Notch Effect on Torsional Fatigue of Austenitic Stainless Steel

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ABSTRACT. *For torsinal fatigue of austenitic stainless steel, the lifetime of circumferentially notched specimens is longer than that of smooth specimen in pure torsion, while the shorter lifetime results from addition of static tension. The cyclic stress-strain response and crack growth behavior at the notch root were investigated to clarify the cause of such unusual notch effect. For pure torsion, rubbing between factory-roof type fracture surfaces delays the crack growth at the notch root and thus results in longer fatigue life in notched specimen. For cyclic torsion with static tension, macroscopically flat crack path and mean tensile stress acting on the crack faces reduce the influence of the crack face contact. Furthermore, the crack growth is promoted by higher strain concentration at the notch root and thus the trend of shorter lifetime in notched specimen results from addition of static tension.*

INTRODUCTION

Many engineering components often experience multiaxial cyclic loadings and contain various kinds of stress concentrations such as notches, fillets and holes. The local elastic-plastic stresses and strains around the stress riser frequently in multiaxial situations due to their geometrical shape, even under uniaxial loading. It has been observed that fatigue failure of the components usually occur as a result of crack initiation and growth from these stress risers. Therefore, accurate estimation of the complicated stresses and strains in the critical region is significant for practical machine design in service loading.

Authors investigated notch effect on torsional fatigue of austenitic stainless steel SUS316NG [1]. As a result, it was shown that the circumferentially notched specimens have longer fatigue life than smooth specimen under cyclic torsion but have shorter lifetime under cyclic torsion with static tension. Such unusual notch effect was not observed in tortional fatigue of low carbon steel SGV410 [1]. The notch effect in stainless steel may be due to the variations of elastic-plastic cyclic stress-strain response and crack growth behavior around the notch root with addition of static loading.

In this study, fatigue tests under cyclic torsion with and without static tension were conducted on circumferential notched specimens of austenitic stainless steel similar to aforementioned SUS316NG. Measurement of strain concentration and observation of crack development were performed at the notch root. Based on the experimental results, the cause of the anomalous notch effect in austenitic stainless steel was investigated. Besides, crack observation was made on notched specimen of low carbon steel SGV410 having a banded ferrite / pearlite microstructure and investigated influence of the microstructure on crack growth around the notch root.

MATERIAL AND EXPERIMENTAL PROCEDURE

The material used was austenitic stainless steel SUS316L. Chemical composition and mechanical properties of the material are given in Tables 1 and 2, respectively. As shown in the tables, these resemble those of SUS316NG employed in previous fatigue life test.

Configurations of specimens are shown in Fig. 1. Thin-walled hollow smooth specimen, A was used to obtain a fundamental cyclic stress-strain relation of the materials. Solid specimen, B with both smooth and semi-circular circumferentially notched test sections was employed to measure elastic-plastic strain concentration at the notch root. Development of fatigue cracks was observed with solid smooth specimen, C and solid semi-circular circumferentially notched specimen, D. Elastic stress concentration factors at the notch root calculated by finite element analysis are K_{zz} =1.500 in tension and $K_{\theta z}$ =1.130 in torsion.

Load-controlled fatigue tests were carried out using a servohydraulic tension-torsion machine under fully-reversed cyclic torsion with and without static tension. Cyclic stress-strain response was measured by rosette gages pasted on the test sections, employing both an incremental step method and comparison specimens method.

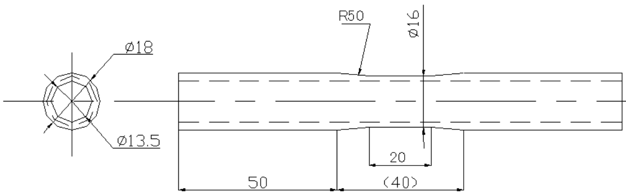
A replication technique was employed to monitor the distribution of microcracks and crack growth at the notch root. Macroscopic crack path and fracture surface were directly observed. Furthermore, cracking behavior was also observed for the low carbon steel SGV410 and was compared with those of the stainless steel.

Table 1. Chemical composition.

