QUALITATIVE ANALYSIS ABOUT EFFECT OF SHOT PEENING ON FATIGUE LIMIT OF A 300M STEEL UNDER THE ROTATING BENDING CONDITION

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ABSTRACT

Rotating bending tests were conducted to determine the fatigue limits of peened and unpeened specimens of a quenched and tempered 300M steel with the up and down method. The fatigue fractograph were observed under a scanning electron microscope. The results show that, for unpeened specimens, the fatigue limit is 840 MPa and the fatigue cracks always initiate at the specimen surface, while for the peened ones the fatigue limit is 1040 MPa and the fatigue cracks initiate in the specimen interior, and the depth of the crack source Z_s measured on the specimens fractured at a stress a little higher than fatigue limit is about 200 μm which is larger than the whole depth of the compressive stress Z_0 induced by shot peening. That is to say, the fatigue source of the peened specimen is located in the region with the tensile residual stress beneath the strengthened layer. In our previous works, a concept of internal fatigue limit has been proposed. This concept represents that the critical stress for the initiation of a fatigue crack in the interior of material (internal fatigue limit) is higher than that at the surface of the same material (surface fatigue limit) and their ratio is about 1.35~1.40. It is believed that the present experimental result can also be analyzed from this standpoint. The result shows that the ratio of the internal fatigue limit to surface fatigue limit is about 1.39. So the internal fatigue limit concept is still valid under the rotating bending condition.

INTRODUCTION

Fatigue strength can be improved considerably by shot peening. This is usually attributed to that the compressive stress field (CSF) induced by shot peening reduced the mean load stress. However, the fatigue crack of a specimen after proper shot peening often initiates in

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the internal region beneath the compressive stress field where tensile stress occurs, while the apparent fatigue limit increases notably and usually reaches the optimum value. To explain this phenomenon, a new concept of internal and surface fatigue limit has been proposed based on experiments and dislocation theory (1~4). This concept represents that the critical stress for a crack to initiate in the interior of a specimen after proper surface strengthening is about 1.35~1.40 times of that at the surface of a specimen without surface strengthening. This concept has been used to predict apparent fatigue limits of shot peened specimens and to optimize shot peening regimes successfully(5~7). However, all our previous experiments are conducted under three bending condition with stress ratio equal to 0.05. The validity of this concept has not been verified experimentally under the rotating bending condition with stress ratio equal to -1 which is a common engineering condition.

MATERIAL AND EXPERIMENTAL PROCEDURES

The material used is a 300M steel which is quenched at 870 ℃ and then tempered at 300 ℃. The chemical composition and mechanical properties are list in table 1 and table 2 respectively. Fatigue limits of peened and unpeened specimens were determined by fatigue tests on a HY rotating fatigue machine with the up and down method. The fatigue cycle number is 10^7 and the rotating frequency is 50Hz. To get the true fatigue limit without effect of residual stress induced by machining, a surface layer was removed by electrolysis from the unpeened specimens before fatigue tests. The residual stress field of the peened specimens was measured by X-ray diffraction and gradual electrolysis of the specimen. The fatigue fractograph of the specimens fractured at a cyclic load a little higher than the fatigue limit was observed under SEM and the depth of the fatigue crack source from the specimen surface was measured.

Table 1 Chemical composition of used steel

element	C	Mn	Si	Cr	Ni	Mo	V	Cu
Content	0.39	0.69	1.61	0.91	1.82	0.42	0.07	0.06

Table 2 Mechanical properties of 300M steel

$\sigma_{0.2}$, MPa	σ_u, MPa	δ, %	ψ, %	a_k kJ/m^2	K_{IC}, MPa	HRc
1643	1950	12.3	52.9	81.5	83.2	53~54

EXPERIMENTAL RESULTS AND DISCUSSION

For the peened specimens, the fatigue crack source is located at the specimen surface and the fatigue limit (surface fatigue limit) $\sigma_{ws(-1)}$ equal to 840MPa. While for the peened specimens, fatigue crack initiates in the internal region beneath the compressive residual stress filed, where the tensile residual stress occurs. The fatigue crack source depth Z_s is 0.22 mm and the apparent fatigue limit is 1040MPa. Fractographs around the fatigue source of the peened and unpeened specimens are shown in Fig.1. The distribution of residual stress σ_r along the depth from the surface of the shot peened specimens is shown in Fig.2.

