Fatigue Strength and Shot-peening

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Abstract

Improving fatigue strength by shot-peening, first of all, it is essential to understand the phenomenon of fatigue fracture. Unfortunately, in these days, there are still serious accidents caused by fatigue fracture. This would be due to both the difficulties of finding small defects causing fatigue fracture and the incomplete quantitative understanding of a notch sensitivity determined by hardness and stress ratio (including residual stress). In addition, the relation between processing conditions for shot-peening, residual stress and surface roughness is not always clear. However, by applying the theoretical approach of fracture mechanics, it has become possible to have clearer understanding of the residual stress distributions and the dimension of surface defect quantitatively for improving fatigue strength.

In this paper, the relations between residual stress distributions by shot-peening and fatigue strength is discussed quantitatively.

Keywords: fatigue, notch sensitivity, hardness, defect, shot-peening, residual stress

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1. Introductions

In the viewpoint of earth environmental safeguards, it has been becoming important to have mechanical parts saved their mass. While the mass saving normally requires the improvement of fatigue strength, it has been well-known that shot-peening process be inevitable for improving fatigue strength. Many research works in the past make it possible to understand the effect of material strength, surface defects and compressive residual stress on fatigue strength qualitatively. However, the mechanism of improving fatigue strength by shot-peening is extremely complicated, affected by the shape of compressive residual stress distributions, defect dimensions, and material hardness(strength). In order to solve this problem experimentally, the experimental volume would be too huge to obtain any substantial results. Applying fracture mechanics, the quantitative approach where the fatigue limit of cracked material and the influence of crack size and residual stress to crack propagation life can be formulated, is proposed. In this paper, the results where the validity of this approach is verified experimentally, are reported

2. Quantitative expression of residual stress, crack length and hardness

2.1 Fatigue limit of cracked material [1],[2]

The fatigue strength with a small crack length (a), $\Delta\sigma_{th,R=R}$ under the stress ratio, $R=\sigma_{\min}/\sigma_{\max}$, can be expressed as the equation (1), by a threshold stress intensity factor range with a large crack, $\Delta K(L)_{th,R=R}$ and a fatigue strength of smooth material, $\Delta\sigma_{w,R=R}$. The stress intensity range is $\Delta K=\alpha\cdot\Delta\sigma\sqrt{\pi\cdot a}$.

$$\Delta\sigma_{th,R=R} = \left\{ \left(\frac{\alpha\sqrt{\pi \cdot a}}{\Delta K(L)_{th,R=R}} \right)^2 + \left(\frac{1}{\Delta\sigma_{w,R=R}} \right)^2 \right\}^{-1/2} \qquad (1)$$

The relationship between $\Delta K(L)_{th,R=R}$ and $\Delta\sigma_{w,R=R}$, and hardness, HV and stress ratio, R can be obtained by following the equations (2) and (3).

$$\Delta K(L)_{th,R=R} = (1-R)^{0.71} \times \left(5.514\times10^{-5} \times HV^2 - 0.0775 \times HV + 30.335\right) \qquad (2)$$

$$\frac{\Delta\sigma_{w,R=R}}{2} = \frac{(1-R)}{(1.205-0.795R)} \times (1.633 \cdot HV - 20.6) \qquad (3)$$

Substituting equations (2) and (3) to equation (1), the equation (4) is obtained. The equation (4) shows the fatigue strength of cracked material which has a certain crack length and hardness under a certain stress ratio.

$$\Delta\sigma_{th,R=R} = \left\{ \begin{aligned} &\left(\frac{\alpha\sqrt{\pi \cdot a}}{(1-R)^{0.71}\left(5.514\times10^{-5} \cdot HV^2 - 0.0775 \cdot HV + 30.335\right)} \right)^2 \\ &+ \left(\frac{1.205 - 0.795 \cdot R}{(1-R)(3.266 \cdot HV - 41.2)} \right)^2 \end{aligned} \right\}^{-1/2} , \qquad (4)$$

where lower limit of stress intensity factor under a minute crack, $\Delta K(S)_{th,R=R}$ is expressed as equation (5).

$$\Delta K(S)_{th,R=R} = \alpha \cdot \Delta\sigma_{th,R=R}\sqrt{\pi \cdot a} \qquad (5)$$

2.2 Calculation of crack propagation life

With lower limit of stress intensity factor under a minute crack, $\Delta K(S)_{th,R=R}$, the relationship between crack propagation rate up to medium rate, da/dN and stress intensity factor range can be expressed as equation (6).

