The Prediction of Fatigue Strength for Shot-peened Materials by Fracture Mechanics

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Abstract

There are few papers concerning the prediction of fatigue strength for a finite life of shot-peened materials. This reflects the complexity of knowing the effects of the magnitude of dent and compressive residual stress distribution on the fatigue strength of shot-peened materials. In this study the effects of the hardness of material and SP conditions on fatigue strength for finite life are evaluated by rotary bending fatigue tests.　Therewith the prediction of fatigue strength for finite life is analyzed by the fracture mechanics.

Key Words : fatigue, fatigue strength for finite life, shot-peening, prediction of fatigue strength

1. Introductions

In the viewpoint of earth environmental safeguards, it has been becoming important to develop 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 $\Delta K = \alpha \cdot \Delta\sigma\sqrt{\pi \cdot a}$.

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

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).

$$\Delta K(L)_{th,R=R} = (1-R)^{0.71} \times \left(5.514 \times 10^{-5} \times HV^2 - 0.0775 \times HV + 30.335\right) \tag{2}$$

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

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.

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

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

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

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).

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

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

$$C=2.018\times10^{-14}\times1.195^{-6.86\times10^{-5}HV^2+0.139HV-3.59}$$

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

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.

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

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.

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

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

$$R = \frac{K_{\min} - K_R}{K_{\max} - K_R} \tag{9}$$

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.

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

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 Effectiveness of equation (6) for crack propagation life

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.1 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.

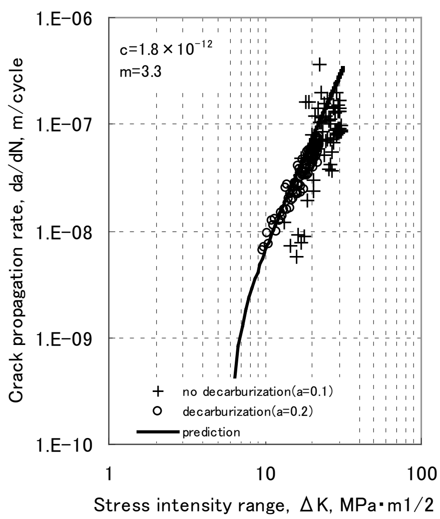

Fig.1 Relationship between crack propagation rate and ΔK, which is the comparison of the calculated values with experimental data

3.2 Fatigue strength of shot-peened material

Comparison between this calculation for crack propagation life of shot-peened material and real fatigue data was carried out. The type of fatigue test was rotary bending fatigue test, R=-1. The shape of specimen was an hourglass with 8mm of diameter. The material was SUP7 0.59%C-1.92%Si-0.81%Mn-0.16%Cr-0.022%P-0.012%S with hardness 416HV, 523HV and 615HV by oil quench and temper treated. Shot peening conditions were below. Shot was conditioned cut wire with 1mm of diameter with hardness 600HV. Shot velocity was 83m/s and arc-hight was 0.818mm(A) and coverage was 300%. Table 1 and Fig. 2 show the results of fatigue test.

Table 1 The results of fatigue test

Hardness	Surface roughness (mm)	Fatigue limit (MPa) at 3000000
416HV	0.062	625
523HV	0.031	750
615HV	0.019	875

The fatigue limit is higher as the hardness is higher. Furthermore in finite life the higher hardness sample indicates higher fatigue strength. Fig.3 shows the results of residual stress distribution due to shot-peening. It seems that the residual stress near the surface is higher as the hardness is higher. And the surface roughness is smaller as the hardness is higher according to Table 1. It can be realized that these phenomena introduces the higher fatigue strength as higher hardness. Fig.4 shows the stress intensity factor distributions due to residual stress distributions for each hardness samples. These calculations are used the equation (10). These value of stress intensity factor are negative. Larger negative value of stress intensity factor is introduced as hardness is higher. As the negative stress intensity factor makes crack close, the this tendency of fatigue strength can be explained.

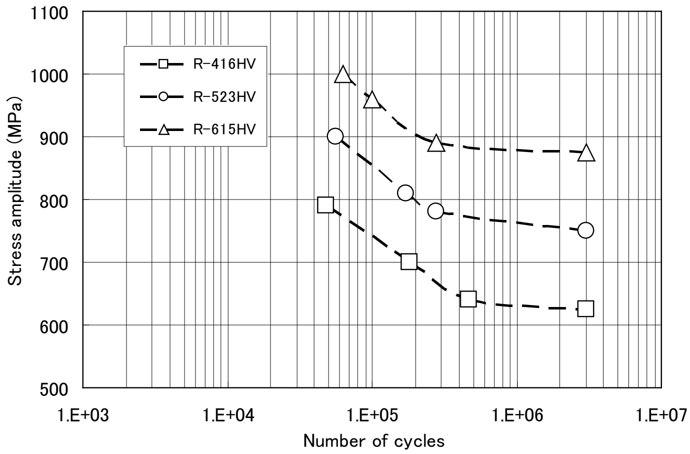

Fig.2 Results of fatigue test

3.2 Prediction for a crack propagation life of shot-peened material

The crack propagation life can be predicted by applying fracture mechanics, equation (7). In this paper, the crack propagation life of fatigue data of the Fig.2 was predicted by using conditions; the hardness, the applied stress ratio, the residual stress distribution and the initial crack size. Where, the hardness is used from Table 1. The applied stress ratio is -1. The residual stress distributions are indicated in Fig.3. But the initial crack sizes

