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ESTIMATION OF HIGH CYCLE FATIGUE LIMIT OF HARD SHOT PEENED AUSTENITIC STAINLESS STEEL

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ABSTRACT

It have been clear that Hard shot-peening (HSP) treatment is very successful for the improvement of the high cycle fatigue strength of austenitic stainless steel. The cause of the improvement is to give the surface hardening layer and compressive residual stress by the treatment, and also the effect of the change of the fracture type from surface crack origin fracture type to subsurface crack origin type. In this study, the fatigue limit at 10^8 cycles of the HSP treated Type 316L stainless steel was estimated by using the hardness distribution, the HVB (Half Value Breadth) distribution and the residual stress distribution of the specimen. The estimation by using the endurance fatigue limit diagram and the modified Goodman's diagram was not insufficient method, however. But the fatigue limit by the new estimation using the stress intensity factor was fairly good coincident with the experimental value.

KEYWORDS

Hard shot-peening, Residual stress distribution, Hardness distribution, Half value breadth, Stress intensity factor, High cycle fatigue strength, Austenitic stainless steel, Fatigue limit estimation

INTRODUCTION

The surface hardening treatment is a useful method for improving of fatigue properties. And it is also reported by some researchers that how to estimate the fatigue limit of the surface treated materials [1-3]. In generally, the fatigue limit was estimated from the relationship between the applied stress amplitude and the local fatigue limit distribution that was often obtained from fatigue test. However almost methods have been not useful practically because of using the information obtained from the fatigue testing.

One of the estimation methods, the suggestion by Murakami et al.[4],using the shot peened spring steel, is well-known because that it is not necessary for the estimation to have fatigue test. But one of the problems of this Murakami's method is that it needs the assumption in which the position of crack origin is depth range from the surface to 0.4mm [4].

In this study, the estimation method of fatigue limit at 10^8 cycles using the peening effects and fatigue limit diagram was supposed on the hard shot-peening (HSP) treated Type 316L austenitic stainless steel.

MATERIAL AND FATIGUE TEST

The material used in this study was Type 316L austenitic stainless steel, having the chemical compositions (weight %) of: 0.017 C, 0.39 Mn, 0.014 S, 12.17 Ni, 16.31 Cr and 2.06 Mo. The average of the austenitic structure was about 88μm. The shape and dimensions of specimens are shown in Figure 1. After machining, the center of the specimen was shot-peened using ϕ0.6mm steel shot with air pressure of 0.196MPa. The Almen intensity was 0.6mmA (hard shot-peening) and the coverage was 100% over.

Rotating bending fatigue tests at 50Hz under water-cooling condition by deionized water were carried out. The results of the fatigue tests were shown in Figure 2. The fatigue limit of the HSP treated specimen, about 370MPa, was remarkably improved in comparison with fatigue limit of the n.p. specimen, about 200MPa.

ESTIMATION METHOD

The fatigue limit was decided by the relation in the local fatigue limit distribution and the applied stress amplitude slope. If the applied stress amplitude slope intersects the calculated local fatigue limit distribution curve, the specimen will be broken. If these two curves do not intersect each other, the specimen will be not broken. And if these two curves intersect in a point, its applied stress amplitude is the fatigue limit of the surface-hardening specimen.

Calculation of Local Fatigue Limit Curve

In generally, the local fatigue limit σ_{wa} can be calculated from the endurance fatigue limit diagram as Eqn.1-a or the modified Goodman's diagram as Eqn.1-b [5].

Endurance fatigue limit diagram : $\sigma_{wa} = \sigma_w(1 - \sigma_m/\sigma_T)$ [MPa] (1-a)

Modified Goodman's diagram : $\sigma_{wa} = \sigma_w(1 - \sigma_m/\sigma_B)$ [MPa] (1-b)

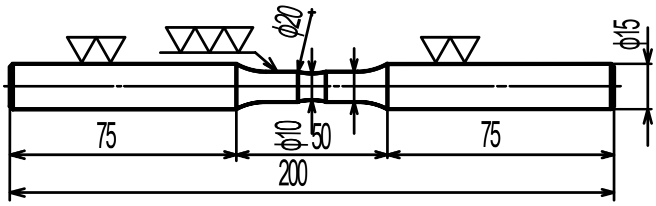

Figure 1: Shape of test specimen (mm)

