THE FATIGUE STRENGTH AND FRACTURE MORPHOLOGY OF LEAF SPRING STEEL AFTER PRESTRESSED SHOT PEENING

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ABSTRACT

Experimental investigations were made on the pulsating bending fatigue properties, residual stress and fracture topography of the prestressed shot peened leaf springs made of the steel grade 55SiMnVB.Their fatigue fracture topographies was observed with SEM and TEM. It has been found that there is a difference between the fracture topography of specimens with or without compressive residual stress. An index is proposed to evaluate the effect of compressive residual stress.

KEYWORDS

Stress peening; fatigue strength; fracture topography; crack initiation; crack propagation; residual stress.

FOREWORD

In automobile industry shot peening has been used as a manufacturing process for a long time to improve the fatigue properties of leaf springs. Many investigators consider (Mattson, 1960; Uchi Yama, 1959) that the residual stress induced by shot peening will act as a mean stress during the material fatigue process. So there is a linear relationship between the mean stress and the fatigue limit. However, the residual stress values in these papers are the peak values which exist on the subsurface and the subsurface is not always the place where a fatigue crack occurs. In fact, due to decarburized layer and other imperfactions, usually existing on commercial quality material, cracks often initiate on the surface. In addition the distribution of residual stress was not considered in these papers either, which would influence the position of the fatigue initiation and the speed of crack propagation (Starker, 1979; Elber, 1974). It is quite necessary to investgate the fatigue strength and fractography of leaf springs under production conditions and to study further the effect of residual stress.

MATERIAL AND METHODS

Specimens are made of 55SiMnVB double-grooved spring steel which is the production material of the Chinese AEOLUS truck, thickness=9 mm; width =75 mm; with a decarburized layer 0.13-0.16 mm in depth. The material was heated to 870°C in the production line by an induction coil for 150 seconds, quenched in oil and then tempered in an air furnace to a core hardness of HB407; the yeild strength=132kgf/mm²; the ultimate strength =143kgf/mm²; its elongation=8%; reduction in area=41%. The prestresses during peening were respectively +100; +75; +50; 0 and -98kgf/mm². The Almen intensity of peening was 0.18-0.20 C. After peening it was cut into specimens, each with 110 mm in length. The three-point bending fatigue test was carried out in an Amsler 10HFP high speed vibrator at a frequency of 125HZ, with mean stress of being 70kgf/mm². The prescribed number of cycles were $5X10^6$. The testing results were then represented in median values and used to draw the S-N curves. The residual stresses were measured by a XYL-73 type X-ray stress analyser with 0°- 45° method, using Cr anode, the specimen surface being removed layer by layer with the electro-corrosion method. Then the stress distribution curve was corrected. Each kind of fracture was observed under a JSM-35C type SEM. More detailed investigations on some fractures were made with TEM.

TESTING RESULTS AND DISCUSSIONS

The S-N Curves and residual stress patterns are shown in Fig. 1 and Fig. 2 As it is shown in figure 1. and figure 2, even if the prestress is higher than the value suggested by J.O.Almen (Almen,1950), for example upto 75% of the yeild strength, (i.e.+100kgf/mm²),the peak value of residual stress induced by shot peening will still rise with the prestress in a linear relationship. The data are shown in Table 1.

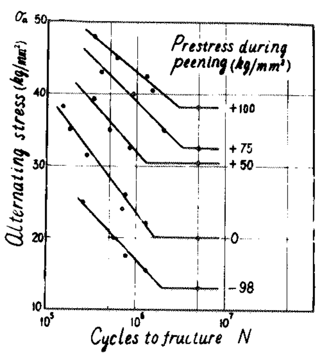


Fig. 1. S-N Curves for various prestress shot peened 55SiMnVB steel (mean stress 70kgf/mm²)

TABLE 1. Data of Prestress and Residual Stress Peak Value

Prestress, kgf/mm²	+100	+75	+50	0	-98
Residual stress, kgf/mm²	-91	-88	-83	-63	+5

