THE EFFECT OF SHOT PEENING ON STRAIN-CONTROLLED FATIGUE BEHAVIOURS

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ABSTRACT

Material's strain-stress behaviours under strain-controlled loading are examined before and after shot peened. SEM analysis for fatigue fractographies shows, although the beneficial compressive residual stress in surface layer can be induced by shot peening, the fatigue cracks in low-cycle range initiate all from the sample surfaces for both peened and unpeened. The relaxation rates of residual stress increase with strain amplitudes, but some residual stresses can be still retained when the strain amplitude is not large enough. Shot peening makes cyclical deformation resistance increase due to work-hardening. Shot peening has little effect on Bauschinger effect for static but some effect on that for cyclical. The strain-life curves of peening and unpeening cross each other at Nc. The inverse effects of shot peening on the low cycle fatigue lives are illustrated below and over Nc, below Nc, the strain amplitude is larger, shot peening makes fatigue life decrease due to increases of surface hardness and roughness; over Nc, some beneficial residual compressive stress can be retained and favourable to lengthening life, so does average compressive stress induced by Bauschinger effect.

KEYWORDS

Strain-Controlled Fatigue, Residual Stress, Relaxation, Bauschinger Effect, Shot Peening

INTRODUCTION

The stress concentrations caused by notch are inevitable in the machine parts. When they are loaded cyclically, although the bulk remains in the state of elasticity, the stress concentration zone may deform plastically. The fatigue resistance of these critical positions can be imitated by strain-controlled fatigue test.

Some works about the effect of cold-deforming on low-cycle fatigue (LCF) have been done. After being cold-formed, the LCF lives of steel and aluminium alloy are decreased by 30-50%, and it was contributed mainly to Bauschinger Effect [1]. But the life of airplane frame can be increased from 650 to over 2700 cycles by shot peening [2]. In order to discern these contradictory results, the effect of shot peening on the crack initiation life of LCF is examined in this paper, and associate problems about Bauschinger Effect and residual stress are discussed as well.

EXPERIMENTAL DETAILS

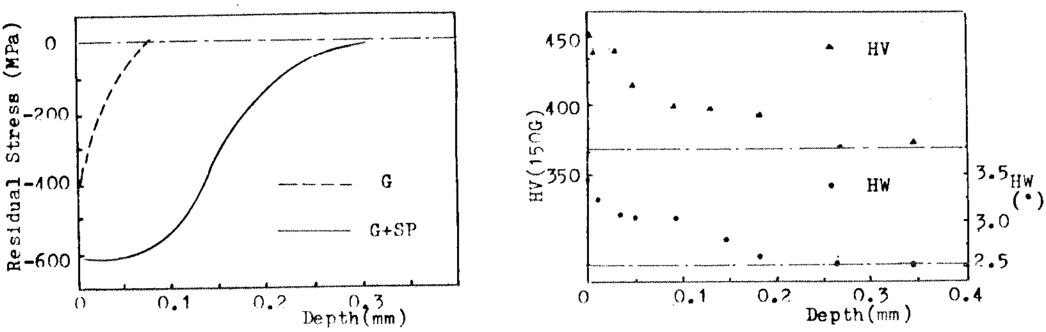
The chemical compositions of the steel investigated are 0.39C, 0.65Mn, 0.24Si, 0.97Cr, 0.015P, 0.011S (weight %). After forged and machined, the specimens, 10 mm diameter and 25 mm long in the gauge section, were austenitized at 860°C and quenched in oil of 20°C, then tempered at 500°C for 90 minutes. After heat treated, the oxidized and decarburized skins of the specimens were removed by grinding. The mechanical properties as follows: E 209000 MPa, σ_y 994 MPa, σ_b 1100 MPa, δ 11.6%, ψ 56%. Finally, the specimens were shot peened for 15 minutes, with the cast iron shot (shot diameter 0.3-0.6 mm), air pressure 5 a.t., shot peening Almen intensity 0.27 - 0.30A(mm). The specimens were rotating when shot peened in order to get the uniform shot peening intensity around the circumference.

