



## Cracking directions in multiaxial low cycle fatigue at high and room temperatures

Masao Sakane, Takamoto Itoh

*Department of Mechanical Engineering, Ritsumeikan University, 1-1-1, Nojibigashi Kusatsu Shiga, 525-8577, Japan*  
*sakanem@se.ritsumei.ac.jp, itohataka@fc.ritsumei.ac.jp*

**ABSTRACT.** Cracking direction in multiaxial low cycle fatigue is an important research subject because crack initiation and propagation behavior is a physical background for developing an estimation method of multiaxial low cycle fatigue lives. However, there are a few open questions on cracking direction in multiaxial low cycle fatigue because cracking direction in multiaxial low cycle fatigue is complex and changes depending on stress multiaxiality, strain range, notch and material. This paper overviews cracking directions in tension-torsion low cycle fatigue of low alloy steels and nickel base superalloys. Two types of cracking directions in these materials, maximum shear direction and maximum principal direction, are discussed in relation with strain multiaxiality and an existence of notch and precrack. The two cracking directions in torsion low cycle fatigue of SUS 304 stainless steel are also discussed in relation with strain range. Detailed micro crack observations are finally presented to discuss the two cracking directions in torsion low cycle fatigue of a SUS 304 unnotched specimen.

**KEYWORDS.** Multiaxial fatigue; Crack mode; Notch; Fatigue life; Torsion.



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### INTRODUCTION

Two types of cracking directions have been reported in multiaxial low cycle fatigue (LCF); Stage I cracking and Stage II cracking. Stage I cracking is the cracking on maximum shear plane (shear crack) and Stage II cracking is that on principal plane (principal crack). In a uniaxial push-pull low cycle fatigue of ductile materials, shear cracks initiate and they turn to be principal cracks as they grow, one of them forming a main crack to bring failure of specimen [1].

However, in multiaxial LCF, cracking direction is not so simple as in the uniaxial case, and cracking direction is influenced by several factors. Numerous papers have discussed influential factors on cracking direction but still some of their effects seem to be conflicting. Major factors influencing cracking direction are strain/stress multiaxiality, type of material, notch and precrack, material anisotropy, strain/stress range, oxidation and so on.



The objective of this paper is to overview factors influencing cracking direction under multiaxial LCF. The factors that this paper overviews are stress/strain multiaxiality, notch and precrack and stress/strain range. This paper discusses the strain range dependency of cracking directions in torsion LCF in more detail. In torsion LCF, shear cracking occurs at high strain ranges but principal cracking at low strain ranges. The reason of the transition of cracking direction depending on strain range has not been well understood so that this paper discusses this topic from micro crack observations on specimens fatigued in torsion.