The relationship can be expressed as

$$\sigma_{rp}=-51.3 - 0.50\,\sigma_p \qquad (1)$$

here $-98kgf/mm^2 \leq \sigma_p \leq +100kgf/mm^2$

The correlation coefficient $r=-0.973$

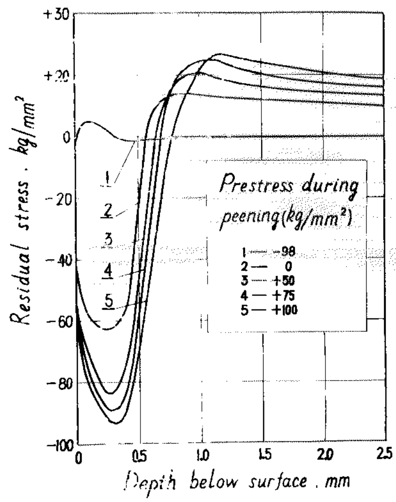
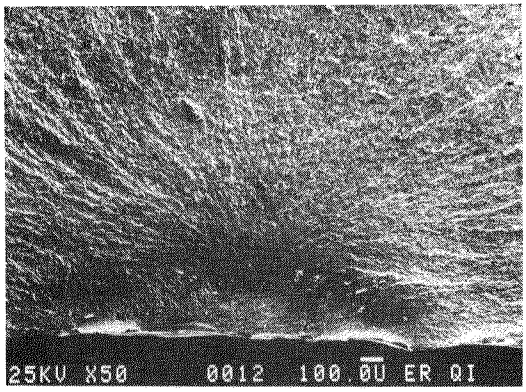


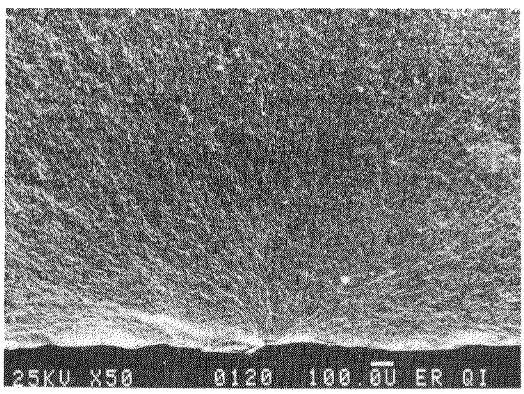
Fig. 2 The residual stress pattern for various prestress shot-peening

After peening with a prestress of $+100kgf/mm^2$, the fatigue limit of the specimen is increased about 70% compared with the un-stress peened ones. X-ray stress analysis shows that before a visible crack appears, the residual stress will not decay obviously. Whether the testing load is large or not, SEM observation indicates that fatigue cracks always initiate at the surfaces of the specimen. However, if there is residual compressive stress in the specimen, in the secondary electronic image there is always semicircular dark spot around the zone of fatigue origin with a diffused boundary as shown in Fig. 3(a). But in the case of fatigue fracture of un-peened specimens or of the minus prestressed ones, since the residual stress is almost zero, there is no dark spot to be observed as shown in Fig. 3(b). Further TEM investigation proves that there are some differences between the fatigue crack propagation area with dark spots and that without them. There are cyclic cleavages and fine striations in the dark spot area as shown in Fig. 4(a). This characteristic is the indication of rather slow propagation of the fatigue cracks. Further way from the dark spot area, striations and dimples appear again. On the other hand, in specimens without dark spots, there are striation and dimples just by the fatigue origin area, as shown in Fig. 4(b). It indicates that cracks propagate rather fast in this case even at the early stage.

In order to investigate the process how the dark spots are formed. The specimens shot-peened under $+75kgf/mm^2$ prestress were tested in an overload condition ($70\pm39kgf/mm^2$). According to the S-N curve, the expected life will be about $9X10^5$ cycles. The tests were stopped before that time was reached and the specimens were broken by static load. Then the fractures were observed under SEM.



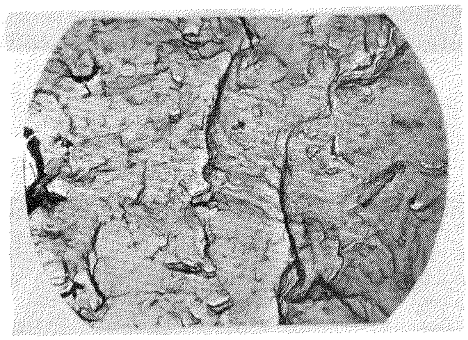
(a) prestress σ_P=+100kgf/mm^2 ; testing load σ_T=(70$\pm$41) kgf/mm^2 ; number of cycles to failure N=14.5X10^5



(b) σ_p=-98kgf/mm^2 ; σ_T =(70$\pm$20)kgf/mm^2 ; N=4.05X10^5

Fig.3 The fractography of specimens with compressive residual stress (a) or without (b)