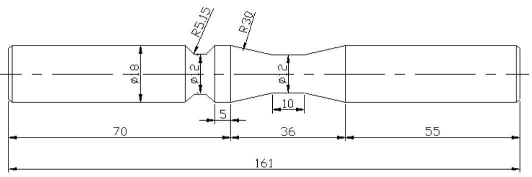
Material	Chemical composition (wt.%)									
	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	N
SUS316L	0.009	0.73	1.26	0.022	0.001	—	12.13	17.59	2.09	—
SUS316NG	0.012	0.43	1.41	0.023	0.0003	0.32	11.53	17.53	2.19	0.10

Table 2. Mechanical properties.

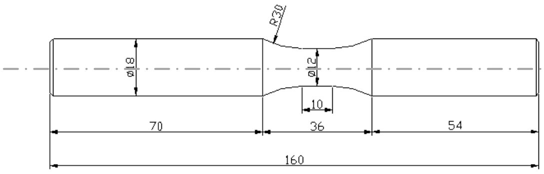
Material	Tensile properties			
	Tensile strength (MPa)	Yield stress (MPa)	Elongation (%)	Contraction of area (%)
SUS316L	564	256	64	—
SUS316NG	591	260	53	83



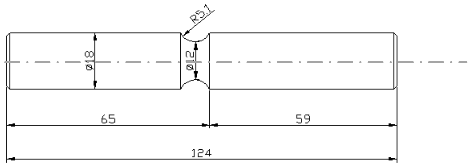
(a) Smooth hollow specimen, A



(b) Smooth and notched solid specimen, B



(c) Smooth solid specimen, C



(d) Notched solid specimen, D

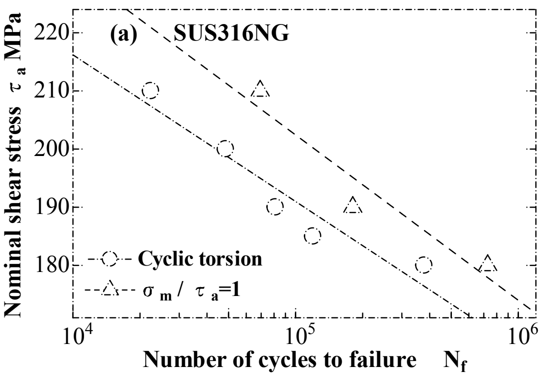
Figure 1. Configuration of specimens.

EXPERIMENTAL RESULT AND DISCUSSION

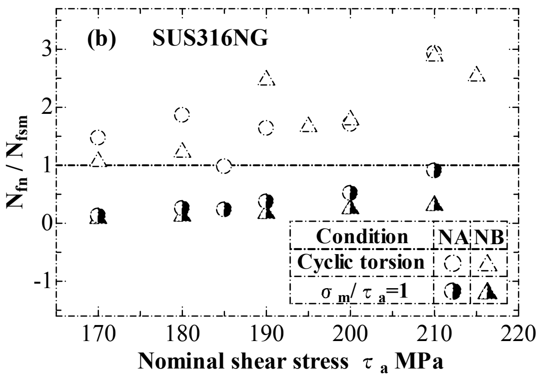
Torsional Fatigue Life with and without Static Tension

Fig. 2 shows the past fatigue test results on SUS316NG under cyclic torsion with and without static tension keeping the nominal tensile / torsion stress ratio σ_m / τ_a =1. As shown in Fig. 2(a), the torsional fatigue life of smooth specimen increased with application of static tension. In Fig. 2(b), the ratio of the lifetime between notched and smooth specimens N_{fn} / N_{fsm} is plotted against the applied nominal shear stress. The symbols NA and NB in the figure denote the circumferentially notched specimens having torsional stress concentration factors of 1.130 and 1.500, respectively. As shown in the figure, the trend of notch effect is markedly different depending on the loading conditions. Namely, the lifetime of notched specimens is longer than that of smooth specimen in pure torsion, while the shorter lifetime resulted from addition of static tension.

It has been reported that the trend of notch effect in the stainless steel SUS316L employed for the present study is almost the same as those of SUS316NG [2].



