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Influence of crack-like surface defects on the fatigue limit of nitrocarburized carbon steel

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Abstract. The aim of this study was to evaluate the influence of surface crack on the bending fatigue limit of nitrocarburized steel. Semicircular slits with depths of 0.040, 0.075, and 0.100 mm were introduced on the surface of nitrocarburized medium carbon steel specimens to simulate the presence of small cracks. Bending fatigue tests were performed at room temperature in air with the stress ratio $R = -1$. It was observed that the fatigue limit decreased as the depth of the slit increased. The acceptable crack size was estimated based on fracture mechanics. The predicted acceptable crack size was consistent with the experimental result. Therefore, the acceptable crack size of nitrocarburized carbon steel could be predicted via analysis based on fracture mechanics.

1. Introduction

A crankshaft is an automobile engine part, and is often subjected to nitrocarburizing treatment to improve its fatigue limit and wear resistance. Nitrocarburizing treatment has an advantage in that deformation after this type of heat-treatment is considerably smaller than that after other heat-treatments, such as carburizing, because the heat-treatment temperature for nitrocarburizing treatment is lower than the transformation temperature of metals. However, when the nitrocarburizing treatment is applied to a long part, such as a crankshaft, deformation tends to exceed the control value. In this case, reworking is performed within the prescribed reworking limit range. However, if the deformation of a part is too large, the part is discarded because surface cracks are induced in the reworking process.

The nitrocarburizing process of steels creates a compound layer consisting mainly of ε-$Fe_{2\text{-}3}N$ on the surface. A diffusion layer is created below the compound layer. Compound layers of nitrocarburized parts are more brittle compared to the base metals. Thus, micro surface cracks tend to initiate in the compound layers if the part is subjected to plastic deformation beyond the reworking limit range. It is well known that, if the size of a surface defect is smaller than that of the critical defects (a_c), the fatigue strength of steels is not reduced by the defect [1,2]. If the value of a_c in nitrocarburized steels is clarified, we can expand the reworking limit range of nitrocarburized parts.

Takahashi *et al* showed that the value of a_c could be increased by the compressive residual stress induced by shot peening [3,4]. The values of a_c depend on the distribution of residual stress. After the nitrocarburizing process, compressive residual stress is introduced near the surface. It is presumed that the value of a_c in nitrocarburized steels depends on the residual stress distribution. However, the effects of compressive residual stress on a_c in nitrocarburized steels have not yet been studied.

The aim of this study was clarifying the effects of surface crack on the fatigue limit of nitrocarburized steel. Plane bending fatigue tests were performed for the nitrocarburized medium carbon steel specimens containing a small semi-circular slit. Furthermore, the value a_c was estimated based on fracture mechanics.

2. Experimental procedure

The test material used in the study was medium carbon steel (JIS-S53C). The chemical composition of JIS-S53C was shown in table 1. Figure 1 shows a flowchart of the preparation of the test specimens. The plates were oil quenched from 1123 K followed by tempering at 873 K. After the heat treatment, the plated were machined into bending fatigue test specimens shown in figure 2(a). The maximum bending stress at the minimum section of the test specimen were evaluated. After machining of the test specimens, nitrocarburizing treatments were carried out. A semicircular slit, as shown in figure 2(b), was introduced perpendicular to the longitudinal direction by electric discharge machining. The depth (a) of the semi-circular slit is 0.040, 0.075, and 0.100 mm. The slit width w is 0.03 mm.

Table 1. Chemical composition of JIS-S53C (wt %).

C	Si	Mn	P	S	Cr
0.54	0.26	0.78	0.019	0.017	0.12

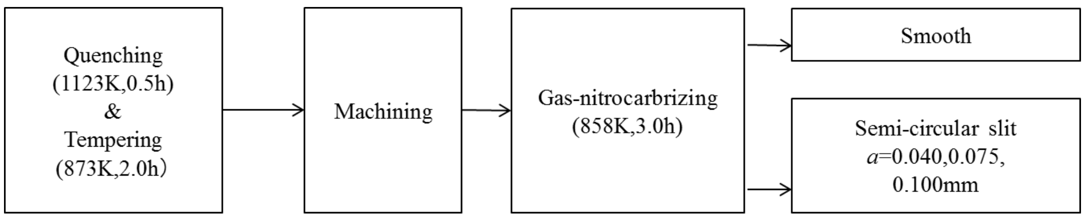

Figure 1. Flowchart of specimen preparation.

