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DESIGN CRITERIA FOR RATCHETING FATIGUE OF 316FR STEEL UNDER FAST REACTOR CONDITIONS

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ABSTRACT

Damage tolerance limit for ratcheting fatigue is discussed to rationalize the design criteria for the commercialized fast reactor system. Ratcheting fatigue tests were conducted at 550C. The effect of ratchet to fatigue strength was investigated experimentally. Fatigue lives decrease with increasing the accumulated strain. Mean stress was increasing during the ratcheting cycle and its maximum value depended on the accumulated strain and the ratchet-expired cycle. Fatigue life reduction was negligible when the maximum mean stress was less than 25 MPa and it was corresponding to the accumulated strain of 2.2 %. The accumulated strain is limited to 2 % in the present design standard so that this strain limit is effective to the ratcheting fatigue. Micro-crack growth behaviors were also investigated in these tests in order to discuss the damage mechanisms in ratcheting conditions.

Keywords: Fast Reactor, Fatigue, Ratchet, Design Criteria, Strain Limit, Micro-crack

1. INTRODUCTION

Feasibility study for the commercialized fast reactor system has been conducting in Japan. This study aims at the development of design technologies that improve economy of reactor with keeping superior reliability. For this purpose, sophistication of the structural design standard has been discussing for the simplification of reactor structures (Kasahara et al, 2004). This simplification, such as small and thin-walled vessel, increases the primary stress at the vessel adjacent to coolant surface level, lower structures and such. Therefore, structural design for ratcheting deformation should be improved and rationalized (Figure 1). The limit for the accumulated

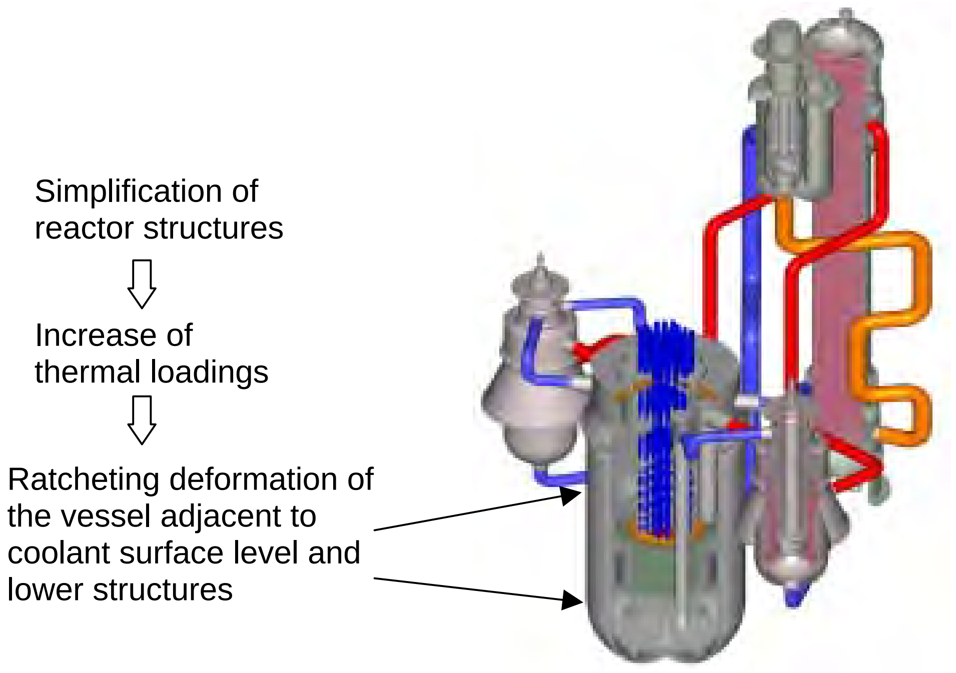


Figure 1. Schematic of commercialized fast Reactor.

inelastic strain including ratcheting strain was 0.01 for membrane and 0.02 for membrane and bending component in the previous fast reactor design standards in Japan (Iida et al, 1987, Kawasaki et al, 1999). The purposes of these criteria is to avoid the ductile and creep rupture and guarantee the adequacy of structural analyses by limiting the inelastic strain within appropriate amounts. On the other hand, ratchet straining would decrease the fatigue life so that it necessitates to confirm the influence of ratcheting behavior on fatigue life and to rationalize the design criteria of the inelastic strain limit.

In this study, we performed ratcheting fatigue test and discussed the design criteria taking the accumulated strain by ratcheting into account in order to improve the structural design methodology for fast reactors. A ratcheting fatigue test introducing a ratchet-expired cycle was proposed and carried out in some organizations in Japan. Fatigue lives under ratcheting condition and effects of the accumulated strain and mean stress increasing by ratcheting were discussed. Micro-crack growth behaviors were also investigated in order to discuss the fatigue life reduction mechanism in ratcheting conditions.