(a) Effect of static tension on fatigue life of smooth specimen.



(b) Notch effect on fatigue life.

Figure 2. Fatigue test results of SUS316NG.

Strain Concentration at Notch Root

Cyclic stress-strain response in smooth specimen

Fig. 3 shows cyclic shear stress-plastic strain response which was measured using thin-walled hollow smooth specimen, A of SUS316L under various condition of static tension. Hardening due to addition of tension is noticeable and the plastic shear strain reduces with increasing tensile stress σ_m. The longer lifetime of smooth specimen for cyclic torsion with static tension (Fig. 2(a)), regardless of contribution of mean tensile stress, is attributed to the reduction of cyclic strain with application of tension.

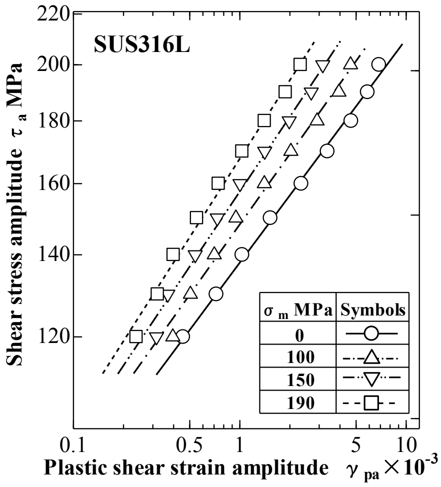
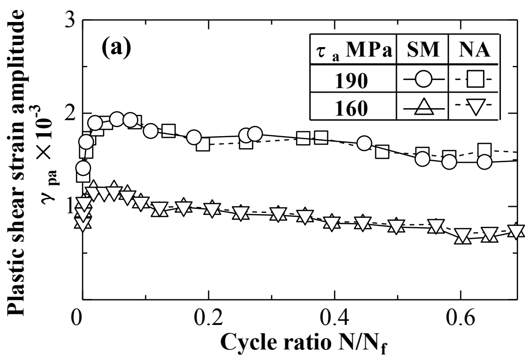


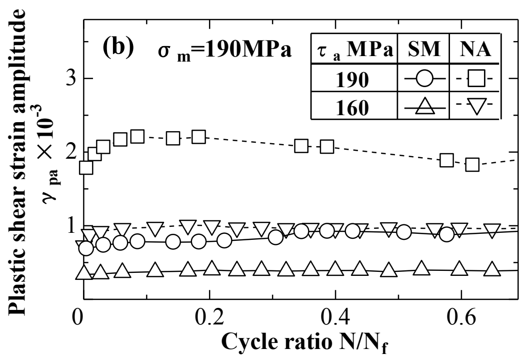
Figure 3. Cyclic shear stress-strain relation in smooth hollow specimen.

Strain concentration in notched specimen

Fig. 4(a) shows variation of plastic shear strain under cyclic torsion for specimen, B with both smooth and notched test sections. After initial softening, both test sections continue to harden with number of cycles. A slightly higher strain at the notch root is consistent with small stress concentration factor in cyclic torsion. However, the difference of strain between the test sections is remarkable for cyclic torsion with static tension σ_m=190MPa shown in Fig. 4(b). Therefore, the strain concentration at the notch root differs noticeably whether static tension is superposed on cyclic torsion or not.



(a) Cyclic torsion.



(b) Cyclic torsion with static tension.

Figure 4. Variation of plastic shear strain with number of cycles.

Crack Initiation and Growth around Notch Root

Fig. 5 shows crack growth around the notch root of circumferentially notched specimen, D under cyclic torsion. Distribution of microcrack at cycle ratio $N/N_f \fallingdotseq 0.3$ and cracks at $N/N_f \fallingdotseq 0.7$ are shown in Fig. 5(a) and Fig. 5(b), respectively. Fig. 5(c) is photographs of the macroscopic failure crack and fracture surface. As can be seen from Fig. 5(a), the microcracks concentrate around circumferential direction (θ=0°) and axial direction (90°) of the specimen and thus crack growth in shear mode is dominant in early stage of the life. The cracks then propagated on the maximum tensile stress planes accompanying the branching and linking of shear cracks. Finally, zigzagged macroscopic failure crack with factory-roof type fracture surface was formed from coalescence of these cracks.