$$\frac{da}{dN} = C(1-R)^{-mG}\left[\Delta K^m - \Delta K(S)^m_{th,R=R}\right] \qquad (6)$$

The dependency of C and m on hardness can be expressed the following equation and G=0.75.

$$C = 2.018\times10^{-14} \times 1.195^{-6.86\times10^{-5}HV^2 + 0.139HV - 3.59}$$

$$m = 1.714\times10^{-6} \cdot HV^2 - 3.481\times10^{-3} \cdot HV + 4.515$$

The crack propagation life can be obtained by integrating the equation (6) as shown in the equation (7). The actual calculation can be carried out by Simpson's numerical integral.

$$N_f = \int_0^{N_f} dN = \int_{a_i}^{a_f} \frac{da}{C(1-R)^{-mG}\left[\Delta K^m - \Delta K(S)^m_{th,R=R}\right]} \qquad (7)$$

2.3 Evaluation of residual stress distributions

The residual stress can act as a mean stress under the fatigue. The compressive residual stress formed by shot-peening, can reduce the mean stress to restrain the growth of fatigue crack. Hence, the compressive residual stress can make the stress where the crack propagation starts higher and make the propagation rate lower to have the fatigue strength higher. The K value when a complicated residual stress distribution caused by shot-peening, exists around the crack area can be expressed by equation (8), taking the superposition principle into consideration. The $m(a,x)$, so-called the weight function is the K-value when a concentrated counterforce of 1 at the location, x in the cracked surface exists[3]. In recent years, for practical applications, the calculation methods of K-value of a semi-elliptical shaped crack when the residual stress distribution approximated as three dimensional equation [4] or four dimensional equation [5] have been reported. In this study, the K-value calculation is applied by equation(10) proposed by API, approximating the residual stress distribution as four dimensional equation.

$$K = \int_0^a \sigma(x) \cdot m(a,x)dx \qquad (8)$$

The stress ratio is represented as equation (9) if there is compressive residual stress by shot- peening.

$$R = \frac{K_{\min} - K_R}{K_{\max} - K_R} \qquad (9)$$

Where K_{max} is maximum stress intensity factor and K_{min} is minimum stress intensity factor on fatigue test. To calculate K_R, equation (10) was used. The equation (10) is referred from API579 (C.3.5 Plate-Surface Cracks, Semi-Elliptical Shape, Through-Wall Fourth Order Polynomial Stress Distribution) [5] for the analysis of the stress intensity factor for surface cracks subjected to arbitrarily distributed surface stress.

$$K_R = \left[M_s G_0 \sigma_0 + G_1 \sigma_1 \left(\frac{a}{t}\right) + G_2 \sigma_2 \left(\frac{a}{t}\right)^2 + G_3 \sigma_3 \left(\frac{a}{t}\right)^3 + G_4 \sigma_4 \left(\frac{a}{t}\right)^4 \right] \sqrt{\frac{\pi a}{Q}} f_w \qquad (10)$$

Where M_s is surface correction factor, G_0 through G_4 are influence coefficient, σ_0 through σ_4 are constants which represent stress distribution, t is thickness of specimen, Q is flaw shape parameter, f_w is finite width correction factor. These parameters are quoted from reference [10].

3. Experimental results and discussions

3.1 Fatigue strength of cracked material

Applying experimental data of fatigue test fractured from the inside, the validity of the equation (4) of fatigue strength of cracked material is verified. Therefore, α is $2/\pi$. The fatigue test data applied are that the material is spring steel SUP7(SAE9260), SUP9(SAE5160), SUP12(SAE9254), and SUP12V(SAE9254V), the hardness range is from 473HV to 655HV, and the stress ratio is $R=-1$ (reversed stress) and $R=0.1$ (pulsating stress). Their fatigue origins occur at the location of 0.2-1.0mm from the surface, where there is no influence of compressive residual stress. In the equation (4), the calculation of R excludes the effect of residual stress where K_R is zero in the equation(9). Fig.1 shows the relationship between the stress amplitudes in the surface of fatigue test specimens, and fatigue life. It is noted that the fatigue life shows many scatterings and the fatigue life of SUP12, 540HV and R=-1 is ranged from $2\times10^5 \sim 9\times10^7$ cycles. It can be also realized from the Fig.1 that there is no correlation between stress amplitudes and fatigue life. This means that the internal fracture can occur accidentally, due to the locations and sizes of internal defects such as non-metallic inclusion. Fig.2 shows the ratio of the actual stress, $\Delta\sigma$ to the fatigue strength of cracked material $\Delta\sigma_{th,R=R}$ obtained by the equation (4), using fatigue origin dimension, $2a$, hardness, HV and stress ratio, R. It can be clearly seen from the Fig.2 that all data satisfy $\Delta\sigma/\Delta\sigma_{th,R=R} \geq 1$ and the fatigue life becomes larger as the ratio
is close to 1. This means that the equation (4) can be applicable