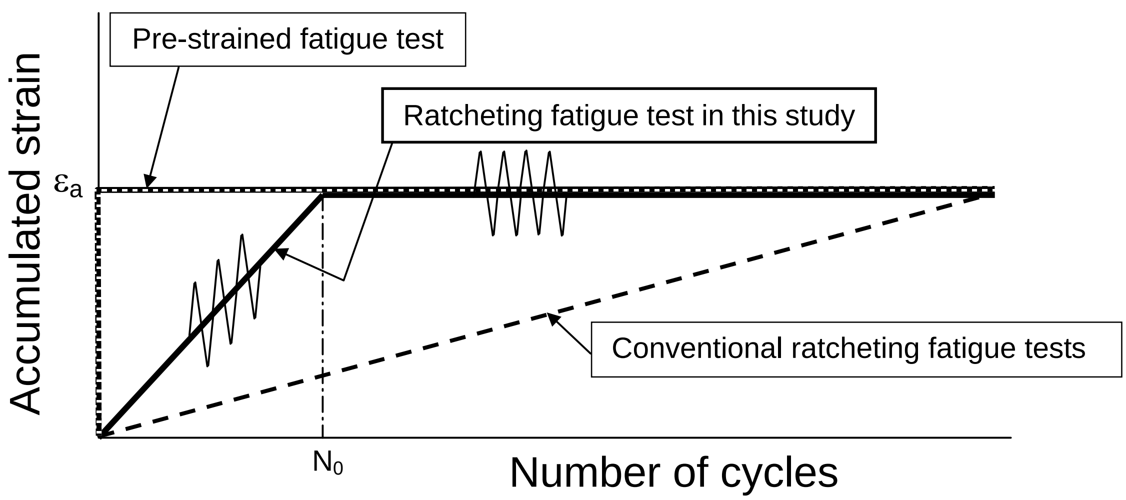


Figure 2. Outline of the ratcheting fatigue test in this study.

2. EXPERIMENTAL PROCEDURE

Strain-controlled low-cycle fatigue tests with accumulating the axial strain by loading cycles were carried out. Figure 2 shows the outline of ratcheting fatigue tests. In conventional ratcheting fatigue tests, ratchet deformation does not expire through the tests. Based on structural model test for the vessel adjacent to coolant surface level subject to thermal loadings due to temperature distribution moving (Igari et al, 1989, Igari et al 1991, Kitade et al, 1993, Wada et al, 1989, Takahashi, 1995), ratcheting deformation in fast reactor components will saturate in several tens of cycles so that a ratchet-expired cycle, N_0, was introduced in this study. The number of ratchet-expired cycle, N_0, was settled as 1000 and 20. N_0=20 is corresponding to structural model test results. N_0=1000 is considered as a conservative condition since the design start-up times is 640 for the commercial fast reactor, and most of ratcheting fatigue tests were conducted with N_0=1000. Pre-strained fatigue tests were also conducted in order to investigate the effect of ratchet-expire cycle.

The material used in this study was a 50 mm thick 316FR stainless steel plate made by hot rolling process (Wada et al, 1991). Ratcheting and pre-strained fatigue tests were carried out at four organizations and round-bar specimens of 6-9 mm diameter were used. All the tests were conducted at 550C. Strain ranges employed were 0.5 and 0.4%. Accumulated strain, $\sum_a$, was changed from 0 to 4% as a parameter in the ratcheting fatigue test. In several tests, cracking observations were conducted by taking the replica of the specimen surface with occasional interruptions of the test.

3. RESULTS AND DISCUSSION

3.1 Fatigue Life Reduction by Ratchet

Relationship between failure life, N_f, and accumulated strain, $\sum_a$, is shown in Fig. 3. Gray colored symbols indicate the test results of 0.4 % strain range and the others are of 0.5 %. Failure lives of low cycle fatigue tests, i.e., zero accumulated strain tests, have a large scatter band. On the other hand, scatter bands in ratcheting fatigue tests were relatively small and they tend to converge at the lowest life in low cycle fatigue tests. Life reduction with increasing of the accumulated strain in was slight in 0.5 % strain range tests by comparing at the lowest lives. In 0.4 % tests, however, fatigue lives drastically reduced to approximately 1/10 of low cycle fatigue lives when the accumulated strain was greater than 3 %. Therefore, fatigue life reduction by ratcheting has a strain range dependency and the effect of ratcheting is severer in lower strain range conditions.