Crack growth behavior under cyclic torsion with static tension is also shown in Fig. 6. The microcracks initiated around the maximum shear stress directions but the percentage of the cracks in the circumferential direction increased than in pure torsion. The cracks grew along the notch root circumference without changing the direction. Thereafter, final failure crack having a macroscopically flat fracture surface was formed by coalescence of these cracks. Accordingly, it was observed that the crack growth at notch root in cyclic torsion was strongly affected by superposition of static tension.

Notch Effect on Torsional Fatigue Life

The crack observation demonstrated the formation of serrated factory-roof type fracture surface in notched specimen under pure torsion. In such situation, crack growth along the notch root may be affected by the crack face contact. The crack development under cyclic torsion with and without static tension was also investigated on the present material employing direct-current electrical potential method [3]. The researchers found that the crack growth in notched specimen was slower than those in smooth specimen under pure torsion. The retardation in crack growth of notched specimen was explained by influence of zigzagged crack face contact. For the present notched specimen with

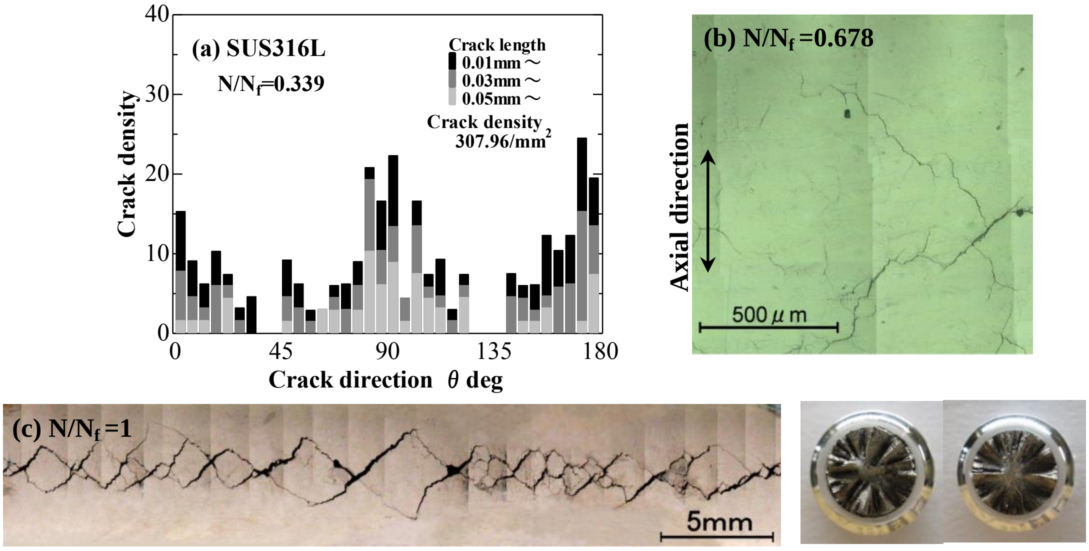


Figure 5. Crack growth under cyclic torsion (τ_a=190MPa).