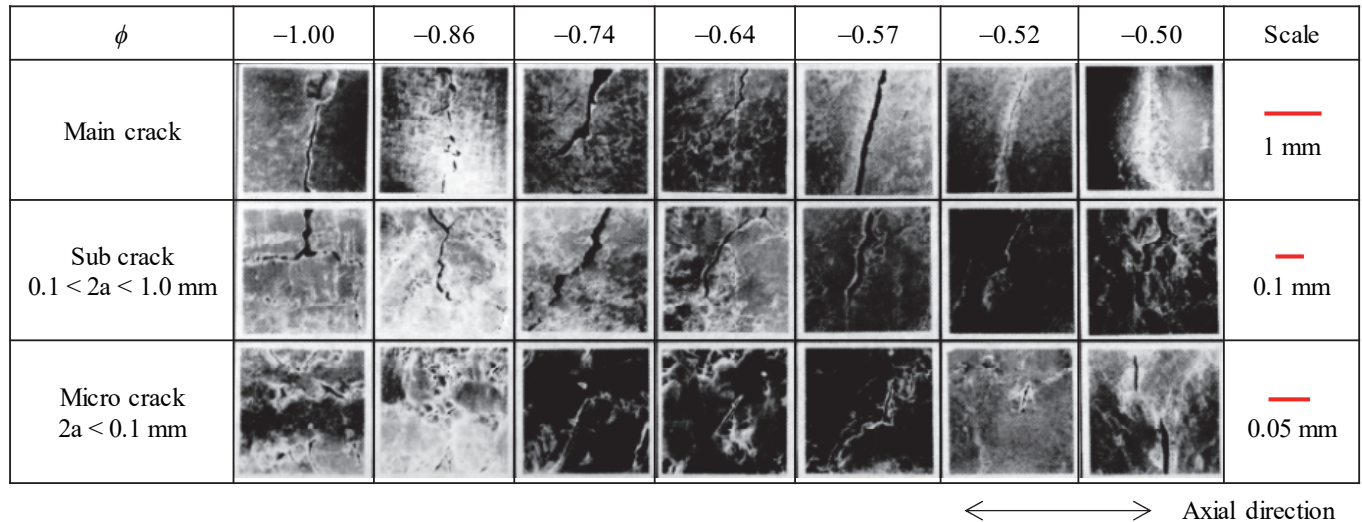


Figure 1: Crack observation in tension-torsion LCF of SUS304 stainless steel at 923K.

## INFLUENTIAL FACTORS TO CRACK DIRECTION

### *Multiaxial strain/stress states*

**M**ultiaxial strain/stress state has an evident influence on cracking mode and many papers discuss this factor. A systematic research of the author's [2] on cracking mode in tension-torsion LCF of a SUS 304 austenitic stainless steel is shown in Fig.1. In the figure, cracking directions are classified according to crack length into three categories. The main crack is a crack that brings specimen to failure, the sub-crack a crack having a length between 0.1 mm and 1 mm, and the micro-crack a crack with a length less than 0.1 mm. Fig.2 depicts the crack angle at failure against the principal strain ratio ( $\phi = \varepsilon_3 / \varepsilon_1$ ) and the strain ratio ( $\lambda = \gamma / \varepsilon$ ) as a summary of the observations shown in Fig.1. The crack angle is the angle from the longitudinal direction of specimen axis,  $\gamma$  the shear strain amplitude and  $\varepsilon$  the axial normal strain amplitude. The  $\phi = -0.5$  test corresponds with the tension test and  $\phi = -1.0$  with the torsion test, assuming that the Poisson's ratio being 0.5 in LCF region. The main cracks at the three strain ranges propagated at an angle of 90 degrees (principal crack) in tension tests ( $\phi = -0.5$  test) but they at an angle of 45 degrees (shear crack) in torsion tests ( $\phi = -1.0$  test). The transition of the cracking mode from principal crack to shear crack occurred at the principal strain ratio of about  $-0.74$ . The cracking mode of sub-cracks is the same as that of the main crack. However, the cracking mode of the micro-crack is different from that of the main and sub-crack, and both principal and shear cracking modes were found in the principal strain ratios of  $-0.86$  and  $-1.0$ .

Principal strain ratios at which the tension-torsion crack transits from the principal mode to the shear mode with decreasing principal strain ratio are listed in Tab. 1 for several materials listed in the table together with testing temperatures. The table indicates that the principal strain ratio at transition does not significantly depend on material and takes the value around  $-0.70$  whereas a slightly smaller value is found in SUS 304 stainless steel at 823 K. Materials listed in Tab. 1 range over wide types of materials, austenitic stainless steel, low alloy ductile steels, conventional cast superalloy, and directionally solidified super alloys. Considering that the steels and the conventional cast superalloy are an isotropic material but the directionally solidified superalloys have a strong anisotropy due to the crystallographic texture the result in the table means that texture and material anisotropy has a weak effect on the principal strain ratio at the transition.