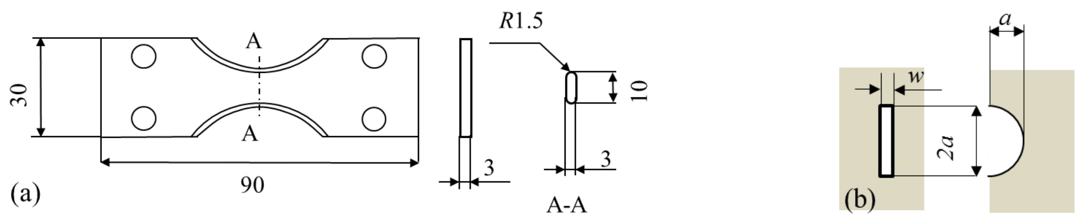

Figure 2. (a) Shape and dimension of a test specimen. (b) Shape of semi-circular slit. (Unit: mm).

The residual stress distributions of the specimen were evaluated using X-ray diffraction. Table 2 lists the conditions of measurement. The X-ray stress constants used were −611 MPa/deg for ε phase and −318 MPa/deg for α-Fe phase [5]. The residual stress distributions of the specimens were evaluated after removing the surface layers by chemically etching.

Table 2. Residual stress measurement condition.

	ε-Fe_3N	α-Fe
Characteristic X-ray	Cr-Kα	
Diffraction plane	211	103
Diffraction angle (deg)	156.4	134-137
Diameter of incident collomator (mm)	1.0	
Tube current (kV)	30	
Tube current (mA)	30	

The surface hardness at the compound layer and hardness distribution at the diffusion layer were measured by using a micro Vickers hardness tester with a holding time of 10 s and at an indenter load of 0.24 N and 0.98 N, respectively.

Plane bending fatigue test were performed by using a bending fatigue test machine. The conditions of fatigue test included a stress ratio $R = -1$ and a cyclic frequency of 25 Hz. After the fatigue tests, the fractured surfaces were observed by using a stereoscopic microscope and scanning electron microscope (SEM).

3. Experimental results

3.1. Vickers hardness and residual stress

The microstructure of the cross-section of the test specimens is shown in figure 3. A compound layer with a depth of approximately 0.033 mm was observed, and a porous layer of approximately 0.015 mm was formed on the outermost surface of the compound layer. Figure 4 shows the distributions of Vickers hardness. The hardness was measured at the center of the gauge section where the gauge width was 10 mm. The hardness of the compound layer was 724 HV, the maximum hardness of the diffusion layer was 374 HV (0.050 mm from the surface), and the depth of the diffusion layer from the surface of the specimen was 0.8 mm.

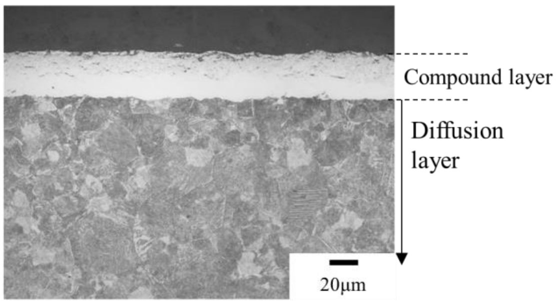

Figure 3. Microstructure of the test specimen.

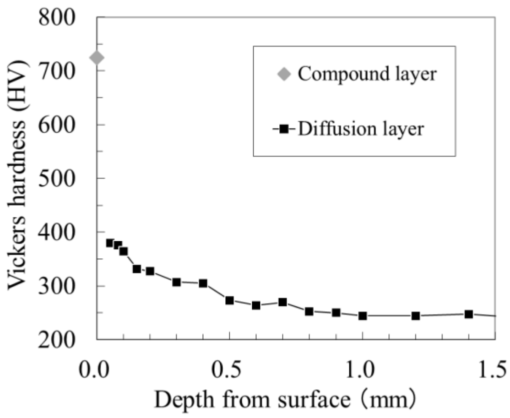

Figure 4. Vickers hardness of the compound and diffusion layers.

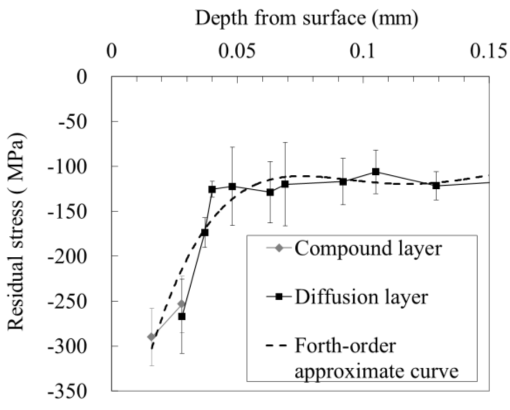

Figure 5. Residual stress distributions and fourth-order polynomial fitting curve.

Figure 5 shows the measurement results of the residual stress distribution. The residual stress at the porous layer was not measured owing to difficulty of measurement. The maximum compressive residual stress of 300 MPa was measured at the compound layer. However, the compressive residual stress sharply decreased at the interface between the compound layer and diffusion layer at the depth of 0.03–0.04 mm. The compressive residual stress gradually decreased at a depth greater than 0.05 mm.