(a) 2.5μ



(b) 2.5μ

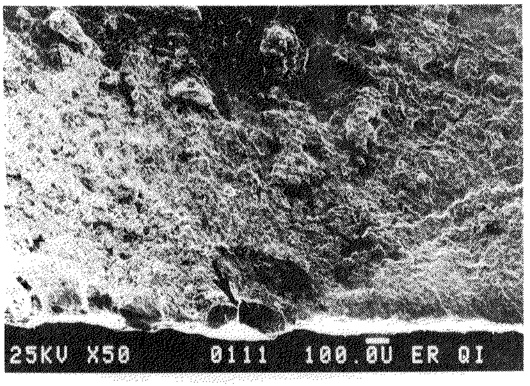
Fig.4 TEM fractography for different fatigue fractures

(a) shot-peened σ_p=+100kgf/mm^2 ; σ_T= (70±45)kgf/mm^2 ; N=6.08X10^5. 0.2 mm below the surface layer, there are fine striation and cyclic cleavage in it.

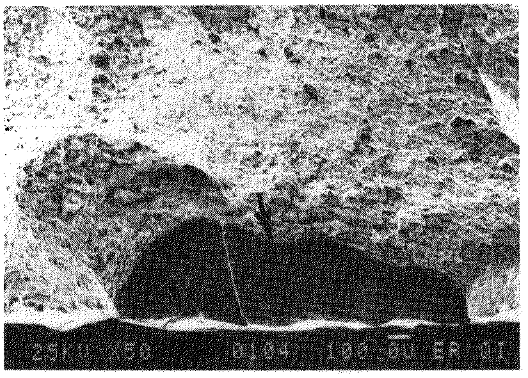
(b) un-peened σ_T=(70±24)kgf/mm^2 ; N=20.3X10^5 0.15 mm below the surface layer. There are striation and dimples in it.

Whenever the specimens were run over 0.31X10^5 cycles,different sizes of dark spots area on the fractures are to be observed.
Fig.5 (a) shows such a specimen with N=0.77X10^5.cycles. But it was further discovered that even in the case of high cycle numbers such as N=8.18X10^5, which is already 90% of the expected life, the depth of dark spot is only about 0.4 mm as shown in Fig.5(b). This proves that crack propagation through the compressive residual stress layer is quite slow,as indicated by a fine appearance in the fracture. So in the SEM observation, the secondary electronic image is characterized by dark spots. It is thus obvious that compressive stress induced by peening improves fatigue life by depressing the speed of crack propagation. Therefore not only the peak value but also the distribution of the residual stress will influence the fatigue life.

We have tried to use this area ,which is under the residual stress distribution curve from surface to the peak value(equivalent to the interforce that exist in the specimen with a depth to peak value and a width in 1 mm), as an index to connect with the fatigue limit.The data are shown in Table 2.



(a) N=0.77X10^5



(b) N=8.18X10^5

Fig. 5.Dark spots (as shown by arrow) in specimens after testing at different number of cycles. σ_p=+75kgf/mm^2 ; σ_T=70$\pm$39kgf/mm^2

TABLE 2. The Correlative Data

Prestress during peening kgf/mm^2	+100	+75	+50	0	-98
Area under residual stress pattern S kgf/mm	-23.4	-21.4	-18.5	-12.1	+0.2
Fatigue limit σ_a kgf/mm^2 (mean stress σ_m=70kgf/mm^2)	38	33	31	20	13

The relationship can be expressed as follows:

$$\sigma_a = 11.3 - 1.04S \quad (1)$$

the correlation coefficient r=-0.970. So it seems to be more reasonable if we use the area as an index to evaluate the influence of compressive residual stress to fatigue limit.

CONCLUTIONS

1. The residual stress of specimen increases with the increase of the prestress during peening (up to 75% of the material yeild strength). Therefore the fatigue limit also increases.

2. For leaf spring steel 55SiMnVB with decarburized layer, the fatigue crack of shot-peened specimen always initiates at its surface. The principal effect of compressive residual stress is to depress the crack propagation.

3. The fracture mechanism of diffused semicircular dark spots observed under the SEM are cyclic cleavages and fine striations. It is evident that the spots are the traces of fatigue crack which propagates rather slowly.

4. The area under the residual stress-distribution curve from surface to peak value can be used to evaluate the influence of compressive residual stress to the fatigue limit.

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