# Effect of combined static loadings on torsional fatigue of carbon steel specimens with circumferential notches

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**ABSTRACT.** *Fatigue tests were performed on smooth and circumferential notched specimens of medium carbon steel under cyclic torsion with static combined tension-torsion loading. The banded microstructure has significant effect on the crack growth in early stage of life. The crack growth after transition of the growth mode was highly affected by condition of static loads. Influence of static load on the fatigue life was different depending on the combination of static loadings. The greater the ratio of static tension component, the shorter was the fatigue life irrespective of the specimen shape. The shortest lifetime for application of static tension results from action of mean tensile stress and easy crack coalescence on macroscopically flat crack plane along the circumferential direction.*

## INTRODUCTION

Many engineering components often contain variety of stress concentration and are often subjected to various combinations of cyclic and static loadings in service. Since cyclic torsion is a typical loading mode in power transmitted shafts, influences of stress concentration and static loading on the torsional fatigue have been studied by many researchers for the practical importance in machine design [1-3].

Authors investigated the fatigue strength under cyclic torsion with and without static tension, using circumferentially notched specimens of austenitic stainless steel and low carbon steel [4]. For the low carbon steel, it was shown that the crack growth and fatigue strength were highly affected by the microstructure in addition to the mechanical condition such as addition of static tension. Accordingly, for application of general static combined loadings, the notch and mean stress effects on the lifetime of carbon steel can change due to interactions of static combined loading and the microstructure.

In the present study, fatigue tests were conducted on smooth and circumferential notched specimens of carbon steel under cyclic torsion with and without static combined tension-torsion loading. The crack initiation and crack growth behavior were observed in details. Based on the experimental results, the influence of combined static loadings on torsional fatigue in notched specimens was investigated from both mechanical and microstructural viewpoint.

## MATERIAL AND EXPERIMENTAL PROCEDURE

The material used was a structural medium carbon steel, JIS S45C with ferrite/ pearlite banded microstructure, whose composition consists of (wt%) 0.45 C, 0.18 Si, 0.67 Mn, 0.03 P, 0.01 S, 0.06 Cu, 0.05 Ni, 0.12Cr. Mechanical properties of the material are 591MPa tensile strength, 371MPa yield tensile stress, 30.5% elongation 50.1% contraction of area, 663MPa torsional strength, 243MPa yield torsional stress, and micro-vickers hardness of 184 HV. Smooth specimen (SM), Semi-circular (NA) and V-shaped (NB) circumferentially notched solid specimens were machined. The elastic stress concentration factors $K_t$ for specimen NA are 1.130 in torsion and 1.500 in tension. Specimen NB has $K_t$ of 1.500 in torsion and 2.514 in tension. After the machining, the specimens were annealed at 850℃ for 1 hour in vacuum.

Fatigue tests were performed at room temperature under load-controlled conditions, using a servohydraulic tension-torsion machine. Fully-reversed torsional stresses 170-220MPa were applied with and without superimposed static loadings. Condition of static loadings are shown in Table 1. $\lambda$ denotes principal stress ratio in combined static loadings. In static tension, applied stresses $\sigma_m$ were 100 or 180MPa. For other static loading conditions, combination of static tension $\sigma_m$ and torsion $\tau_m$ was imposed so as to be the static equivalent stress $\sigma_{eqm} = \sqrt{\sigma_m^2 + 3\tau_m^2} = 180MPa$. A replication technique was employed to monitor the distribution of microcracks and development of the dominant crack.

Table 1. Condition of static loadings.

| Static loadings | $\lambda = \sigma_2 / \sigma_1$ | $\tau_m$ (MPa) | $\sigma_m$ (MPa) |
|---|---|---|---|
| Tension | 0 | 0 | 100, 180 |
| Combined tension-torsion | -0.2 | 73 | 127 |
|  | -0.5 | 96 | 69 |
| Tosrion | -1 | 103 | 0 |