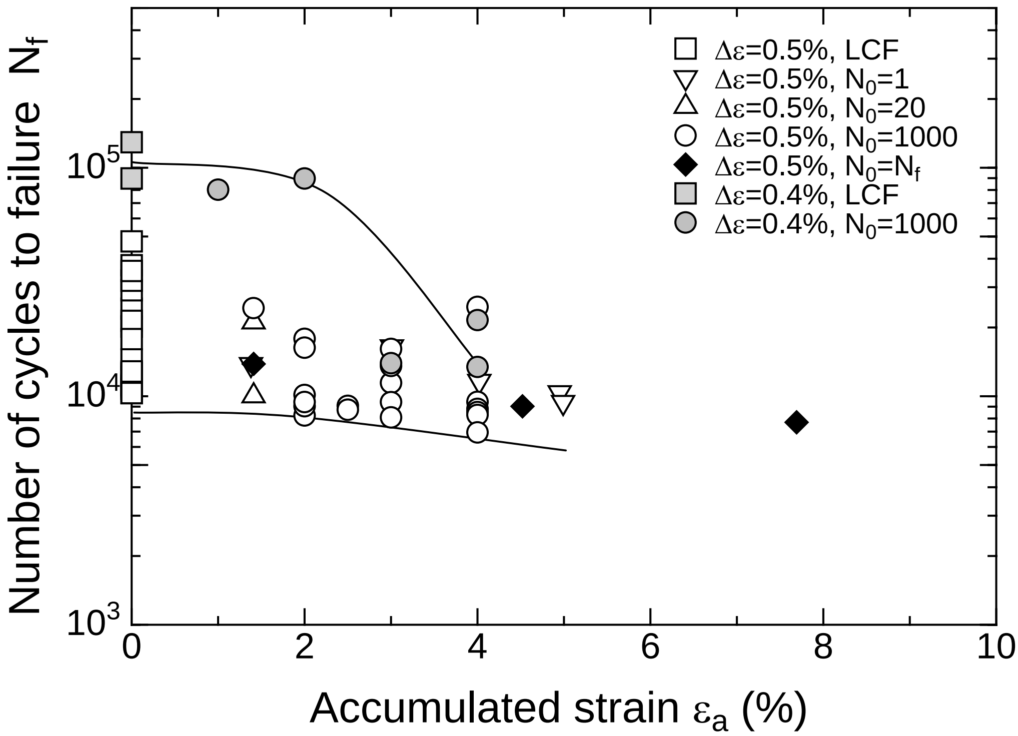


Figure 3. Relationship between failure life and accumulated strain.

Figure 4 show the variation in mean stress for tests of 0.5 % strain range. The ratchet-expired cycle, N_0, was 1,000 for all tests indicated in this figure. Mean stress was increasing accompanying with the strain accumulation and got the maximum value at N_0. The maximum value increased with increasing the accumulated strain. Stress range also increased as shown in Fig. 5. Cyclic hardening saturated about 500 cycles in low cycle fatigue tests whereas stress range increased until the ratchet-expired cycle in ratcheting fatigue tests. After the ratchet-expired cycle, mean stress and stress range were decreased gradually, and both of them were higher than that of low cycle fatigue tests in the latter stage of life. Therefore, mean stress and stress range increase by ratcheting could be regarded as a cause of life reduction.

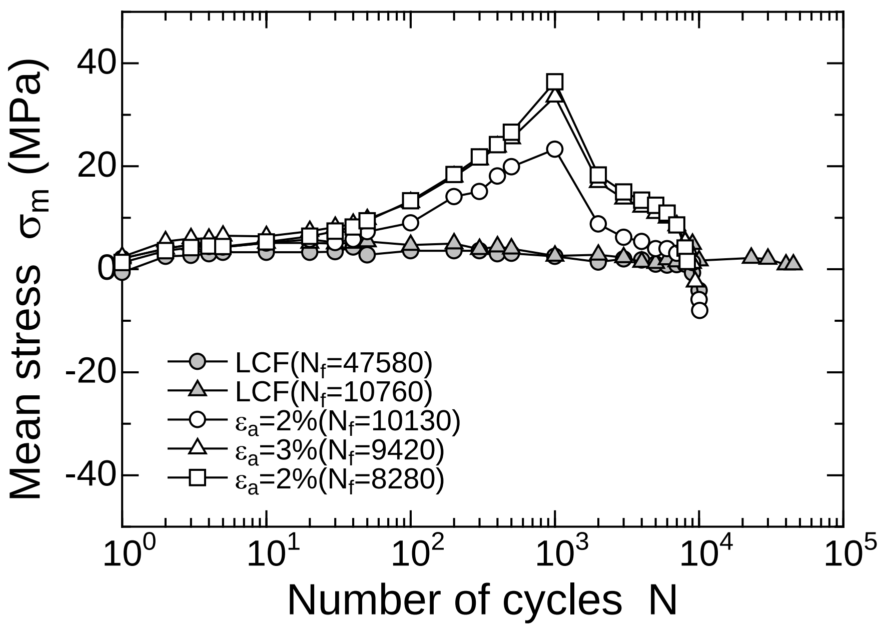


Figure 4. Variations of mean stress in fatigue tests of 0.5 % strain range.