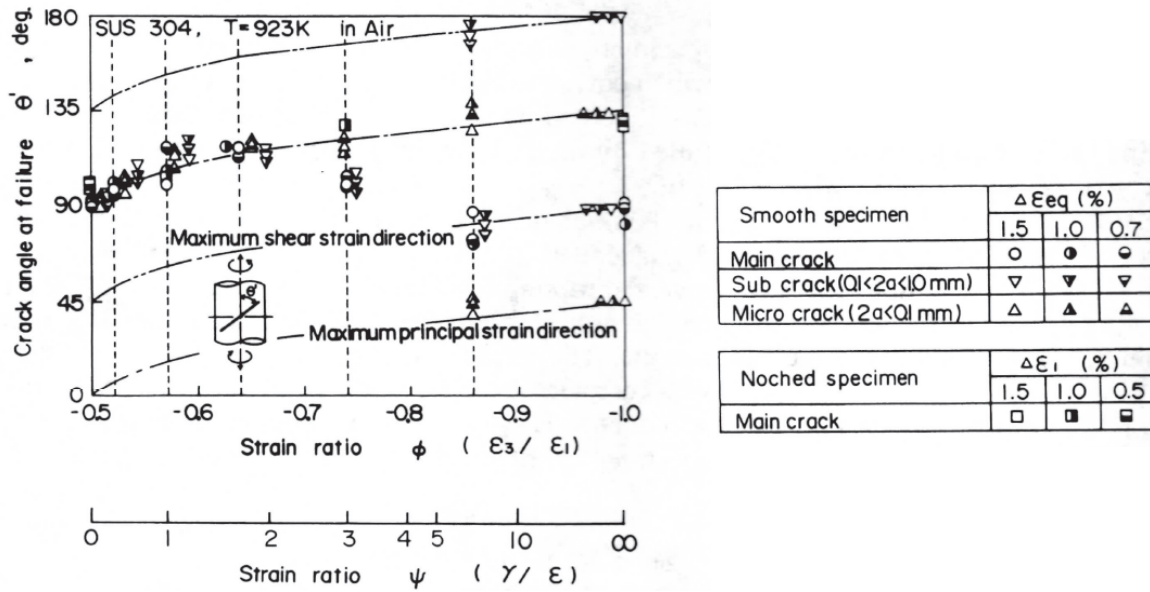


Figure 2: Cracking modes in tension-torsion LCF of SUS304 stainless steel at 923K.

Materials	Temperature, K	$\phi = \epsilon_3 / \epsilon_1$	Ref.
1Cr-1Mo-1/4V	838	-0.79	[3]
1Cr-1Mo-1/4V*	293	-0.74	[3]
1Cr-1Mo-1/4V**	823	-0.74 ~ -0.70	[4]
SUS 304	923	-0.74	[2]
SUS 304	823	-0.64	[5]
AISI 316	673	-0.74	[3]
Mild steel	R.T.	-0.74	[6]
Inconel 738LC	1123	N. T.	[7]
Rene'80H DS	1173	-0.70	[8]
Mar-M247LC DS	1173	-0.70	[9]

\*  $\Delta\gamma \geq 1.2\%$ , \*\*  $\Delta\gamma \geq 1.2\%$ , N.T. No Transition (Shear crack), DS Directionally solidified superalloy

Table 1: Principal strain ratio at which crack changes propagation plane.

Note that the above discussion does not hold for all materials listed in the table. Cracks of Inconel 738LC conventional cast superalloy remain on the principal strain plane in all principal strain ratios. Tab. 1 mainly summarizes the crack transition in elevated temperature LCF so that oxidation may bring some influence on cracking direction [2,3] but this paper is not discuss the oxidation effect in more detail because there are conflicting reports on the oxidation effect on cracking direction [2-4]. Material anisotropy also has some influence on the cracking direction as seen in the literature [10].

Cracking direction is a physical background for developing a multiaxial LCF damage model and therefore studying the relationship between cracking direction and fatigue life is meaningful. The relationship of the three materials is shown in Fig.3 [7]. The ordinate of the figure is the life ratio obtained by dividing the multiaxial LCF life by the uniaxial LCF life in a test with the same von Mises strain amplitude. The dashed lines indicate a factor of two band from unity value of the ordinate. As stated earlier, Inconel 738LC showed principal cracking in all principal strain ratios and most of all fatigue lives fall into the factor of two band. Fatigue lives of SUS 304 and 1Cr-1Mo-1/4V steels with principal cracking also fall



into the factor of two band but those of the two steels with the shear cracking exceed the band. This result suggests that a fatigue life with shear cracking is slightly longer than that with principal cracking at the same von Mises strain condition.