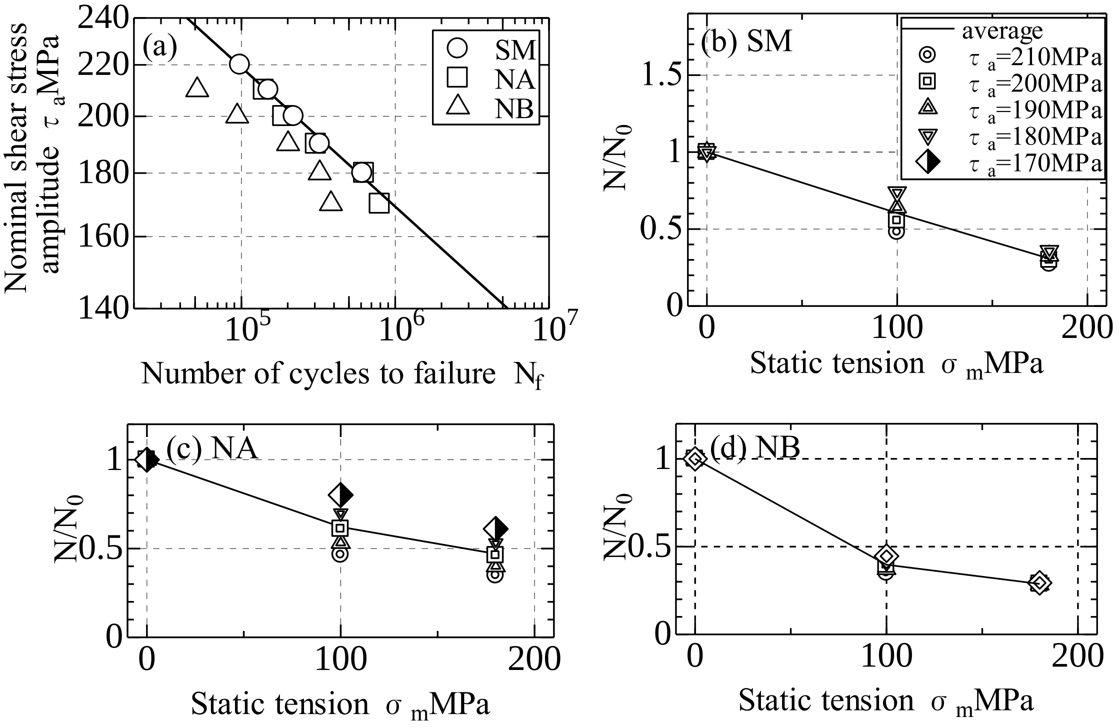

Figure 1. (a) Notch effect on fatigue life in pure torsion, (b)-(d) effect of static tension on fatigue life.

## RESULTS AND DISCUSSION

### *Notch effect in pure torsion*

Figure 1 (a) illustrates the notch effect in pure torsion. As can be seen in the figure, reduction of fatigue life was not so significant for semi-circular notched specimen NA. In sharper notched specimen NB with higher stress concentration, the decrease of the lifetime was noticeable.

### *Effect of static combined loadings*

Figure 1 (b)-(d) shows the effect of static tension on fatigue life. $N/N_0$ denotes the ratio of lifetimes in application of static loading to those in pure torsion.

Although the values of $N/N_0$ scattered considerably with cyclic torsional stress amplitude $\tau_a$, the fatigue life of smooth and notched specimens clearly decreased with the increase of static tension $\sigma_m$. For addition of $\sigma_m$=180MPa, the fatigue life reduced to 30~50% of those in pure torsion. Because the notched specimen NB has higher stress concentration in tension, the lifetime decreased markedly even for $\sigma_m$=100MPa.

Figure 2 shows the effect of static combined loadings on torsional fatigue. For addition of static torsion ( $\lambda = -1$), the lifetimes of SM and NA are longer than those in pure torsion . However, the fatigue life tends to decrease with the increase of static tension component. The shortest life resulted from application of static tension ( $\lambda = 0$).