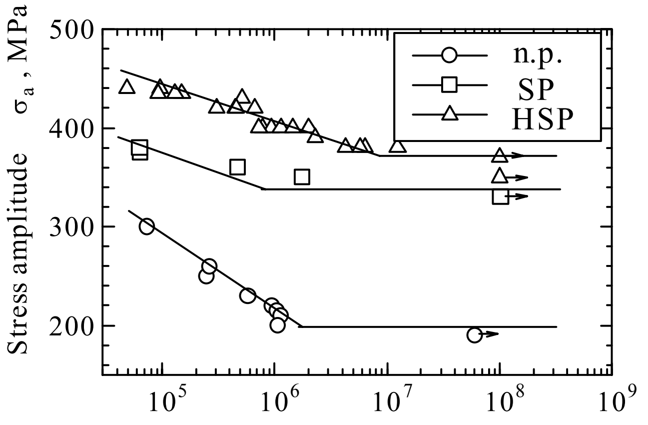

Figure 2: S-N curves under water-cooling condition.

Here, σ_m is the mean stress as the residual stress at the local position, σ_T is the true stress of fracture and σ_B is the tensile strength. The σ_w which is the local fatigue limit for the case of mean stress does not affect, can be calculated from local vickers hardness Hv. Next equation as shown Eqn.2 was supposed on the austenitic stainless steel [6].

$$\sigma_w = 0.16Hv \times 9.81 \qquad \text{[MPa]} \qquad (2)$$

However, an attention is necessary for following fact in the Modified Goodman's diagram. Although the true stress of fracture σ_T is not related to the matrix hardness, but the tensile strength σ_B is depended on the matrix hardness. Namely, the estimation of the fatigue limit by using the modified Goodman's diagram requires investigating of the relation between σ_B and Hv.

Peening Effects Measurements

In order to calculate the local fatigue limit from Eqn.1, the peening effects as the residual stress distribution and the hardness distribution, were measured of HSP treated Type 316L steel. Figure 3 shows the residual stress distribution of the HSP treated specimen using the X-ray diffract meter and the electro-polishing technique. Here, as the residual stress release by the electro-polishing, experimental values must be corrected. The corrected curve is also shown in Figure 3 by the solid line. This corrected curve is assumed as the mean stress.Figure 4 shows the vickers hardness distributions. Because of the scattering of vickers hardness value, the master curves of the hardness was obtained by converting from the half value breadth (HVB) distributions. This hardness master curve is used to calculate the σ_w distribution from Eqn.2.

FATIGUE LIMIT ESTIMATION

Using Endurance Fatigue Limit Diagram

At first, the estimation method of the fatigue limit by using the endurance fatigue limit diagram is shown as the followings.

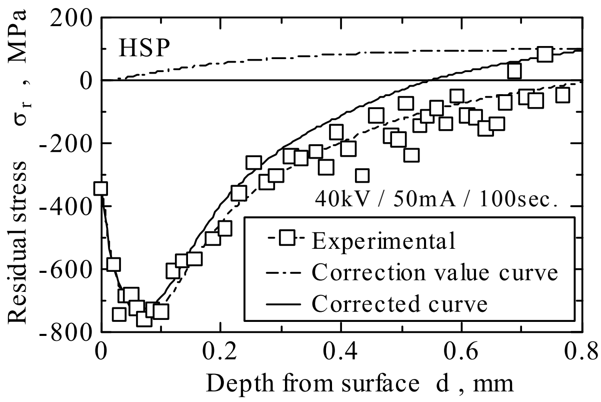

Figure 3: Residual stress distribution of HSP treated specimen

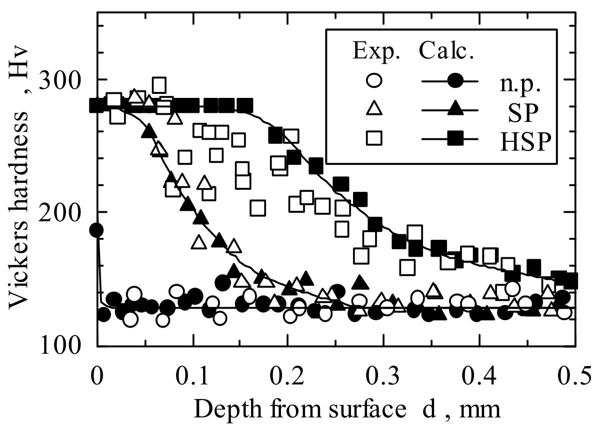

Figure 4: Hardness distribution

Figure 5 shows the local fatigue limit distribution calculated by using Figure 3 and Figure 4. Here, the value of 1811MPa was used at σ_T that obtained by the tensile test and that is not depended on the matrix hardness of Type 316L steel. The fatigue limit is estimated about 225MPa from Figure 5, however, the estimation value is not agreement with the experimental value as 370MPa.