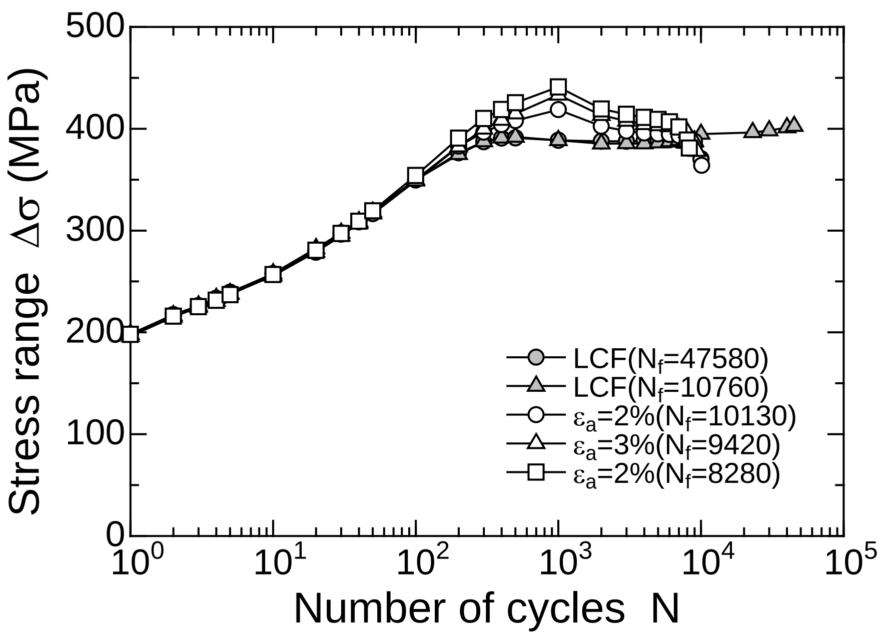


Figure 5. Variations of stress range in fatigue tests of 0.5 % strain range.

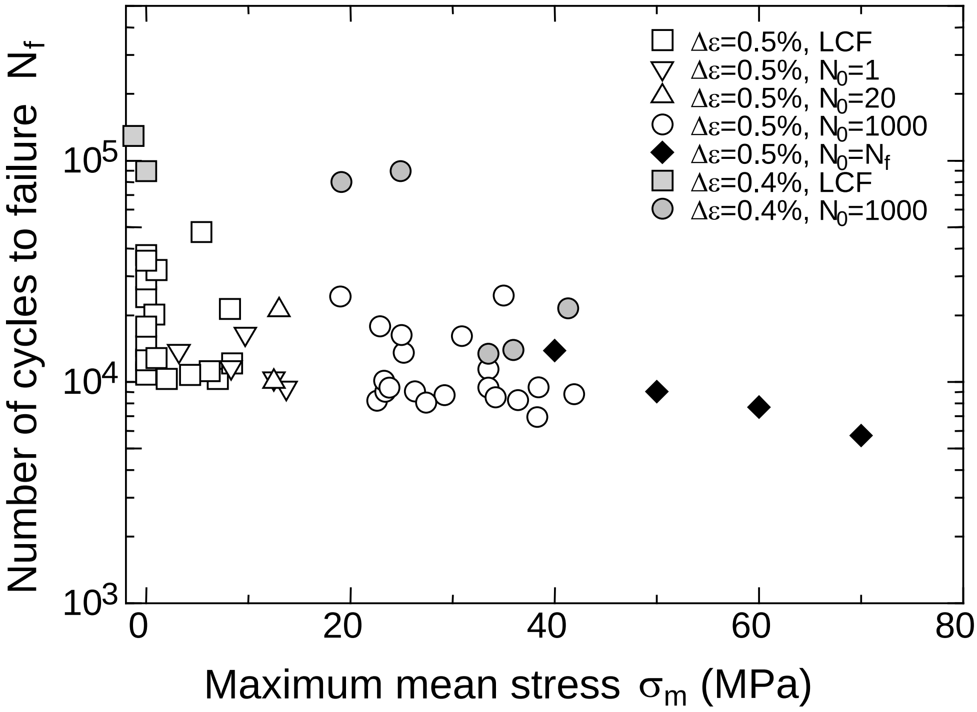


Figure 6. Relationship between failure life and maximum mean stress.