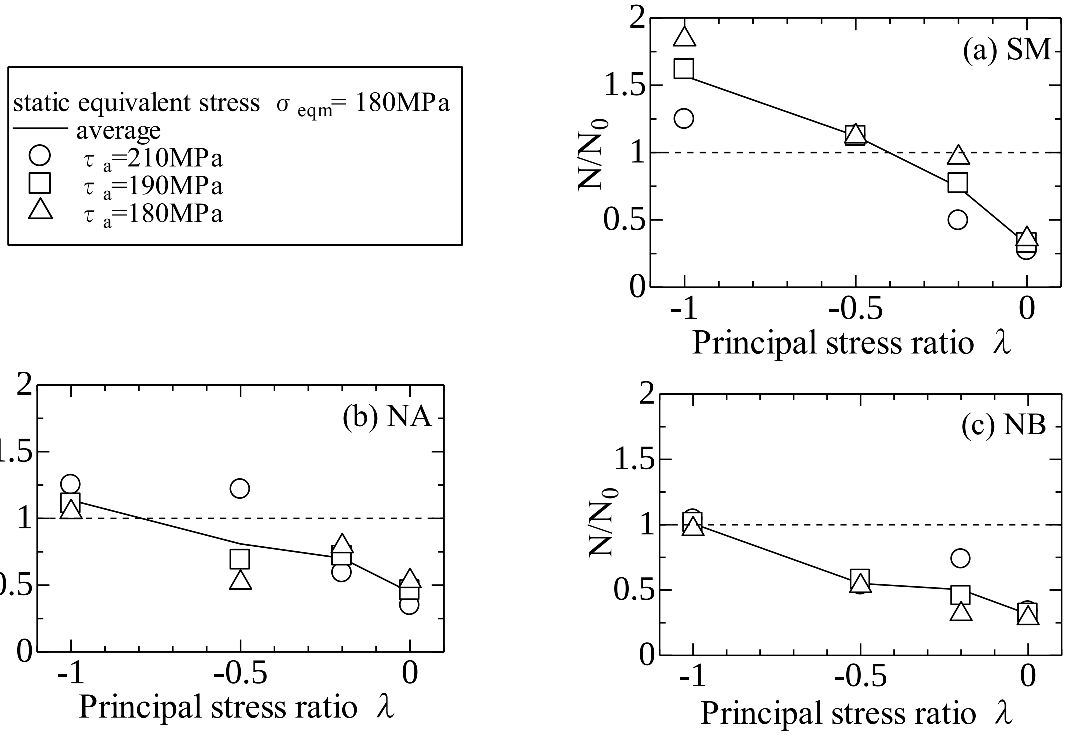

Figure 2. Effect of static combined loadings on fatigue life.

***Crack growth behavior in smooth specimen***

Figure 3 shows distribution of crack orientation at cycle ratio $N/N_f \fallingdotseq 0.3$, micrographs of cracks just after transition of the growth mode and macroscopic failure crack profile in various static loading conditions. Here, $N_t/N_f$ is cycle fraction at transition of the growth mode and $l_t$ denotes transition crack length.

As can been seen in Figure 3 (a), microcracks in pure torsion initiated in the vicinity of axial direction (θ=90°) due to the existence of banded ferrite/pearlite microstructure. Two branch crack shown in (b) then developed on the principal stress planes. Eventually, macroscopic crack shown in (c) was formed at the final failure. For application of static torsion ( $\lambda = -1$), microcracks initiated in the axial direction as well as in pure torsion. However, one branch crack was formed on the maximum tensile stress plane as seen in (d)-(f). Figure3 (g)-(i) shows the crack development for addition of combined static loadings ( $\lambda = -0.2$). The crack growth behavior resembles to those for addition of static torsion. In the case of addition of static tension ( $\lambda = 0$) shown in (j)-(l), microcracks initiated around both the maximum shear stress planes. Subsequently, two branch crack developed from longitudinal shear crack. However, the cracks often propagated along the circumferential direction and finally formed the failure crack with a flat crack path as shown in (m).

The cycle fractions at transition of crack growth mode $N_t/N_f$ were approximately 50-60% of the total fatigue life regardless of the condition of static combined loadings. However, the transition crack length $l_t$ was different depending on the static loading conditions. While the length $l_t$ for static torsion was shorter than in pure torsion, longer shear crack developed for addition of static tension.