3.2. Fatigue test results and observation of fracture surface

Figure 6 shows the *S–N* curves. Figure 7 shows the relationship between the stress amplitude and the semi-circular slit depth. The open and solid symbols indicate the fractured and non-fractured specimens under 10^7 cycles, respectively. The maximum stress amplitude in the non-fractured specimen corresponds to the fatigue limit. The results prove that the fatigue limit of the specimens decreased with an increase in slit depth.

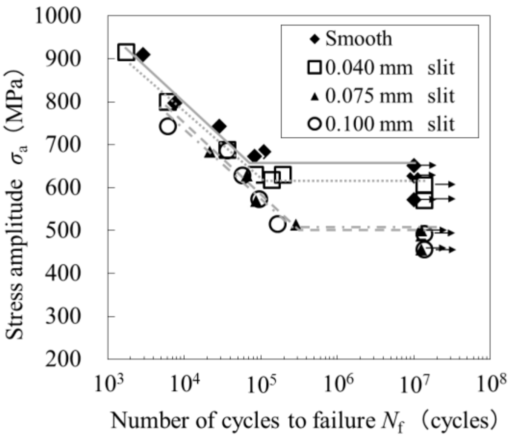

Figure 6. *S–N* curves.

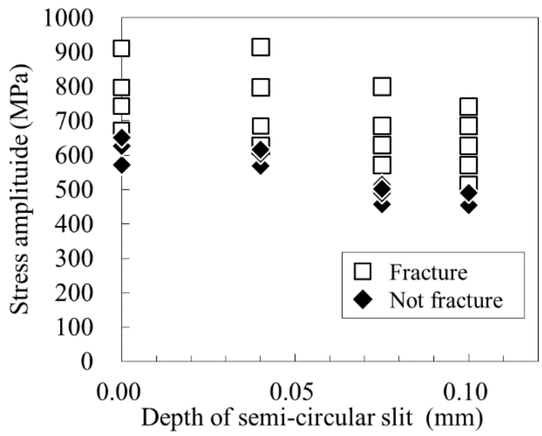

Figure 7. Stress amplitude as a function of depth of semi-circle slit.

Figure 8 shows the typical fracture surface of the specimen with a semi-circular slit. All the test specimens with a semi-circular slit fractured from the slit. From the results of the fatigue test and fracture surface observation, it was observed that a_c of this material is smaller than a = 0.04 mm.

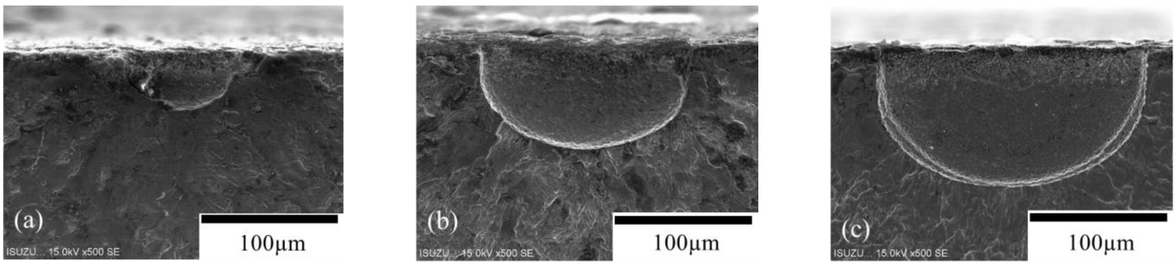

Figure 8. Typical fracture surface of specimen with a semi-circular slit. (a) a = 0.040 mm, N_f = 141800; (b) a = 0.075 mm, N_f = 88200; (c) a = 0.100 mm, N_f = 96900.

3.3. Evaluation of crack size which does not affect the fatigue limit

To expand the limit range for reworking, it is necessary to clarify the micro crack size which does not affect the fatigue limit (a_c). The values of a_c were evaluated based on fracture mechanics by assuming that the semicircular slit is equivalent to a semicircular crack. We used the following equation in order to evaluate the effective stress intensity factor range (ΔK_T) [6].

$$\Delta K_T = K_{max} + K_r \quad (1)$$

where K_{max} is defined as the stress intensity factor under maximum applied stress σ_{max}. To determine the values of K_{max}, σ_{max} = 662 MPa corresponding to the fatigue limit of the smooth specimens was substituted into the equation proposed by Newman and Raju [7]. K_r is the stress intensity factor owing to residual stress, which is a negative value in the compressive residual stress field. The equations of the American Petroleum Institute Recommended Practice (API RP 579) were used to determine the value of K_r for the surface cracks [8]. The K_r for a semielliptical crack is indicated as follows.