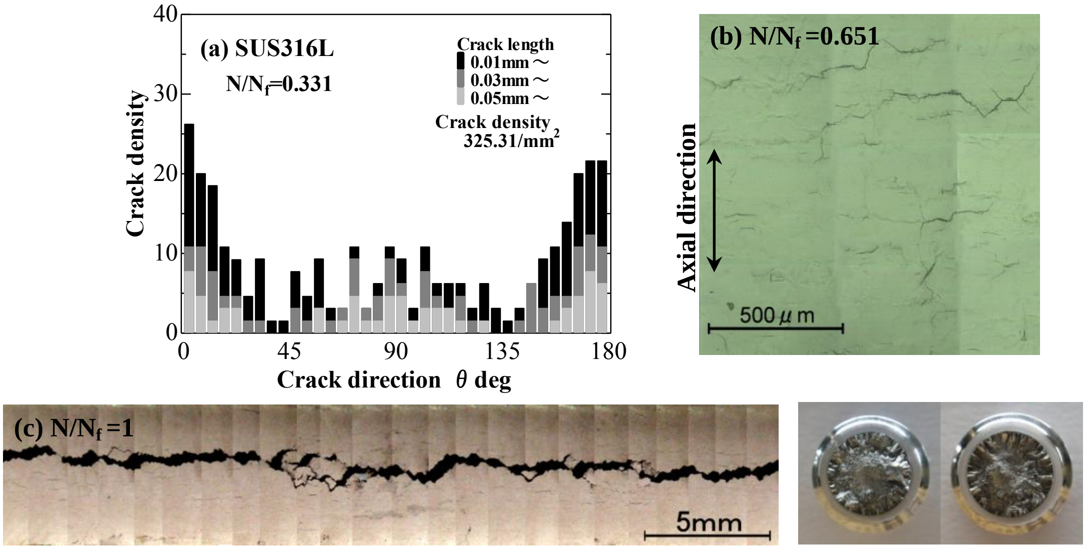


Figure 6. Crack growth under cyclic torsion with static tension (τ_a=σ_m=190MPa).

slight strain concentration, prevention of the crack growth due to rubbing between the crack faces appeared to result in a notch-strengthening effect, namely, the longer lifetime of the notched specimen than that of smooth specimen under pure torsion.

For cyclic torsion with static tension, relatively flat fracture surface and mean tensile stress can reduce the influence of crack face contact [4]. In addition, the higher strain concentration at the notch root promotes the crack growth. Therefore, addition of static tension gives rise to the trend of notch-weakening effect on torsional fatigue life.

Effect of Microstructure on Cracking of Notched Specimen

Effect of microstructure on crack growth at the notch root was studied using circumferentially notched specimen of low carbon steel SGV410. The material has ferrite / pearlite banded microstructure and the interval of the bands varies continuously along the circumferential direction of the specimen. Crack growth behavior at the notch root in pure torsion (cyclic stress τ_a=160MPa and fatigue life N_f =4.28×10^5) is shown bellow. Fig. 7(a) shows the region with a wide band interval denoted by Location A and the distribution of microcracks around here at cycle ratio N/N_f ≒0.3 is shown in Fig. 7(b). The cracks initiated in the vicinity of circumferential and axial directions and then grew macroscopically in the circumferential direction as shown in Fig. 7(c). Fig. 8 also shows crack growth in the region with a narrow ferrite/pearlite band interval, denoted by Location B (Fig. 8(a)). Although the microcracks initiated around both maximum shear stress directions (Fig. 8(b)), the crack propagated mainly in the axial direction because of the microstructural barrier of pearlite bands lined along axial direction (Fig. 8(c)).

Fig. 9 shows macroscopic failure crack developed along the notch root. Around Location A with wide band interval, the crack propagated circumferentially consistent with Fig. 7(c) and formed the failure crack with comparatively flat surface. On the other hand, in Location B with narrow band interval, a turtle shell-like serrated crack was formed by linking after shear mode growth in the axial direction (Fig. 8(c)). Thus, the cracking at the notch root was highly affected by the banded microstructure. The notch-weakening effect in SGV410 was revealed in pure torsion as well as in cyclic torsion with static tension [5], which appears to suggest that influence of the crack face rubbing may be not so serious as in a factory-roof type fracture surface.