Therefore next, the fatigue limit estimation of the n.p. specimen by using this method was carried out. When this method was applied to the n.p. specimen, the estimation value was obtained as 201MPa. In the n.p. specimen, the estimation value was good agreement with the experimental value of 200MPa.

The reason of disagreement between the estimation value and the experimental value in the HSP-treated specimen is for the assumption in which the threshold condition for the internal crack extension is identical with that of the surface crack. In short, the local fatigue strength that calculated from the fatigue limit diagram and Eqn.2 is assumed as the fatigue limit at internal portion, providing that fatigue limit at surface portion is equivalent to the fatigue limit at internal portion of the specimen.

In this study, the difference in the local fatigue limit between the internal portion of specimen and the surface portion of specimen is investigated by using the equation to calculate the stress intensity factor as a general theory. Figure 6 shows the stress intensity factor model of internal crack type in rotating bending loading [7]. In this case, the stress intensity factor was calculated from Eqn.3 at point B.

$$K_{Iin} = F\left\{\frac{1}{E(a,b)}\cdot\frac{s}{R} - f(a,b)\cdot\left(\frac{b}{R}\right)\right\}\sigma_{in}\sqrt{\pi b}$$

$$= C_{in}(a,b,d,s,R)\cdot\sigma_{in} \qquad [\mathrm{MPa}\sqrt{m}\,] \qquad (3)$$

Here, F(a,b,d,R),E(a,b) and f(a,b) are function on the crack position as “d” and crack size as “a” and “b”.

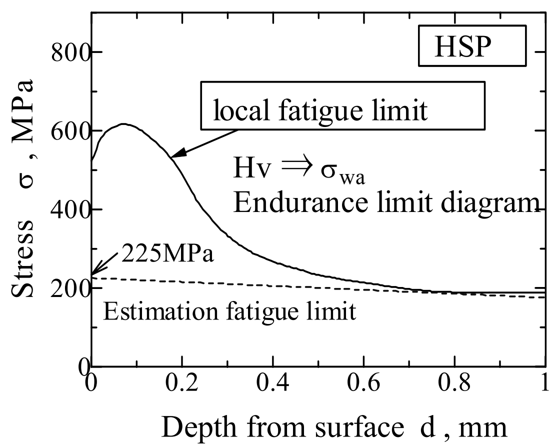

Figure 5: Local fatigue strength distribution inside the HSP treated specimen (using Endurance limit diagram)

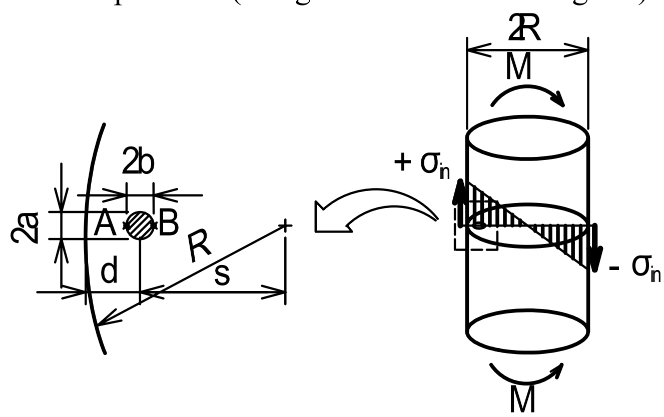

Figure 6: Stress intensity factor model of internal crack

On the other hand, the stress intensity factor of surface crack type was calculated from Eqn.4 [8].

$$K_{Isurf} = 0.65\sigma_{surf}\sqrt{\pi\sqrt{area}}$$
$$= C_{surf}(a,b)\cdot\sigma_{surf} \qquad [\mathrm{MPa}\sqrt{m}] \qquad (4)$$

Here, the "area" is the fatigue crack area which is depended on the half crack length "a" and crack radius "b".