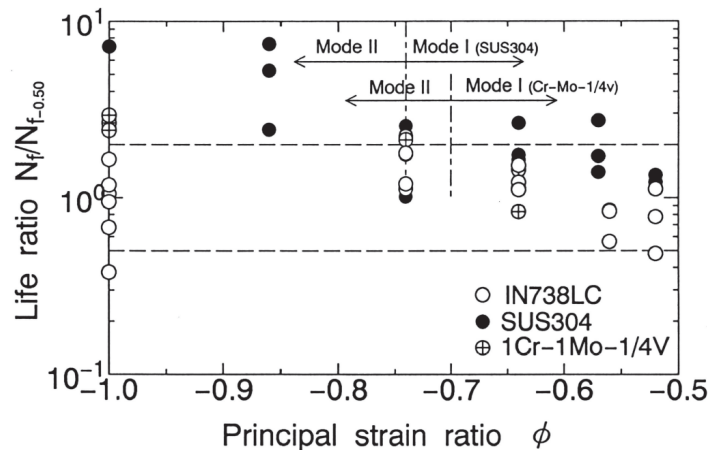


Figure 3: Cracking mode and transition angle of main crack for three materials.

### Notch and pre crack

Notch and precrack also have evident but complex influences on cracking direction in multiaxial LCF. Sakane et al. [12] reported effects of a notch and precracks on cracking direction in torsion LCF of a SUS 304 stainless steel. The geometry of the notch and precracks is shown in Fig.4. The diameter of the notch is 0.6 mm and the notch was machined with a drill to penetrate a 1.5 mm wall thickness of tube specimen. Two types of precracks were provided by applying high cycle fatigue cyclic loading for Type I precrack with tension loading and for Type II precrack with torsion loading. The length of the precracks is 1.0 mm including the notch hole for Type I and Type II precracks.

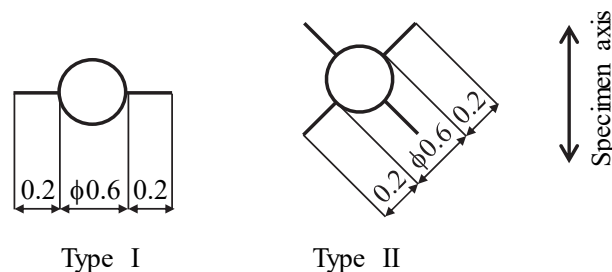
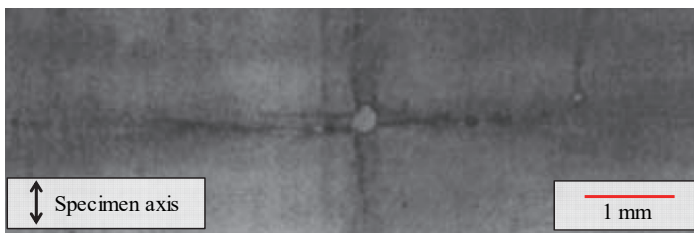
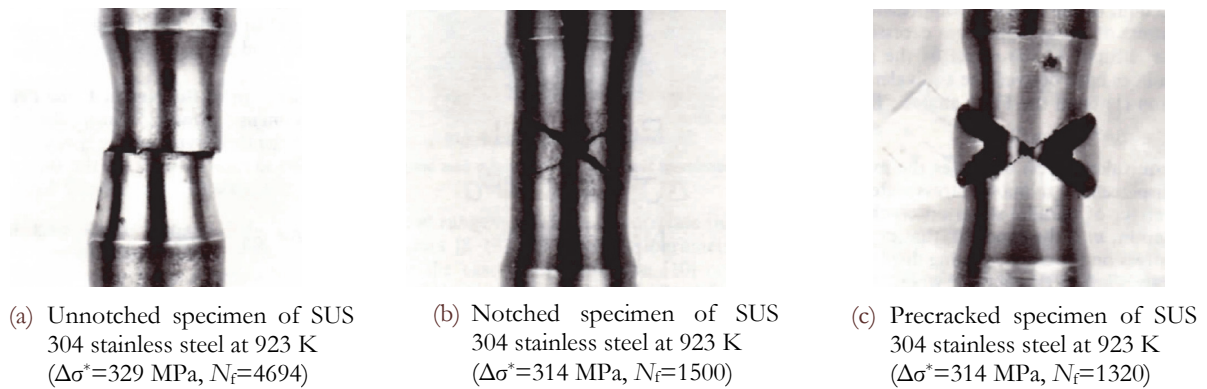


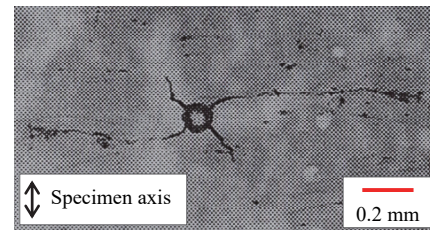
Figure 4: Schematic of two precrack directions.