The strain-controlled fatigue tests were performed in air at room temperature on a closed loop electrohydraulic system (MTS 880 Material Test System), using fully reversed triangular strain waves of controlled total strain amplitude. The strain rate, controlled and measured by a 25 mm gauge length clip-on gauge, was 8.33×10^{-3} sec^{-1} for cyclic and 3.5×10^{-5} sec^{-1} for monotonic test. During the test, the maximum and minimum stresses under total strain controlled were recorded. Cr-Kα radiation, (211) of plane α-Fe are used to measure residual stress, meanwhile the half-width values of X-ray diffraction at 0° were calculated. The workhardening state produced by shot peening was evaluated by micro-hardness test (150 grams). The distributions of residual stress and micro-hardness vs. depth were determined by tests after electro-polishing removing. The fractures of LCF were examined by T - 300 scanning electron microscope.

EXPERIMENTAL RESULTS

Material States after Shot Peening

The longitudinal residual stress, half-width, and micro-hardness are shown in Fig. 1. The magnitude of surface residual stress is about -600 MPa and microhardness of peening surface is approximately 100 HV higher than that of unpeening. The mean value of surface roughness is 3 μm for grinding and 16 μm for shot peening.



(a) (b)

Fig. 1 Profiles of Residual Stress, Hardness, and Half Width
(a) Residual Stress vs. Depth (b) HV and HW vs. Depth

Stress-Strain Behaviour

The monotonic and cyclic stress-strain curves for shot peened and unpeened specimens are shown in Fig. 2, determined by the incremental step test for cyclic. The yield part (micro-plastic deformation stage) of monotonic curve for peening is lightly lower than that for unpeening due to the residual stress induced by shot peening[3], but the cyclic stress-strain resistance of peened specimen is higher than that of unpeened, it may be contributed to the increase of hardness produced by peening hardworking. The cyclic softening occurred during the cyclic loading for both peened and unpeened specimens. The stable cyclic stresses σ and plastic strain amplitudes $\Delta\varepsilon p$ are fitted to $\sigma = K' * (\Delta\varepsilon p)^{n'}$, here K', n' are cyclic hardening coefficient and exponent respectively. For shot peening, $K' = 1210$ MPa, $n' = 0.08546$.

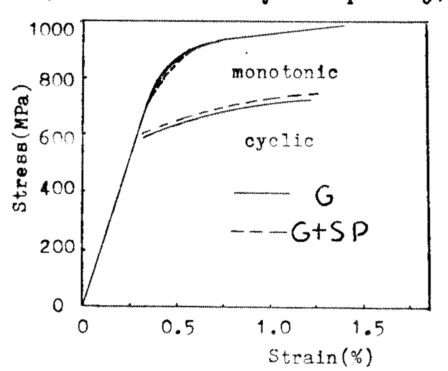


Fig. 2 Monotonic and Cyclic Resistances

Strain-Controlled Fatigue Test

The strain - controlled fatigue tests of shot peened and unpeened specimens were carried out under the same test conditions. Fig. 3 are plots of the strain amplitude vs. life for both kinds of specimens, and different trends are demonstrated. There is a cross point Nc by two curves, shot peening can increase the life of material under the smaller strain amplitude (the lower portion below Nc), but does decrease the life under the larger strain amplitude (the upper over Nc).

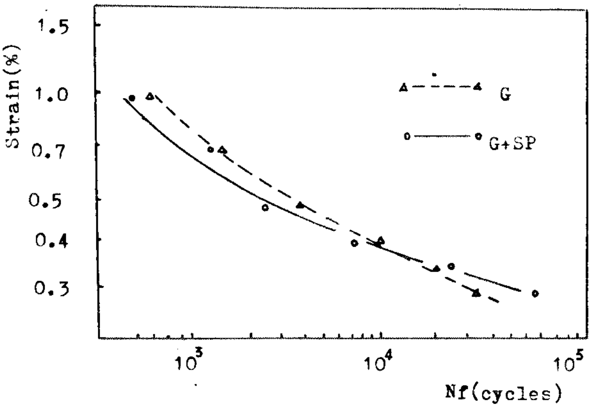


Fig.3 Strain Amplitude vs. 2Nf

According to the procedures of Landgraf et al [4], the total strain amplitude can be divided into the elastic and plastic portions, $\Delta\varepsilon e = \sigma/E$, $\Delta\varepsilon p = \Delta\varepsilon t - \Delta\varepsilon e$ (σ is the stable cyclic stress), and then they are fitted to Manson-Coffin formula (equ.1) by the least squares technique, the strain-life parameters obtained are given in Table 1.