$$K_r = [G_0\sigma_0 + G_1\sigma_1\left(\frac{a}{t}\right) + G_2\sigma_2\left(\frac{a}{t}\right)^2 + G_3\sigma_3\left(\frac{a}{t}\right)^3 + G_4\sigma_4\left(\frac{a}{t}\right)^4]\sqrt{\frac{\pi a}{Q}}f_{\mathrm{w}} \quad (2)$$

$$Q = 1 + 1.464(\frac{a}{c})^{1.65} \quad (3)$$

$$f_{\mathrm{w}} = \left[sec\left(\frac{\pi c}{2W}\right)\sqrt{\frac{a}{t}}\right]^{\frac{1}{2}} \quad (4)$$

In the above equation, G_0 to G_4 represent the influence coefficients for a semielliptical crack according to API RP 579. a and c indicate the depth and half-length of the semielliptical surface crack, respectively. t and W are the thickness and width of the specimens, respectively. The coefficients, σ_0 to σ_4, are obtained using the fourth-order polynomial fitting curve of the residual stress distribution by using the following equation (see figure 5):

$$\sigma(x) = \sigma_0 + \sigma_1\left(\frac{x}{t}\right) + \sigma_2\left(\frac{x}{t}\right)^2 + \sigma_3\left(\frac{x}{t}\right)^3 + \sigma_4\left(\frac{x}{t}\right)^4 \quad (5)$$

where x indicates the distance from the specimen surface in the depth direction.

Figure 9 shows ΔK_T, K_r, K_{max}, and the effective threshold stress intensity factor range ($\Delta K_{eff,th}$) as a function of the crack depth (a). The value of the stress intensity factor depends on the position of the crack front. The values of ΔK_T are the highest at the deepest point of the crack. Thus, the values of ΔK_T at the deepest point are plotted in figure 9. It is reported that the value of $\Delta K_{eff,th}$ for steel is 3.0 MPa·m$^{1/2}$[9]. Thus, it is presumed that $\Delta K_{eff,th}$ is 3.0 MPa·m$^{1/2}$ in this study.

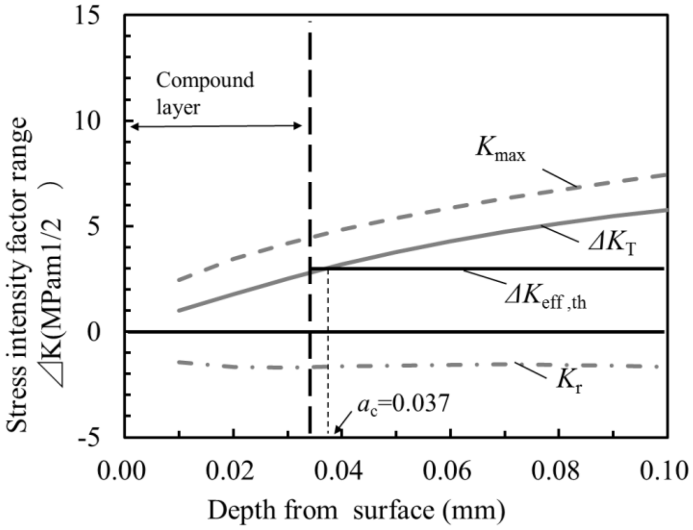

Figure 9. Estimation of acceptable defect size.

The surface slit is considered to be harmless if ΔK_T is less than $\Delta K_{eff,th}$. Thus, the intersection between ΔK_T and $\Delta K_{eff,th}$ yields a_c. The value of a_c is estimated to be 0.037 mm. The value of a_c is consistent with the experimental result, which indicated that its value is less than a = 0.04 mm.

As shown in figure 5, the compressive residual stresses at the compound layer were much higher than that those at the diffusion layer. Thus, surface cracks that were less in dimension compared to the depth of the compound layer were acceptable in the nitrocarburized specimen used in this study. To

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increase the value of a_c, it is effective to increase the value of the compressive residual stress or deepen the regions with high compressive residual stress.

4. Conclusion

The objective of the present study was clarifying the effect of the surface crack on the fatigue limit of nitrocarburized steel. Plane bending fatigue tests were performed using the test specimens of nitrocarburized medium carbon steel containing a small semicircular slit. Furthermore, the value of the maximum acceptable crack size (a_c) was predicted based on the theory of fracture mechanics. Following conclusions were obtained:

- The results of the fatigue test and fracture surface observation indicated that a_c of this material is smaller than a = 0.04 mm.
- The value of a_c estimated based on fracture mechanics was determined to be 0.037 mm, which was consistent with the experimental result.
- In order to increase the value of a_c, it is effective to increase the value of the compressive residual stress or deepen the regions with high compressive residual stress.

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