This result indicates that the critical stress for a crack to initiate in the interior is higher than that at the surface of the same material.

The critical condition of the internal fatigue crack initiation is that the load stress σ_{li} at a internal position plus the residual stress σ_{ri} at the same position equals to the internal fatigue limit $\sigma_{i(-1)}$:

$$\sigma_{i(-1)} = \sigma_{ri} + \sigma_{li} \tag{1}$$

Tensile residual stress field can be described in the following empirical equation (3,9,10):

$$\sigma_{rt}(Z) = \frac{(Z - Z_0)^{1.35}}{a(Z - Z_0) + b} \tag{2}$$

where σ_{rt} (Z) is the tensile residual stress at the depth of Z , Z_0 is the depth of the whole compressive residual stress, a, b are constants that can be determined in following equations:

$$\frac{(Z_{mt} - Z_0)}{Z_0} = 0.23 \tag{3}$$

$$-\int_0^{Z_0} (r-Z)\,\sigma_{rc}(Z)\,dZ = \int_{Z_0}^{r} (r-Z)\,\sigma_{rt}(Z)\,dZ \tag{4}$$

where r is the radius of the fatigue specimens, σ_{rc} (Z) is the residual stress at the depth of Z, Z_{mt} is the depth of the maximum tensile residual stress. In equation (2) and (4) the units of stress and length are MPa and μm respectively.

During fatigue tests, the local stress in the compressive stress layer exceeded the yield strength and the compressive residual stress relaxed which can be described in following equation:

$$\sigma'_{rc} = \begin{cases} \sigma_{-y} + \sigma_a & (\text{for } \sigma_a - \sigma_r > -\sigma_{-y}) \\ \sigma_r & (\text{for } \sigma_a - \sigma_r < -\sigma_{-y}) \end{cases} \qquad (5)$$

where σ'_{rc} is the relaxed residual stress, σ_{-y} is the compressive yield strength, σ_a is the cyclic stress range. For 300M steel σ_{-y} approximately equals to $-\sigma_{0.2}$. When the specimen is tested at a cyclic stress equal to the apparent fatigue limit, σ_a at the depth of Z is equal to $\sigma_{a\,p(-1)}\,(1 - Z/r)$. The calculated distribution of the compressive residual stress after stress cycling is shown in Fig.3.

According to the distribution of the compressive residual stress field after stress cycling, the residual tensile stress distribution is calculated. The calculated results show that the maximum tensile residual stress σ_{mt} is about 200 MPa and Z_{mt} is about 0.22mm. So Z_{mt} is approximately equal to the depth of fatigue crack source Z_s. Then the load stress can be calculated in following equation:

$$\sigma_{li} = (1 - 2Z_{mt}/d)\,\sigma_{a\,p(-1)} \qquad (6)$$

where d is the diameter of fatigue specimens, $\sigma_{a\,p(-1)}$ is the apparent fatigue limit when fatigue crack initiates in the interior. The residual stress at the internal fatigue source, σ_{ri}, is equal to σ_{mt}. Substituting the value of σ_{ri} and σ_{li} into the equation (1), the critical stress for a fatigue crack to initiate in the interior can be calculated:

$\sigma_{i(-1)} \approx 1170$MPa

$\sigma_{i(-1)}$ is the internal fatigue limit of the tested material. Then the ratio of the internal fatigue limit to the surface fatigue limit can be calculated:

$\sigma_{i(-1)}/\sigma_{s(-1)} \approx 1.39$

The above results show that the critical stress for a fatigue crack to initiate in interior is higher than that at the surface of the same material and the internal fatigue limit concept is still valid under the condition of rotating bending condition.