Fig.5 shows cracking directions of smooth, notched and precracked specimens in torsion LCF loading. The cracking direction of the smooth specimen, Fig.5 (a) [12], is the shear direction that is commonly observed cracking direction at high strain/stress ranges. However, the cracking direction of the notched specimen with a 0.6 mm diameter is the principal directions as shown in Fig.5 (b) [12]. Putting the notch hole changes the cracking direction. To induce shear cracking, the specimen with shear precrack (Type I crack) in Fig.4 was fatigued but the cracking direction was the principal directions as shown in Fig.5 (c) [12]. Type II precracked specimen also yielded the principal crack.

However, notch and precrack do not always bring the principal crack. The influence of the notch may change depending on the notch size and material. The 1CrMoV specimen with a through hole with 0.2 mm diameter in Fig.5 (d) [11] showed shear cracking as well as the smooth specimen. Furthermore, the SUS 304 specimen with a surface hole with 0.1 mm diameter and 0.1 mm depth yielded a short principal cracking followed by a shear cracking, Fig.5 (e) [13]. The last two results, shown in Fig.5 (d) and Fig.5 (e), presumably indicate that the notch effect on cracking direction may change depending on the geometry of notch and material.



(d) Notched specimen (0.2 mm through hole) of 1CrMoV at 823 K



(e) Notched specimen (0.1 mm diameter, 0.1 mm depth) of SUS 304 stainless steel at 823 K

Figure 5: Cracking direction in torsion tests of unnotched, notched and precracked specimens.

*Strain range dependency of cracking direction in torsion low cycle fatigue*

Cracking direction in torsion LCF is also influenced by strain range, shear cracking at high strain ranges and principal cracking at low strain ranges shown in Fig.6 [14] as a typical case for a SUS 304 stainless steel, but the mechanism of the transition of cracking direction is still an open question whereas many researchers discussed this topic. The strain ranges with shaded area are the strain ranges at which crack transits its direction. Micro-cracks on the specimen fatigued until a half-life shown with the solid circles in the figure were observed in detail with a scanning electron microscope.

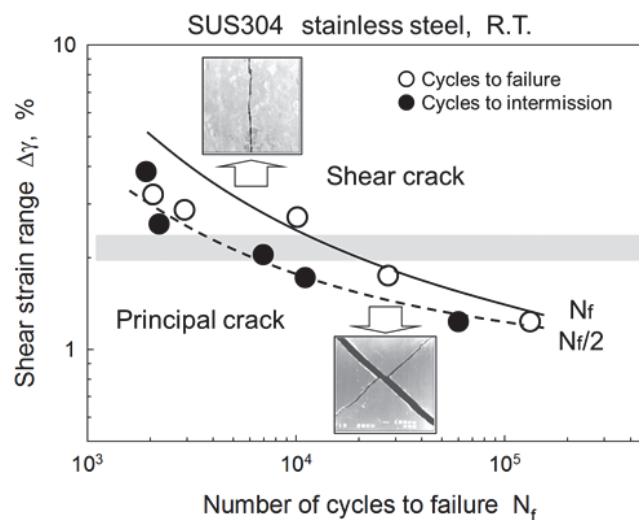


Figure 6: Torsion low cycle fatigue life and cracking mode of SUS 304 stainless steel.

Four type of cracks were observed on the specimen surface shown in Fig.7 [14]. They are classified according to the propagation behavior as shown in Fig.8 schematically. Type 1 and Type 2 cracks extended in the shear direction in some



distance and branched into the principal directions. Type 3 crack propagated in the principal directions and Type 4 crack is the crack that only propagated in the shear direction. More than 400 cracks were observed on each specimen. Type 1 and Type 2 cracks were most frequently found and Type 3 and Type 4 cracks are scarcely found. This result indicates that the coalescence of micro cracks is not a major mechanism of the shear cracking at high strain ranges and of the principal cracking at low strain ranges because the number of shear cracks should be dominant at high strain ranges and that of principal cracks should be dominant at low strain ranges if the coalescence of cracks is a major mechanism of failure.