Figure 3 (n) shows the crack growth curves. Closed symbols denote the transition of crack growth mode. The crack growth curve for addition of static torsion is almost identical with that in pure torsion. As the component of static tension increases, shorter lifetime resulted from the higher crack growth rate. The trend of crack growth behavior in various loading conditions is consistent with the effect of static loadings on the fatigue life shown in Figure 2 (a).

### *Crack growth behavior in notched specimen*

Figure 4 shows crack growth behavior in semi-circular notched specimen NA. For pure torsion shown in (a)-(b), the cracks grew mainly in axial direction along the banded ferrite/pearlite microstructure. Since the shear mode growth is prevented by the stress gradient in axial direction, a turtle shell-like serrated crack is formed along circumferential direction by linking of the shear cracks.

For addition of static torsion in (c)-(d) and combined static loading in (e)-(f), the crack growth behavior resembles those in smooth specimen SM shown in Figure 3. The cracks propagated along the maximum tensile stress plane, linking of the cracks were not observed after transition of the growth mode. For addition of static tension in (g)-(h), microcracks grew predominantly along the axial direction like other loading conditions. Two branch cracks then grew accompanying coalescence and finally formed relatively flat crack path along the periphery of the notch root. Figure 4 (i)-(k) shows failure crack profile in notched specimen NB. The profiles resemble those in specimen NA and are different depending on the type of static loading.

Crack growth curves in specimen NA are shown in (l). Transition of the growth mode is earlier than in smooth specimen SM except for the case of addition of static tension. This may result from prevention of shear mode growth due to existence of stress gradient along axial direction. The fastest crack growth for addition of static tension is accord with the trend of the fatigue life shown in Figure 2 (b).

### *Effect of static combined loadings on fatigue life*

Superposition of static combined loadings on cyclic torsion in smooth and notched specimens showed quite different fatigue behavior according to the combined stress ratio. Crack growth in early stage was highly affected by the banded microstructure. Thus, the cracks propagated predominantly on the maximum shear plane along axial direction except the growth in circumferential direction was also observed for addition of static tension. Static combined loadings exert great influence on the growth after transition of the growth mode. Macroscopic failure cracks with different profiles were