CONCLUSION

(1) The fatigue crack of 300M specimens after proper shot peening initiates in the internal region where the tensile residual stress occurs and the apparent fatigue limit increases considerably.

(2) The internal fatigue limit of 300M steel is about 1.39 times of the surface fatigue limit under the rotating bending condition.

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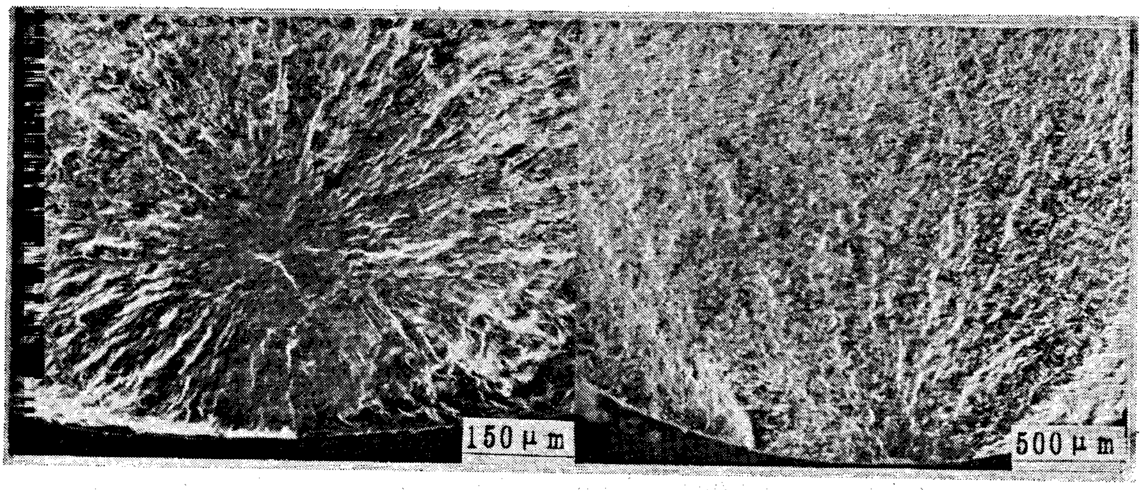

Fig. 1 Fatigue faractograph
a) peened b) unpeened

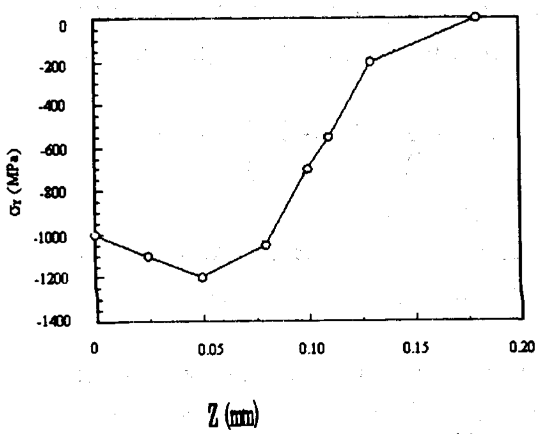

Fig. 2 Compressive residual stress field of shot peened specimen

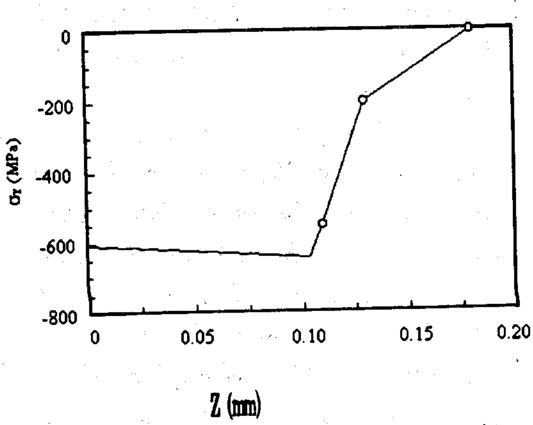

Fig. 3 Compressive residual stress field of shot peened specimen after fatigue test