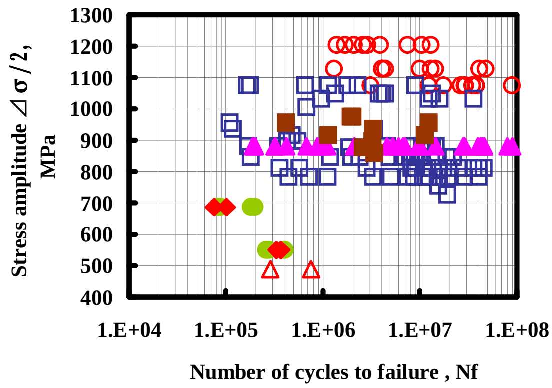

Fig.1 S-N diagram of internal fracture

SUP12V 615HV R=-1 | SUP7,SUP12V 580HV R=
SUP7 655HV R=-1 | SUP7 515HV R=-1
SUP9 510HV R 0.1 | SUP9 473HV R 0.1

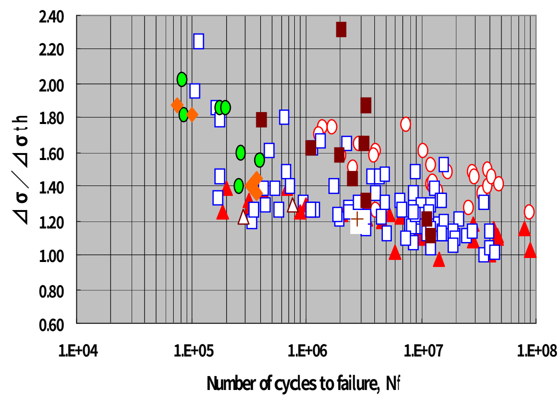

Fig.2 ⊿σ／⊿σth and Number of cycles

SUP12V 615HV R=-1 | SUP7,SUP12V 580HV R=-1
SUP12 540HV R=-1 | SUP7 655HV R=-1
SUP7 515HV R=-1 | SUP9 530HV R=0.1
SUP9 510HV R=-1 | SUP9 475HV R=-1

for evaluating cracked material, considering crack length, hardness and stress ratio.

Propagation life of cracked material

The propagation life of cracked material can be calculated by the equation (7). In order to verify the applicability of the equation (7), the four point bending fatigue tests of cracked plate material were carried out. The fatigue test specimens are SUP9(SAE5160) with 470HV by quenching and tempering. The dimension is 27mm width, 7.5mm thickness and 300mm length. The crack defects were applied to specimens by electrical discharge machining. The semi-elliptical shaped defects of which the depth is 0.05,0.1,0.2, and 0.3mm, and the width is 0.03mm are shape enough to be evaluated. The crack of which surface face with the perpendicular direction to bending stress, was given in the center of width and length. Therefore, the crack can stay in a constant stress area of 4-point bending. First, the relationship between da/dN and ΔK was measured and compared with the equation (6). The measurement of crack length was carried out by the crack gauge. It can be seen from Fig.3 that the measured crack propagation rates, $da/dN-\Delta K$ show good agreements with the calculated values by the equation (6). Therefore, it is concluded that the prediction of crack propagation life calculated by the equation (6) and (7) is applicable for the practical use.

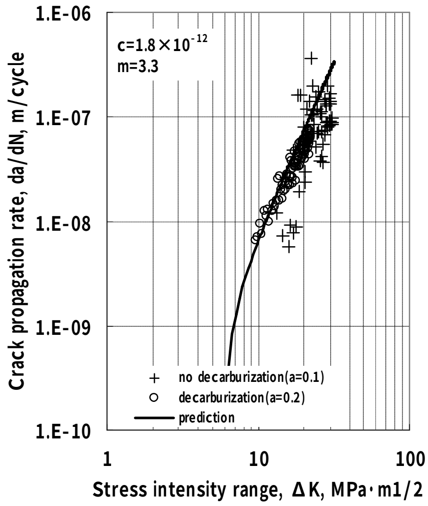

Fig.3 Relationship between crack propagation rate and ΔK, which is the comparison of the calculated values with experimental data