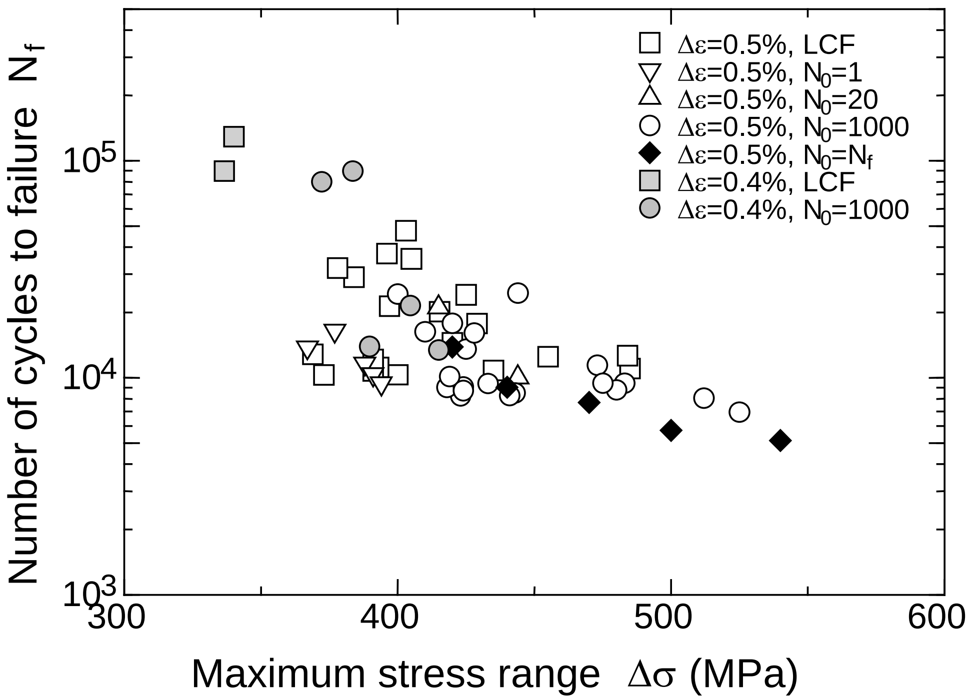


Figure 7. Relationship between failure life and maximum stress range.

Figures 6 and 7 indicate the relationships between failure life and the maximum mean stress, stress range. “Maximum” means the maximum value of mean stress and stress range through the life in each test. The maximum value was generated at the ratchet-expired cycle, N_0, when N_0 was greater than 1,000 in this study. Failure life slightly decreases with increasing mean stress and stress range. As for stress range in Fig. 7, the scatter in low cycle fatigue tests is large and it would be difficult to discuss the effect of strain range on the life reduction in ratcheting fatigue test. Even the life reduction with mean stress increasing is slight in 0.5 % strain range tests, it seems not to be negligible when mean stress greater than 25-30 MPa. Furthermore it is significant in 0.4 % tests as shown in Fig. 6. The ratchet-expired cycle dependency on mean stress can be also seen in Fig. 6. We will discuss the limit for the accumulated strain by taking the mean stress increasing into account in the next chapter.

3.2 Strain Limit for the Ratcheting Condition

The present design standard (Kawasaki et al, 1999) for fast reactors employs strain limits of 0.01 for the membrane component and 0.02 for the membrane plus bending component to avoid excessive inelastic deformations and guarantee the applicability of infinitesimal deformation theory. In this study, we discussed the strain limit in the design standard taking into account the accumulated strain by ratcheting. The life ratio that is normalized fatigue life was used for taking away the effect of testing equipments such as specimen diameter, heating equipment and so on, since the scatter of low cycle fatigue life was large in this study. The life ratio was calculated as normalizing the failure life by the average low cycle fatigue life. The average low cycle fatigue life means the average life of low cycle fatigue tests conducted in each organization so that it differs with organizations. Figure 8 shows the relationship between life ratio and the maximum mean stress. Life reduction when the maximum mean stress is greater than 25 MPa is not negligible. The maximum mean stress can be considered as the dominant factor of life reduction since the variation by the other factors, such as the ratchet-expired cycle and strain range, are not significant in Fig. 8. Therefore, the life reduction by the accumulated strain will be able to estimate by evaluating the mean stress variation. The solid line in the figure indicates the average trend curve for the relationship and the broken line is its lower limit. It was concluded that life reduction could be negligible when the maximum mean stress is less than 25 MPa from Fig. 8.