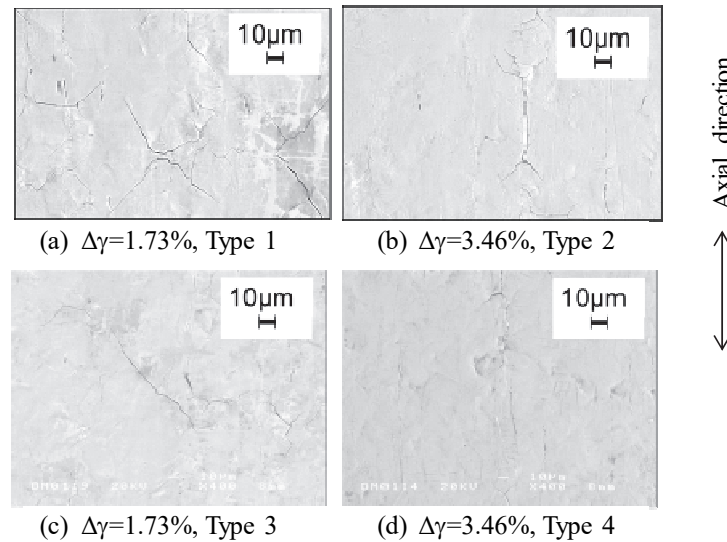


Figure 7: Four crack type in torsion low cycle fatigue of SUS 304 stainless steel.

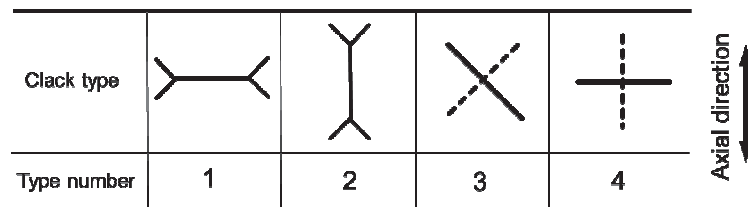


Figure 8: Schematic of four crack types in torsion low cycle fatigue of SUS 304.

Shear crack lengths before branching to principal cracks for Type 1 and Type 2 cracks (critical crack length) were measured and the average values of the critical crack lengths (average crack length) against shear strain ranges are plotted in Fig.9 [14]. The averaged crack length was obtained by observing 1956 cracks within a gage length of the intermitted specimens. The figure clearly indicates that the average crack length has constant values at the low and high low strain ranges. The transition of the average crack length is found in the shear strain range between 2.0% and 2.5%. This transition strain range well corresponds with the transition strain range of main cracks shown in Fig.6. The correspondence of the transition strain range implies that one of the mechanisms of the crack direction change results from that both a macro shear crack and a macro principal crack microscopically propagate zigzag in the respective directions but the propagation length in shear direction is longer at high strain ranges and that in the principal directions longer at low strain ranges. Makabe et al. [15] made a similar discussion but on the notched specimen. They reported that the critical crack length before branching increased momentarily with shear strain range.

To investigate the reason of the two propagation directions, aspect ratios of a shear crack and a principal crack were measured by continuing stepwise polishing off the material from the specimen surface and measuring the removed depth and crack length on a respective new surface. The observations are shown in Fig.10 [14]. The figure clearly indicates that the shear crack has a small aspect ratio while the principal crack a large aspect ratio, the shear crack mainly propagating near the specimen surface but the principal crack extending deep into the specimen.