The relationship between the residual stress distribution by shot-peening and fatigue life

The improvement of fatigue strength by shot-peening has been said to be mainly due to the compressive residual stress distribution. The shape of residual stress distribution by shot peening is also known that the value at the surface is relatively lower, and the value increases along the inner side up to a maximum value and then the value decreases to be zero at a deeper location, see the Fig.4. The value of the compressive residual stress in the surface extremely contributes to improving the fatigue strength. Therefore, the relation between number of cycles and crack propagation length was calculated by applying the equation (7) for realizing the effect of the compressive residual stress in the surface on the fatigue strength. The calculating conditions are below. The bar, ф4 of diameter, is carried out rotary bending fatigue test. The stress condition is $\sigma_a = \pm 1001$MPa. The shape of the crack is a semi-circle with the 0.01mm of radius locating in the surface. The cracked plane is perpendicular to the direction of bending stress. The hardness of bar is 540HV. The Fig.4 shows the 3 types of the residual stress distributions for calculation, the value of surface residual stress of each type are -570MPa, -450MPa and -350MPa. The Fig.5 shows the results of the calculations. According to the Fig.5, the propagating crack grows as the numbers of cycles increase. The rate of growth is slow until the growth becomes about 0.05mm. This 0.05mm corresponds approximately with the depth of peak residual stress in the Fig.4. The rate of crack growth becomes to be faster and faster over than 0.05mm. Therefore, it can be considered that the whole life of crack propagation is the number of cycles

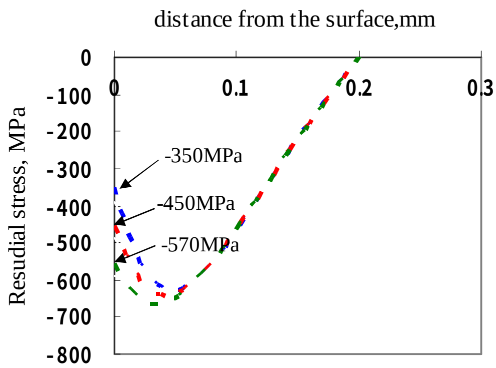

Fig.4 Residual distributions for simulations

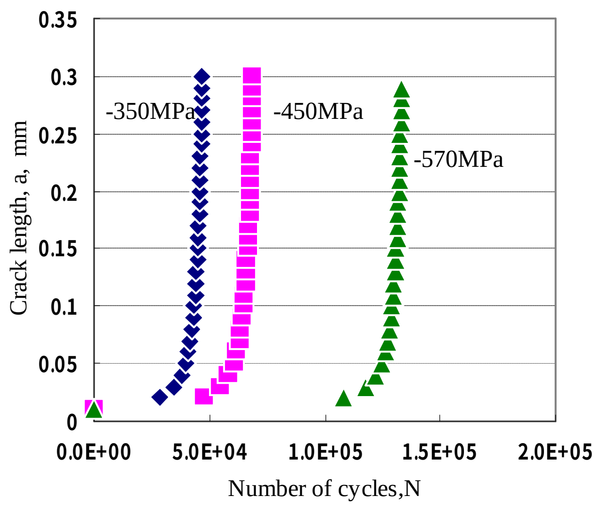

Fig.5 Effect of the values of surface resudial stress on the relation between the propergating crack length and the number of cycles

corresponding to the 0.3mm of length of the crack propagating. Comparing with the relation between the life and the value of surface residual stress, it is well known that the life becomes to be longer as the value of surface residual stress is larger. Comparing the surface residual stress, -570MPa and -350MPa, the fatigue life of -570MPa shows three(3) times larger than -350MPa. Based on this calculated results, it can be well realized that the effect of double shot-peening on improving fatigue strength is mainly due to a higher surface residual stress.

4. Conclusions

Conclusions are summarized as below.

(a) Fatigue limit of cracked material is calculated by using equation (4).

(b) Propagation life of cracked material is decided by the equation (6) and the equation (7).

(c) The relationship between the residual stress distribution by shot peening and fatigue life is also decided by the equation (6), the equation (7), the equation (9) and the equation (10).

(d) The higher value of compressive residual stress in the surface is effective to have the crack propagation life longer. This can correlate with the effect of double shot peening on increasing fatigue strength.

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