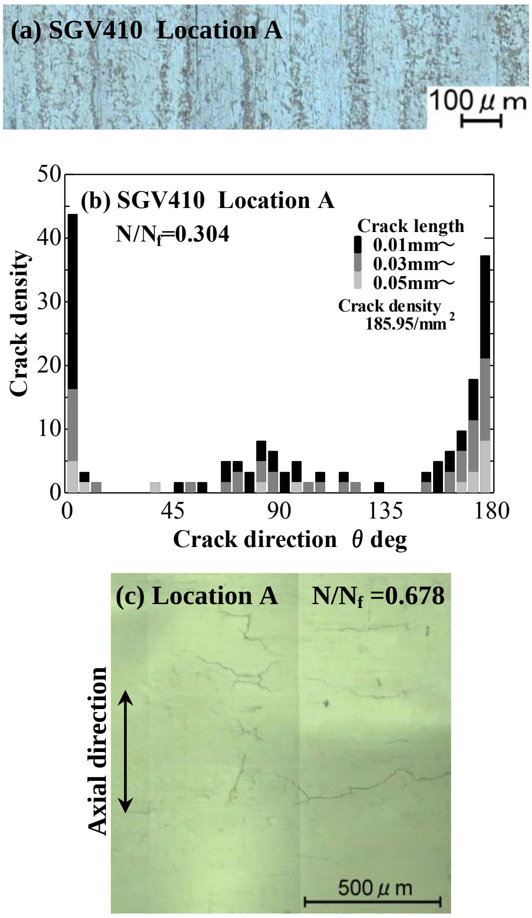


Figure 7. Crack growth in the region with wide ferrite / pearlite band interval (location A) under cyclic tor ion.

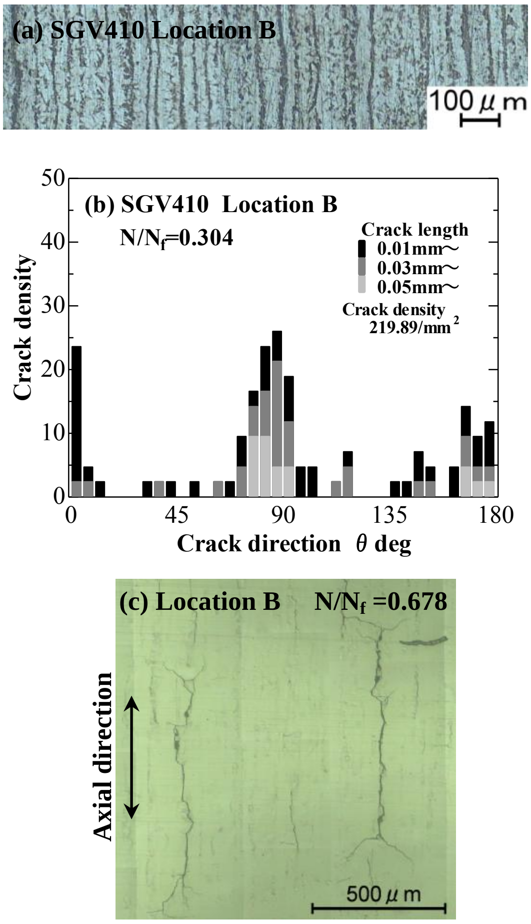


Figure 8. Crack growth in the reagion with narrow ferrite / pearlite band interval (location B) under cyclic torsion.

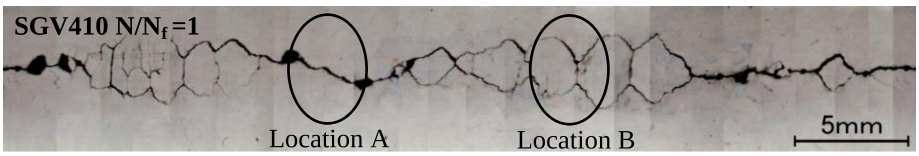


Figure 9. Macroscopic failure crack at locations A and B under cyclic torsion.

CONCLUSIONS

The different notch effects, namely notch-strengthning in pure torsion and notch-weakening in cyclic torsion with static tension were revealed for austenitic stainless steel. From the measurement of stress-strain response and the observation of crack growth behavior at the notch root, the followings were resulted.

For pure torsion, effect of the strain concentration is not so significant but the rubbing of a serrated factory-roof type crack faces delays the crack growth along the notch root. Therefore, the notched specimen has longer lifetime than smooth specimen. For cyclic torsion with static tension, macroscopically flat crack path and mean tensile stress reduce the rubbing between the crack faces. The crack growth is promoted by higher strain concentration at the notch root and thus shorter lifetime of notched specimen, so-called notch-weakening, results from addition of static tension.

Furthermore, the crack observation in low carbon steel showed that the crack growth at the notch root in cyclic torsion was highly affected by microstructure of the material.

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