stress level varied from 422-844 MPa. Stress relaxation is related to fatigue life. Greater the stress relaxation, the lesser is the fatigue life\(^ {14} \). There occurs damage of the material in surface region of the high shot peening intensity 22A and this damage is responsible for higher relaxation of the CRSF. The damage caused is the main reason of reduction of fatigue life at 22A. Fig. 6 shows that stress relaxation is higher when shot peening intensity is 22A as compared to 18A. Hence, fatigue life is greater at 18A as compared to 22A.

Effect of shot peening intensity on fatigue design for a semi-elliptical laminated leaf springs with the following specifications \( P = 1580 \text{ kg}, L = 685 \text{ mm}, t = 12 \text{ mm}, b = 70 \text{ mm}, n = 8 \), total length of laminated springs \( L_T = 8.195 \text{ m} \) and density \( (\rho) = 7800 \text{ kg/m}^3 \), is given in Table 1.

![Fig. 4—Finite life S/N curves of leaf springs at various shot peening conditions](image)

![Fig. 5—Shot peening conditions and compressive residual stress field](image)

**Table 1— Effect of Almen intensity on fatigue design of leaf springs**

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Parameters</th>
<th>Base Material</th>
<th>Shot peening intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Static Load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(i)</td>
<td>Permissible stress ( (S_{p_l}) ) MPa</td>
<td>721</td>
<td>903</td>
</tr>
<tr>
<td>(ii)</td>
<td>Calculated, ( t ) (mm)</td>
<td>12.5</td>
<td>11.2</td>
</tr>
<tr>
<td>(iii)</td>
<td>Weight of leaf springs (kg)</td>
<td>58.16</td>
<td>50.11</td>
</tr>
<tr>
<td>2.</td>
<td>Dynamic Load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(i)</td>
<td>Fatigue life for alternating stress (422-844 MPa) cycles</td>
<td>54604</td>
<td>70050</td>
</tr>
<tr>
<td>(ii)</td>
<td>Fatigue strength ( (S_f) ) MPa</td>
<td>762</td>
<td>795</td>
</tr>
<tr>
<td>(iii)</td>
<td>Calculated, ( t ) (mm)</td>
<td>12.91</td>
<td>12.30</td>
</tr>
<tr>
<td>(iv)</td>
<td>Weight of leaf springs (kg)</td>
<td>57.72</td>
<td>55.03</td>
</tr>
</tbody>
</table>
Weight of leaf spring, \( W = L_Tbt \times \rho \) \( \ldots (10) \)

Bending stress \( (\sigma_b) = \frac{6PL}{nbt^2} \)

Alternating stress = 422-844 MPa

A factor of safety 1.6 is considered for laboratory testing.

**Validation**

S/N curves for the base material and for the four Almen intensity of specimens 6A, 12A, 18A, 22A were determined on an axial fatigue testing machine. Each test gives one failure point on S/N curve. Sixteen specimens (Fig. 7) were tested in order to plot an S/N curve, (Fig. 8). Only the average points were presented for each level. The points were scattered and a line was faired by eye through. The best fatigue life was observed when the Almen intensity was 18A. It may be noted that fatigue life decreases at higher Almen intensity of 22A. Reduction in fatigue life at higher Almen intensity occurs due to surface defects, which lead to crack initiation on the surface/early relaxation of compressive residual stress field during the fatigue process.

It is observed that in both cases, the optimum Almen intensity is 18 A. Fatigue strength varies with shot peening intensity, though, the extent of improvement in fatigue strength is different in specimens testing and full-scale testing. Best fatigue data are obtained by full-scale testing of components under realistic load. But, the method in usually expensive and time-consuming.

**Conclusions**

The paper has accomplished the following for 65Si7 spring steel with conditions used in leaf springs industries:

1. A systematic procedure for improvement in fatigue design has been experimentally developed simulating with industrial environment. Designing various components, keeping into account the effect of shot peening intensity, will eliminate failure of existing design, reduce the weight of components and increases reliability. Thereby, for large volume of material, there will be tremendous saving in material and manufacturing cost.

2. Full-scale testing give more reliable result during fatigue loading as compared to specimen testing. In both cases, fatigue strength varies with shot peening intensity and it is highest at optimum shot peening intensity.

3. An increase in the shot peening intensity does not necessarily increase the fatigue life of 65Si7 spring steel.

4. In axial fatigue test, CRSF suffers a decrease in stress after a finite number of cycles during fatigue process. The stress relaxation is different at various shot peening intensity.

5. An increase in shot peening intensity resulted in an increase in compressive residual stress field.

**Acknowledgement**

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**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>A</td>
<td>Almen ‘A’ scale</td>
</tr>
<tr>
<td>CRSF</td>
<td>compressive residual stress field</td>
</tr>
<tr>
<td>RCRSF</td>
<td>relaxed compressive residual stress field</td>
</tr>
<tr>
<td>$R_a$</td>
<td>average value of surface roughness</td>
</tr>
<tr>
<td>$\sigma_b$</td>
<td>bending stress in leaf springs</td>
</tr>
<tr>
<td>$S_m$</td>
<td>mean fatigue stress</td>
</tr>
<tr>
<td>$S_a$</td>
<td>alternating fatigue stress</td>
</tr>
<tr>
<td>$S_e$</td>
<td>endurance limit</td>
</tr>
<tr>
<td>$S_f$</td>
<td>fatigue strength</td>
</tr>
<tr>
<td>$S'_f$</td>
<td>fatigue strength of shot peened component</td>
</tr>
<tr>
<td>$S'_a$</td>
<td>alternating stress of shot peened component</td>
</tr>
<tr>
<td>$S'_m$</td>
<td>mean stress of shot peened component</td>
</tr>
<tr>
<td>$S'_e$</td>
<td>endurance limit of shot peened component</td>
</tr>
<tr>
<td>$S_y$</td>
<td>yield point tensile strength</td>
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<tr>
<td>$S_{ut}$</td>
<td>ultimate tensile strength</td>
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**References**