The values of the coefficient *Cin* of Eqn.3 is smaller than *Csurf* of Eqn.4, when the crack radius "a" of Eqn.3 and the one of Eqn.4 are the same, and 2a and 2b are the same also. M. Larsson et al [9] indicated that the fatigue limit of internal crack is explained by using the threshold of the stress intensity factor. In short, fatigue crack propagates when the stress intensity factor at crack tip reaches the threshold of the material. Here, because the threshold stress intensity factor does not vary with location in the specimen, the relationship between σ_{in} and σ_{surf} is indicated as next equation.

$$\sigma_{in} = (Csurf/Cin)\times\sigma_{surf} \qquad (5)$$

There is two consideration points in this Eqn.5. One is that the local fatigue limit inside the specimen is *Csurf/Cin* times as the local fatigue limit at surface. And the other is that the coefficient ratio *Csurf/Cin* depends on the depth of the crack position and the local fatigue limit is dependent on the depth from surface. Figure 7 shows relationship between the coefficient ratio *Csurf/Cin* and the depth from the surface. Estimated local fatigue limit distribution can be modified by this value.

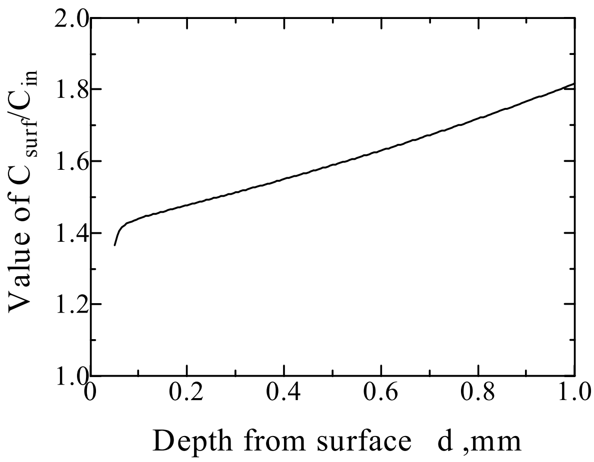

Figure 7: Relationship between coefficient ratio *Csurf/Cin* and depth from surface

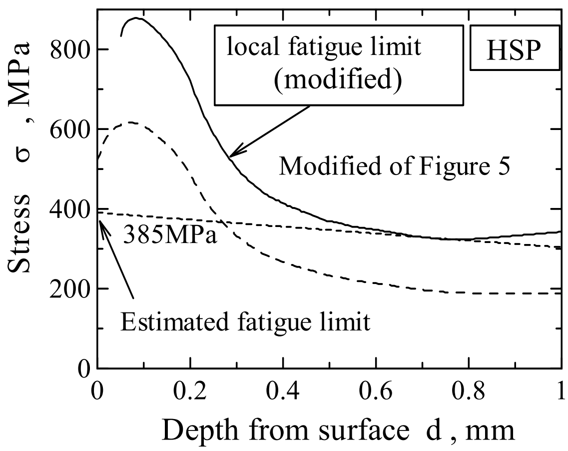

Figure 8: Modified local fatigue strength distribution inside the HSP treated specimen (using Endurance limit diagram)

Figure 8 shows the modified curve that was based on Eqn.5 for Figure 5. The fatigue limit was estimated as 385MPa from Figure 8, and this value agrees well with the experimental value of 370MPa.

In the other materials which authors have used in a series of research as the SP-treated Type 316L, the HSP-treated Type 316 and the HSP treated Type 304 etc., sufficient estimation results were obtained with the accuracy of 10% [10-13].

Using Modified Goodman diagram

In this paragraph, the estimation by using the modified Goodman's diagram as Eqn.1-b is investigated.

Since the tensile strength σ_B is depended on the hardness of matrix, relationship between the hardness and the tensile strength must be investigated of the Type 316L steel if the fatigue limit estimate by using the modified Goodman's diagram. In this study, the tensile test using pre-strain specimen was carried out. As a result, next equation was obtained.

$$\sigma_B = 356 + 1.378Hv \qquad \text{[MPa]} \tag{6}$$

The fatigue limit was estimated by using the Eqn.1-b as modified Goodman's diagram, Eqn.6 and the coefficient ratio *Csurf/Cin* as Eqn.5. As a result of this method, like the estimation using endurance fatigue limit, the fatigue limit of HSP-treated Type 316L was also estimated about 385MPa.

CONCLUSION

In order to estimate the rotating bending fatigue limit of the hard shot peening (HSP) treated Type 316L stainless steel, the method using the fatigue limit diagram, was applied. In this paper, it was clarified that there was the necessity to reconsider on these methods, and the new method to modified using the coefficient of equation to calculate the stress intensity factor was proposed. As a result of the investigation based on this modified method, the fatigue limit of HSP treated specimens was well estimated for the experimental values.

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