$$\Delta\varepsilon t = \Delta\varepsilon e + \Delta\varepsilon p = \sigma f'/E \times (2Nf)^{b} + \varepsilon f' \times (2Nf)^{c} \quad (1)$$

Table 1 Strain-life Parameters

state	$\sigma f'$	b	ρ	$\varepsilon f'$	c	ρ
G	1161	-0.0549	0.9667	1.2579	-0.7463	0.9913
G+SP	1100	-0.0497	0.9964	0.1520	-0.4978	0.9116

Shot peening decreases the absolute value of fatigue strength exponent $|b|$ due to the rise in hardness, and abnormally reduces the absolute value of fatigue ductility exponent $|c|$. The linear relationship of $\Delta\varepsilon p$ vs. 2Nf for shot peening becomes worse.

DISCUSSION

Relaxation of Residual Stress under Strain-Controlled Loading

Fig.4 shows the changes of residual stresses induced by shot peening under constant total strain amplitute. When the strain amplitute is larger, the residual stress relaxes rapidly, the relaxation rate slows down with the decrease of strain amplitute. A part of residual stress can be remained until the fracture of the specimen for the smaller strain amplitude.

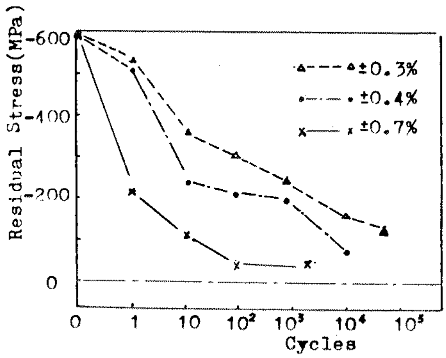


Fig. 4 Residual Stress vs. Cycles for SP

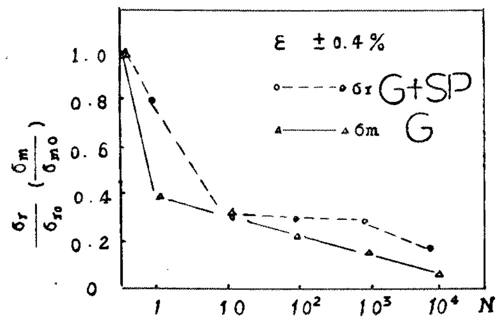


Fig. 5 The Comparison of Relaxations

The changes of mean stress under cyclic loading are often used to quantitatively evaluate the residual stress relaxation. The comparison of cyclic relaxations for residual stress and mean stress is made in Fig. 5. Two stages exhibit in σ_m/σ_{mo} vs. logN curve, the first stage is considered as static relaxation (after first cycle), the second stage, there is a linear relation between $\sigma_m(N)$ and logN. Although the relaxation of residual stress has a similar trend to that of the mean stress, some difference can be seen, and the relaxation rate of residual stress by shot peening is less than that of mean stress, it may be related to the change of material structure and ununiform distribution of residual stress along the section by shot peening. The half width in X-ray diffraction can be used to evaluated the fatigue damage, it includes two factors: microstrain, i.e. micro residual stress, and grain size. Fig. 6 shows HW vs. N. The similar trends are illustrated for shot peening and unpeening. The values of HW increase rapidly at the early stage of cycling, then decrease slowly until fracture. V. Weiss et al [5] have reported such phenomenon, and micro-crack initiation was considered as the mechanism of HW peak.

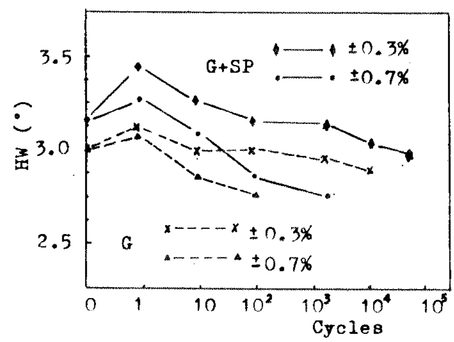


Fig. 6 HW vs. Cycles

Bauschinger Effect Analysis

Bauschinger Effect (BE) is a very important mechanics phenomenon, it can affect many material's properties, including low cycle fatigue . The Bauschinger Effect Factor is used to analyze here, i. e. BEF = σ_r^y / σ_f, as shown in Fig. 7. The strain rate was $3.50\times10^{-5} sec^{-1}$, firstly forward loading up to a certain prestrain, then reverse loading, and the loading stress-strain curves were simultaneously recorded. The values of BEF for peened and unpeened specimens are 0.4 and 0.405 respectively when the prestrain is 2.0%, so no evident effect of shot peening on BEF is produced.