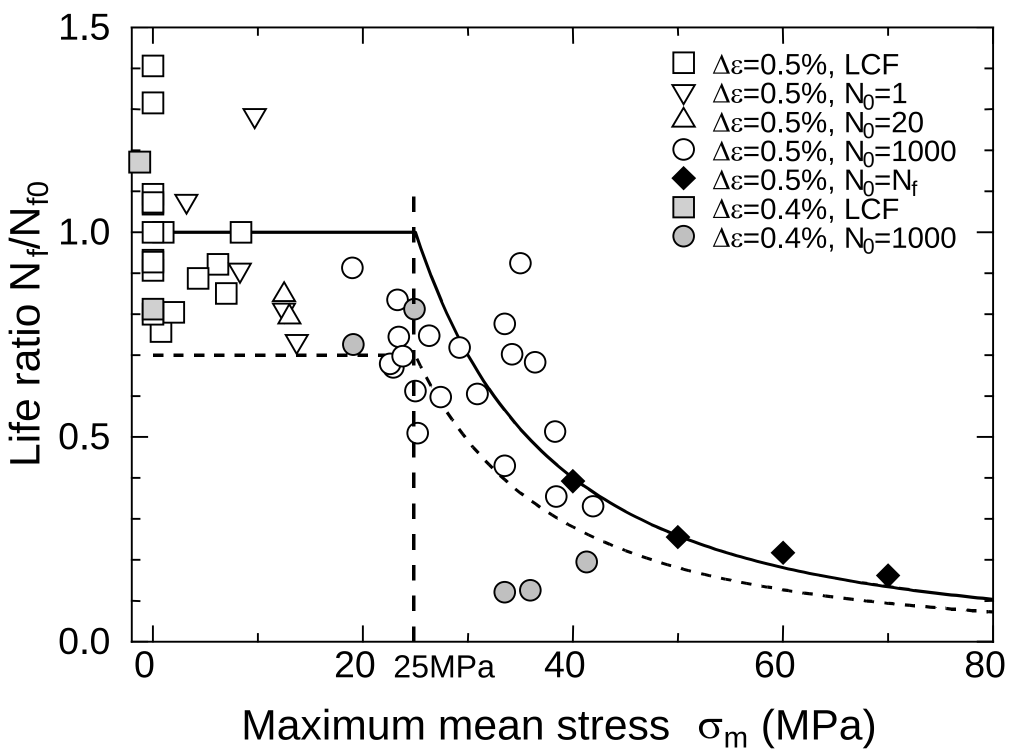


Figure 8. Relationship between life ratio and maximum stress range.

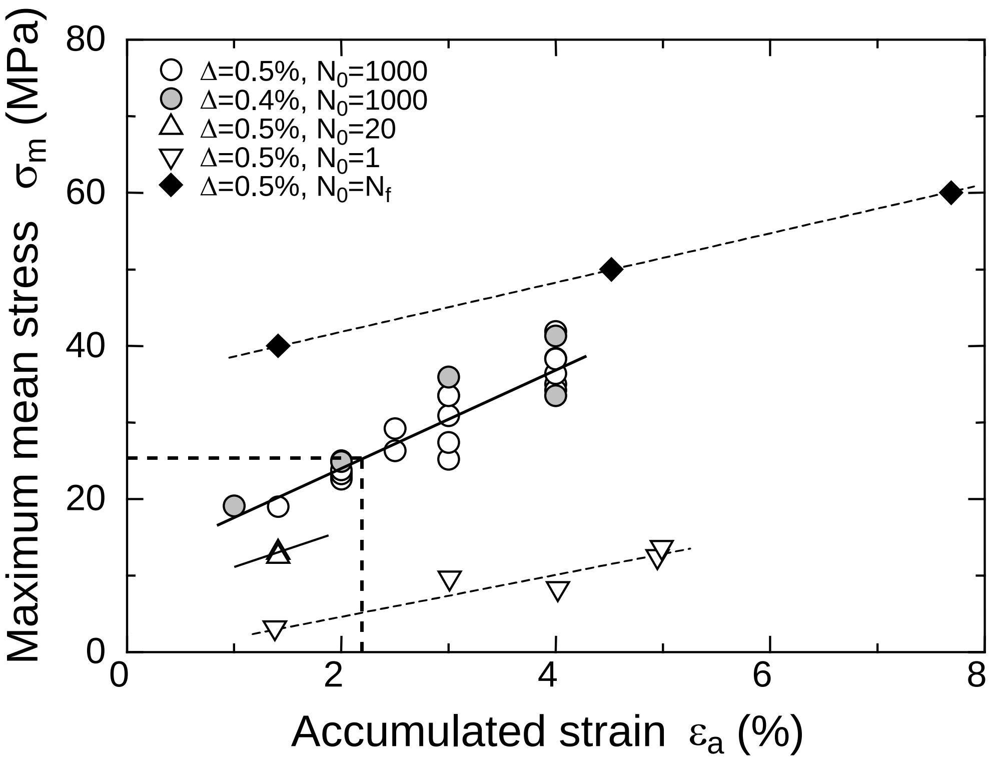


Figure 9. Relationship between maximum mean stress and accumulated strain.