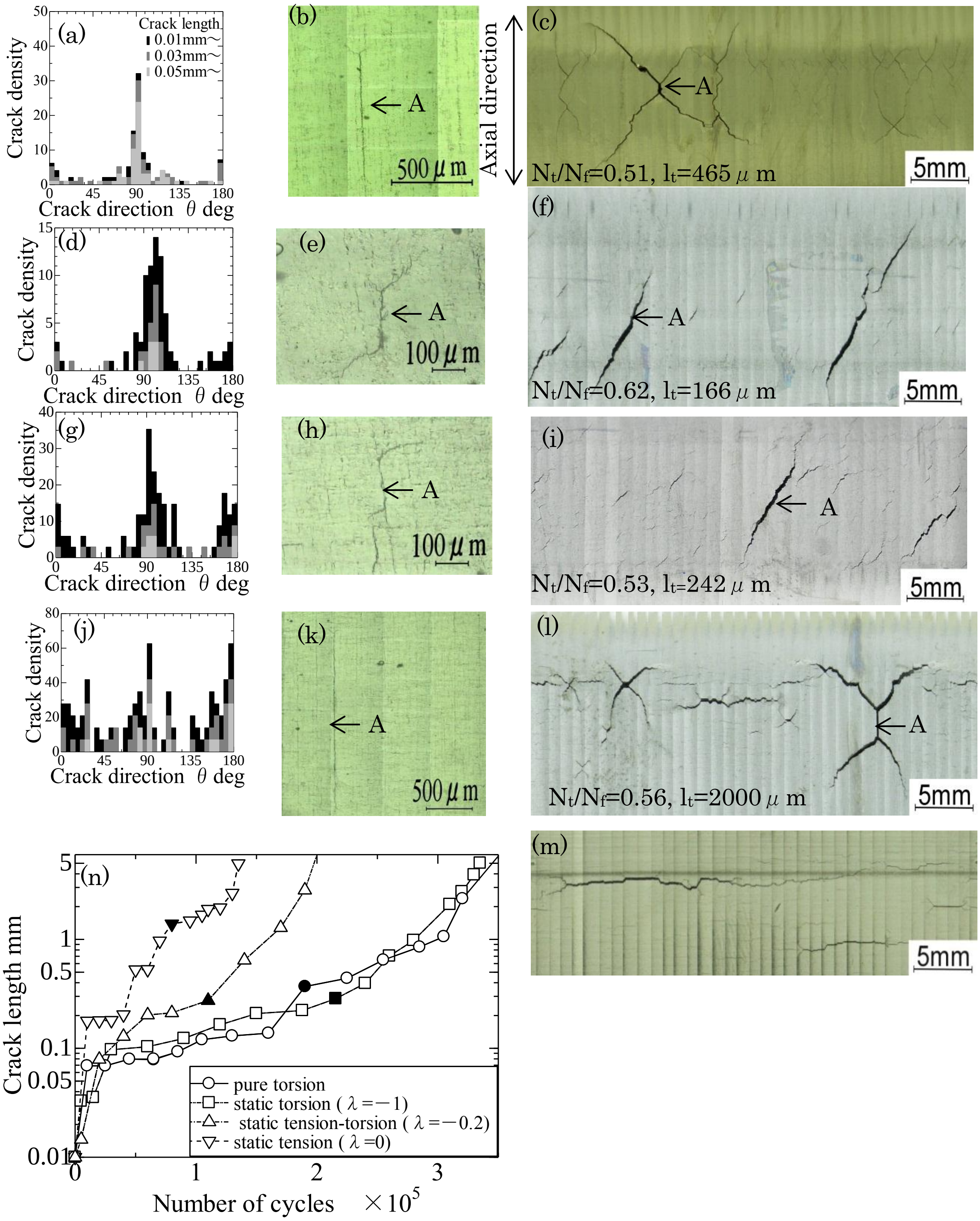

Figure 3. Crack growth in smooth specimen ($\tau_a$=190MPa): (a)-(c) pure torsion; (d)-(f) with static torsion (λ=－1); (g)-(i) with static tension-torsion (λ=-0.2); (j)-(m) with static tension (λ=0); (n) crack growth curves.