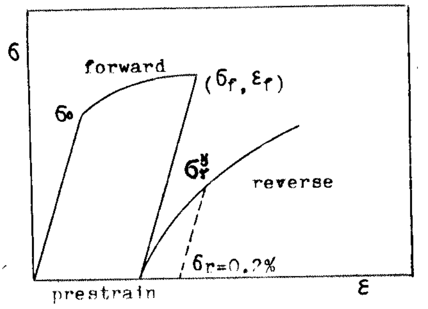


Fig.7 BEF Measurement Sketch

BE in cyclic loading can be indirectly expressed by the maximum and minimum stresses under constant strain amplitude [6]. Here, their average value (mean stress) is considered ($\sigma_m = 0.5\times(\sigma_{max}+\sigma_{min})$). The data tested are shown in Table 2, the increases of comprssive mean stress by shot peening are observed, and this effect increases with the decrease of strain amplitude as well.

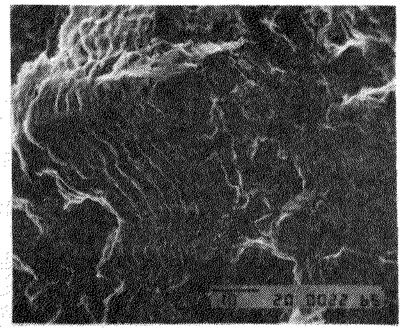
Table 2 Mean Stress for Shot Peening and Unpeening(MPa)

N	$\Delta\varepsilon_t$= 1.0%		$\Delta\varepsilon_t$= 0.4%	
(cycles)	unsp	sp	unsp	sp
1	-1.5	-7	-1	-23.5
100	-7.5	-19.5	-4.5	-26
500	-8	-18.5	-9	-62

Fractography Analysis

The fractures of LCF were examined by scanning electron microscope. Their cracks initiate all from the specimen surfaces for both shot peening and unpeening, so that the mechanism of LCF is not changed by shot peening. Fig.8 shows the fracture photos for shot peening, the surface origin (Fig.8a) and fatigue striations below subsurface (Fig.8b) can be seen.

The residual stress of peened surface is entirely removed under the larger strain amplitude loading. Some residual stress can be retained under the smaller one, but it is not enough to offset the weakening factors at surface, so the LCF cracks for peening initiate also from the sample surface.



(a) (b)

Fig.8 Fatigue Fracture Appearances for SP ($\Delta\varepsilon t$= 0.3%)
(a) origin (×50) (b) striations (×1000)

The strain fatigue plays a major part in the larger strain amplitude range, the residual stress is easily eliminated, the increase of surface roughness enhance the stress concentration, and the rise in hardness is unfavourable to the strain fatigue, so the decrease of LCF life occurred for peening. While the sress fatigue plays a major role in the smaller strain range, some compressive stress can be retained, and the increase of hardness is favourable to the stress fatigue, thus the rise of the life is observed. It can be used to explain the results mentioned in the introduction. The bad linear relationship of $\Delta\varepsilon p$ vs. 2Nf and abnormal reduction of the absolute value of fatigue ductility exponent |c| for shot peening may be contributed to the rise in hardness and the effect of residual stress.

CONCLUSIONS

1. Residual stress is entirely eliminated under the larger strain amplitude, but some residual stress can be retained under the smaller one in LCF range.

2. Shot peening does not evidently affect the Bauschinger Effect of static, it can increase the compressive mean stress under cyclic constant strain amplitude, especially under smaller strain amplitude.

3. The cracks initiate all from the specimen surfaces for both shot peening and unpeening. Shot peening can increase the LCF life under smaller strain amplitude, but decrease the life under the larger one.

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