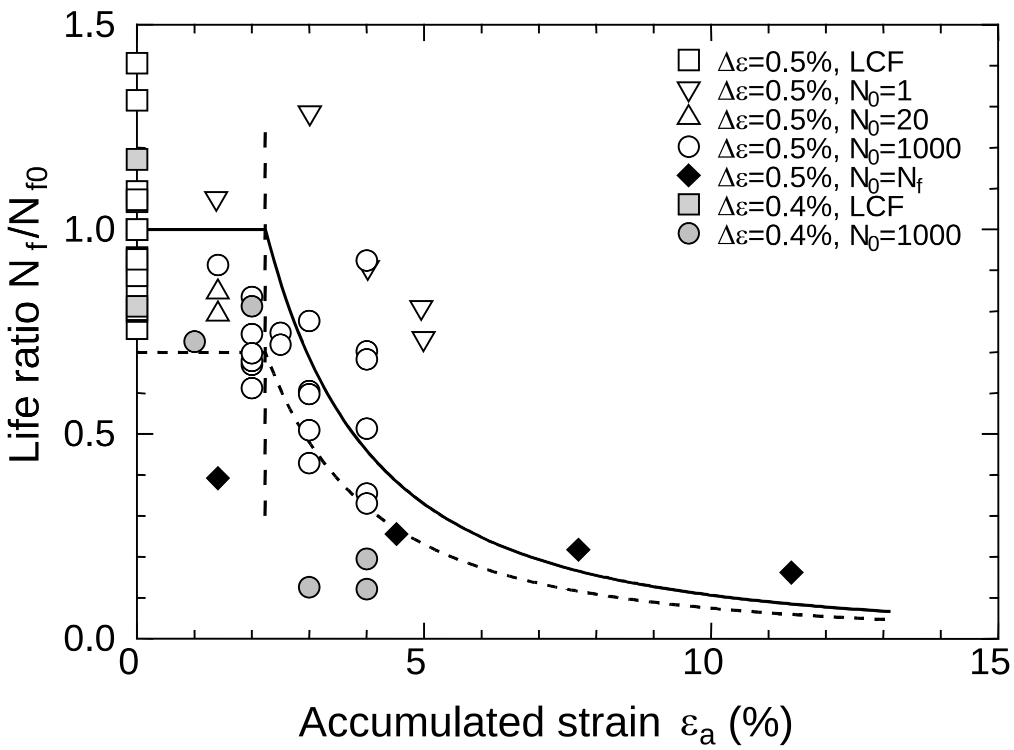


Figure 10. Relationship between life ratio and accumulated strain.

Relationship between the maximum mean stresses and the accumulated strain obtained from ratcheting fatigue tests is shown in Fig. 9. The maximum mean stress increased linearly with increasing the accumulated strain and the ratchet-expired cycle dependency could be seen. The bigger ratchet-expired cycle increases the maximum mean stress so that the failure life would decrease with increasing the ratchet-expired cycle. On the other hand, strain range does not affect the maximum mean stress. The accumulated strain corresponding to the maximum mean stress of 25 MPa is 2.2 % for the ratchet expired cycle, N_0, of 1,000 cycle. The accumulated strain of 2.2 % is larger than the strain limit for membrane plus bending strain of 2% and the ratchet expired cycle N_0=1,000 was considered as conservative for the design condition of fast reactors. Therefore, the strain limit in the present design standard is effective for ratchet conditions, i.e., life reduction by ratcheting does not need to consider when the accumulated strain is less than 2 %. Figure 10 shows the relationship between life ratio and the accumulated strain. The solid and broken lines are the average and lower limit trend for the ratchet expired cycle N_0=1,000, described to correspond to the lines indicating in Fig. 8. We concluded the present strain limit conservatively covers for the fatigue life reduction by ratcheting.

3.3 Micro-crack Growth Behaviors and the Life Reduction Mechanism

Micro-crack initiation and growth is considered as the damage process of fatigue and creep-fatigue failure (Pineau, 1983, Sakurai et al, 1987). The accumulated strain would affect the micro-crack growth behavior since fatigue life reduces in the ratcheting conditions. Figure 11 shows micro-crack growth behaviors observed in ratcheting and low cycle fatigue tests with 0.5 % strain range. Initiation life of micro-crack of about 0.1 mm surface length was several tens percent in the low cycle fatigue test, whereas it was almost negligible in ratcheting fatigue tests. The gradient of the data in the ratcheting fatigue tests are also higher than that in the low cycle fatigue test, but the initiation life shortening would be the dominant factor for the life reduction in the ratcheting fatigue test.