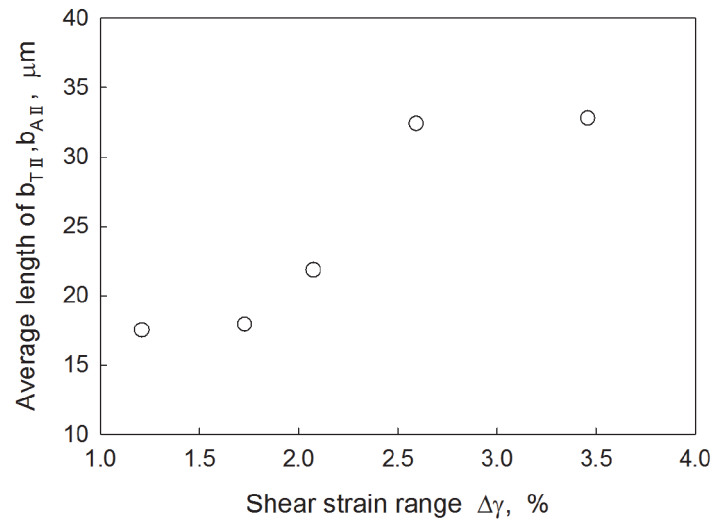


Figure 9: Variation of average crack length with strain range in torsion low cycle fatigue of SUS 394 stainless steel.

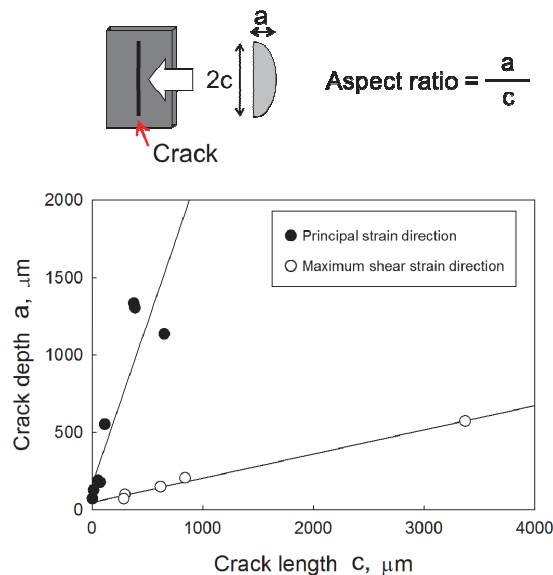


Figure 10: Aspect ratio of principal and shear cracks in torsion low cycle fatigue of SUS 304 stainless steel.

Considering that a crack propagates in a direction to release strain energy most, elastic-plastic strain energy release by a crack formation was analyzed by a finite element method for three models. The three models have a same cracked area but the cracking direction is changed. Two models have a deep semi-circular crack, 2 mm surface length and 1 mm depth, one directing to principal orientation (Model A) and the other to shear orientation (Model B). The third model has a shear shallow crack with 5 mm surface length and 0.4 mm depth directing to shear direction (Model C). The energy release of Model C is larger than that of Model B at high strain ranges but the latter showed larger energy release than the former at low strain ranges. The results of the energy release well accounts for the transition of crack direction depending on strain range from an energy release viewpoint. The graphical representation of this discussion is not presented from the shortage of the space of the paper. The cracking direction in torsion LCF depends on material and the discussion on this topic is made in the literatures [16,17] in detail.



## CONCLUSIONS

- (1) Strain multiaxiality dependence of cracking direction in tension-torsion multiaxial low cycle fatigue is discussed. The transition of cracking direction occurred at the principal strain range of about  $-0.70$  for low alloy steels of SUS 304, SUS 316 and CrMoV and directionally solidified superalloy of Mar-M247 and Rene'80. Only conventional cast superalloy of Inconel 738 showed shear cracking in all principal strain ratios.
- (2) The specimen with the principal cracking showed slightly smaller low cycle fatigue life than that with the shear cracking fatigued at the same von Mises strain amplitude.
- (3) Notches and precracks changed the cracking direction in torsion low cycle fatigue. The specimen with large through hole and through precrack yielded principal cracks in the testing condition that the smooth specimen yielded shear crack. However, the specimen with a small through hole and a surface hole had a shear crack.
- (4) The strain ranges at which macro cracks transit the direction between the shear direction and the principal direction corresponded to the transition strain range at which the average crack length increase.
- (5) The aspect ratio of the shear crack was smaller compared with the principal crack. Finite element analysis revealed that the strain energy release of the shear crack was larger at high strain ranges but that of the principal crack was larger at low strain ranges.

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