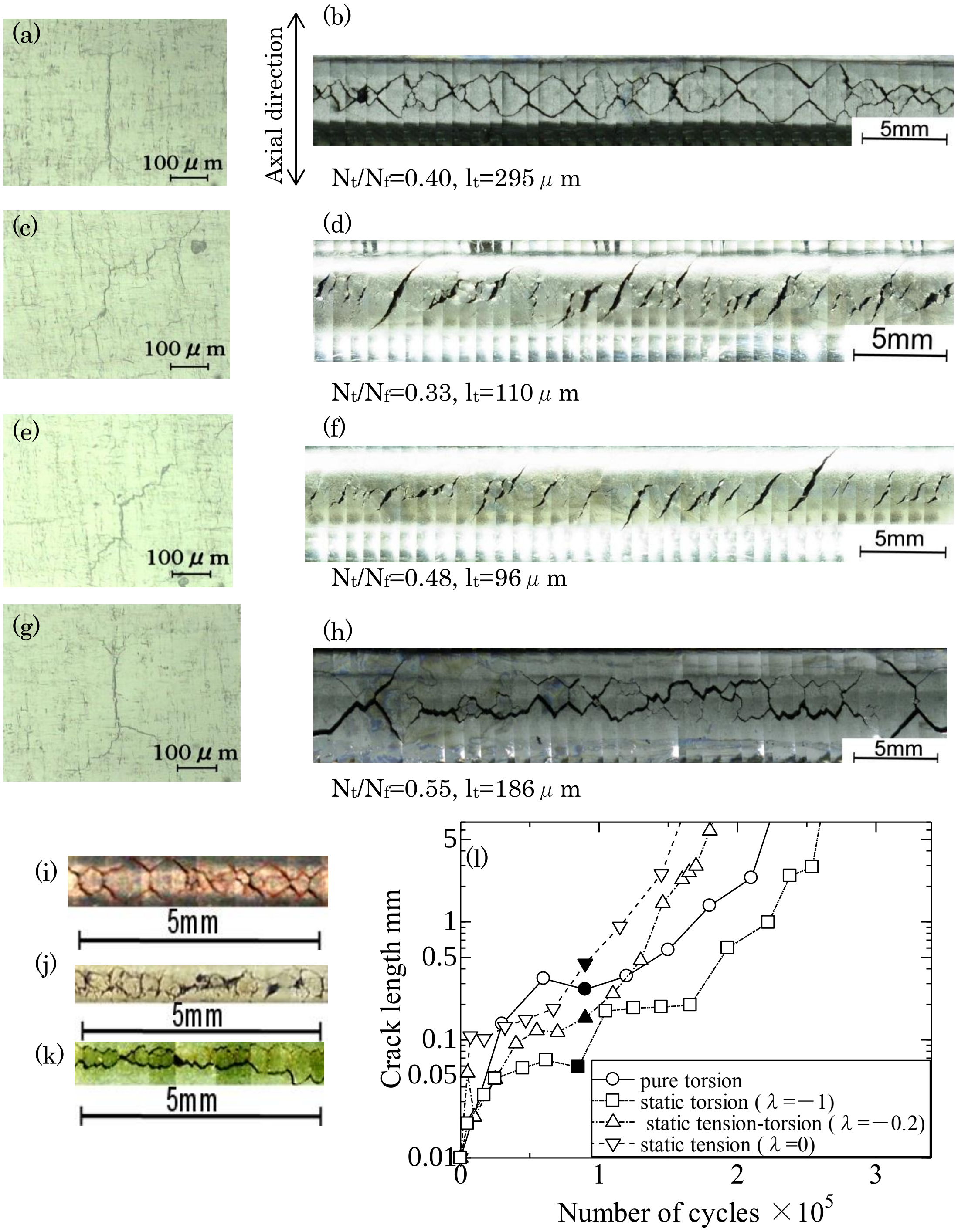

Figure 4. Crack growth in notched specimens ($\tau_a$=190MPa): (a),(b) pure torsion in NA; (c),(d) with static torsion($\lambda$=−1) in NA; (e),(f) with static tension-torsion ($\lambda$=−0.2) in NA; (g),(h) with static tension ($\lambda$=0) in NA; (i) pure torsion in NB; (j) static torsion in NB; (k) static tension in NB; (l) crack growth curves.

formed according to the conditions of static combined loading. Here, the crack growth behavior in notched specimens was basically the same as those in smooth specimen.

A quantitative study of the effects of static combined loading on crack initiation life and crack growth rate under cyclic torsion was not done yet. However, on the basis of the crack observation, it was confirmed that the torsional fatigue life of the steel was governed by mean stress acting on the critical planes determined from both mechanical and microstructural aspects. For application of static tension, the crack growth is promoted by mean tensile stress acting on a relatively flat plane in circumferential direction. These cracks are easy to coalesce and thus the most significant mean stress effect is observed. For addition of static torsion, a weak mean stress effect results from rubbing between the crack faces and difficulty of the crack coalescence. For the case of static combined loadings, intermediate effect between static tension and torsion will be expected depending on the stress ratio of combined static loadings.

## CONCLUSIONS

Influence of static loadings on torsional fatigue was investigated in smooth and circumferential notched specimens of medium carbon steel under cyclic torsion with and without static combined tension-torsion. Reduction of the lifetime was not found for addition of static torsion irrespective of the specimen shape. However, the fatigue life tends to decrease with the increase of the ratio of tension component occupied in combined static loadings. The banded microstructure plays a dominant role for the crack growth in early stage of the life. After the transition of the growth mode, the crack growth is predominantly governed by the condition of static combined loadings. For application of static tension, the most significant mean stress effect was observed due to promotions of the crack growth by action of mean tensile stress and the crack coalescence on the macroscopically flat crack plane. In the case of static combined loadings, intermediate effect between static tension and torsion was observed according to the stress ratio in the combined loadings.

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