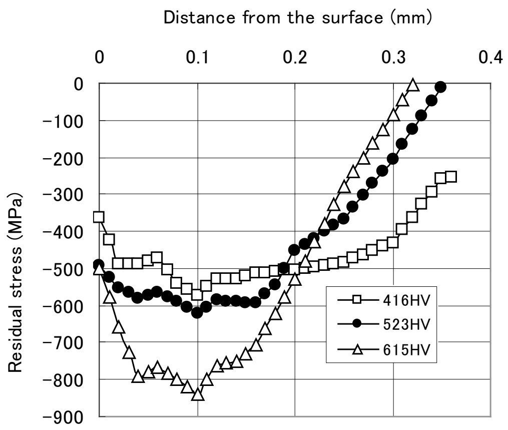

Fig. 3 Residual stress distribution for 418HV, 523HV and 615HV

are not known in the case of shot-peened smooth materials. Therefore, as the initial crack size, the maximum surface roughness (a) in Table 1 was applied. Moreover while the shape of crack has to be decided, the half of surface crack length (c) was assumed as (c) = 3.3x(a). Since the maximum surface roughness is introduced from dent by shot-impact. This assumption had been adopted in reference [6]. Besides the assumption is applied that this relation (c)=3.3X(a) is kept while the crack is propagating. Fig.5 and Fig.6 show the comparison between the predicted crack propagation life and the real S-N curve from Fig.2. In the fatigue limit it can be seem that the difference between the predicted value and the real one is small in each hardness data. On the other hand, it can be seem that the predicted crack propagation life of the finite life range is shorter than the real life. In general a finite life consists a sum of a crack generation life and a crack propagation life. Therefore it can be explained that the predicted crack propagation life is shorter than the real life in Fig.5.

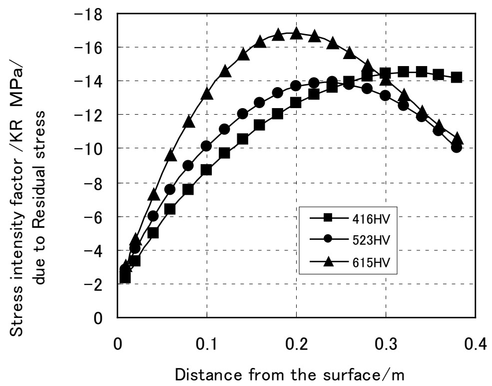

Fig. 4 Stress intensity factor distribution due to residual stress for 416Hv, 523HV and 615HV

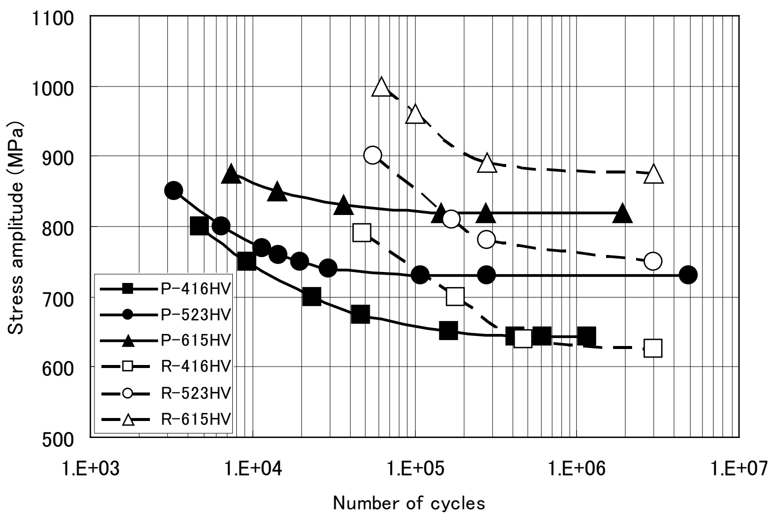

Fig.5 Comparison between real faitigue data and predicted data

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).

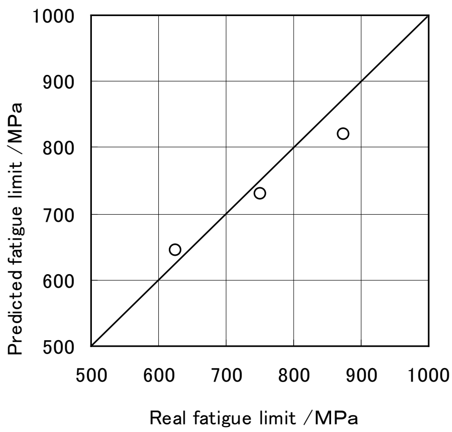

Fig.6 Comparison between predicted fatigue limit and real fatigue limit

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