The ratio of micro-crack initiation life to the failure life depends on the strain range, that is, failure life, and the ratio becomes larger in the lower strain range, i.e., the longer life condition. More than half of the life is spent for the micro-crack initiation when the failure life is longer than several ten thousands of cycles for the 316FR steel (Sakurai et al, 1998). Figure 12 shows the relationship between crack length and life fraction. Life fraction is number of cycles normalized by the failure life of each specimen. Micro-crack initiation life was about 70 % of failure life in low cycle fatigue tests 0.4 % strain range, and it was almost negligible when the accumulated strain is greater than 3 %. Assuming the accumulated strain reduces the micro-crack initiation life, the effect of ratcheting on the failure life is larger in the lower strain range tests. Life reduction in 0.4 % strain range tests was much larger than that in 0.5 % tests as shown in Fig. 3. Furthermore life reduction was almost negligible in the higher strain range tests such as 1.0 % (Ishikawa et al, 2003) where crack growth process dominates the life. Crack growth process dominates the fatigue life at the higher strain range and it transfers to initiation life dominant stage with decreasing the strain range and the 0.5 % strain range is considered as the transition stage of them so that the scatter of low cycle fatigue life would be large. Since the crack initiation life decreases due to the accumulated strain, failure lives in ratcheting conditions converged at the lowest limit of low cycle fatigue tests and the scatter of failure life also became small. It is reasonable to regard the initiation life shortening as the life reduction mechanism in ratcheting conditions and the accumulated strain effect is important in lower strain range, longer failure life conditions.

Figure 13 shows the microstructure of cross section around the crack initiation site for a low cycle fatigue test and a ratchet fatigue test of 3 % accumulated strain. Traces of slips were found around the crack initiation site can be seen in the low cycle fatigue test specimen, whereas no traces were found in the ratcheting fatigue test. It suggests that a certain slip deformation in grains is necessary to initiate micro-cracks in low cycle fatigue of lower strain ranges and the accumulated strain by ratchet facilitate the micro-crack initiation so that the failure life reduces in ratcheting fatigue. It will depend on the amount of the accumulated strain whether micro-crack initiation life is negligible or not, and its limit is considered as 2 % in this study.

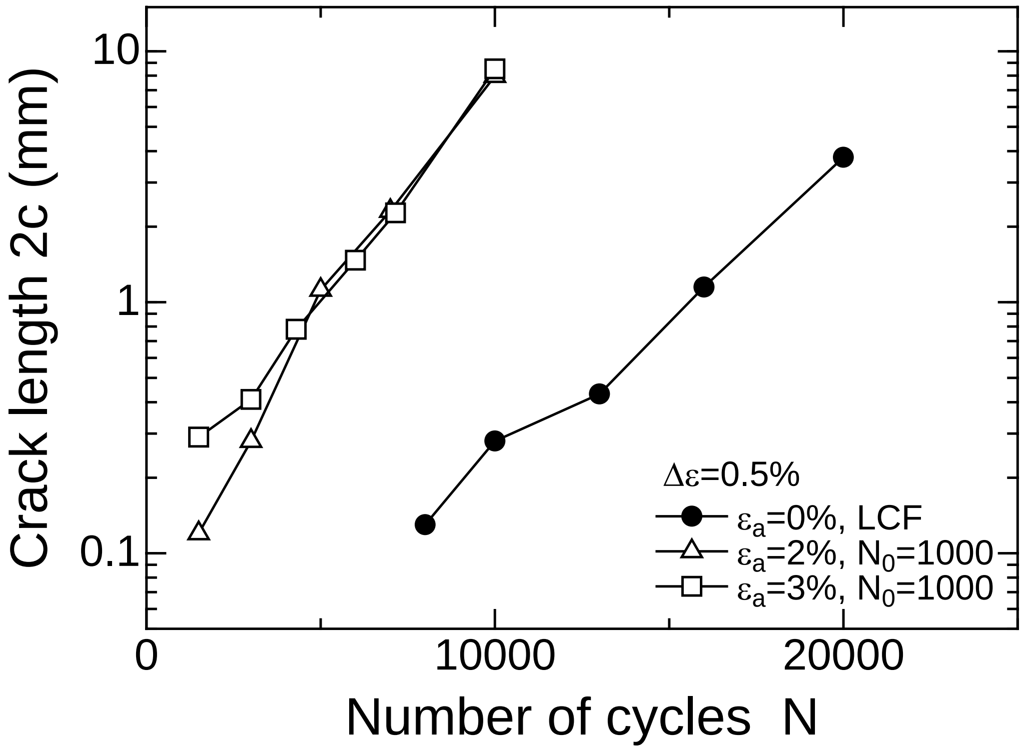


Figure 11. Micro-crack growth behavior observed in low-cycle and ratcheting fatigue tests of 0.5 % strain range.

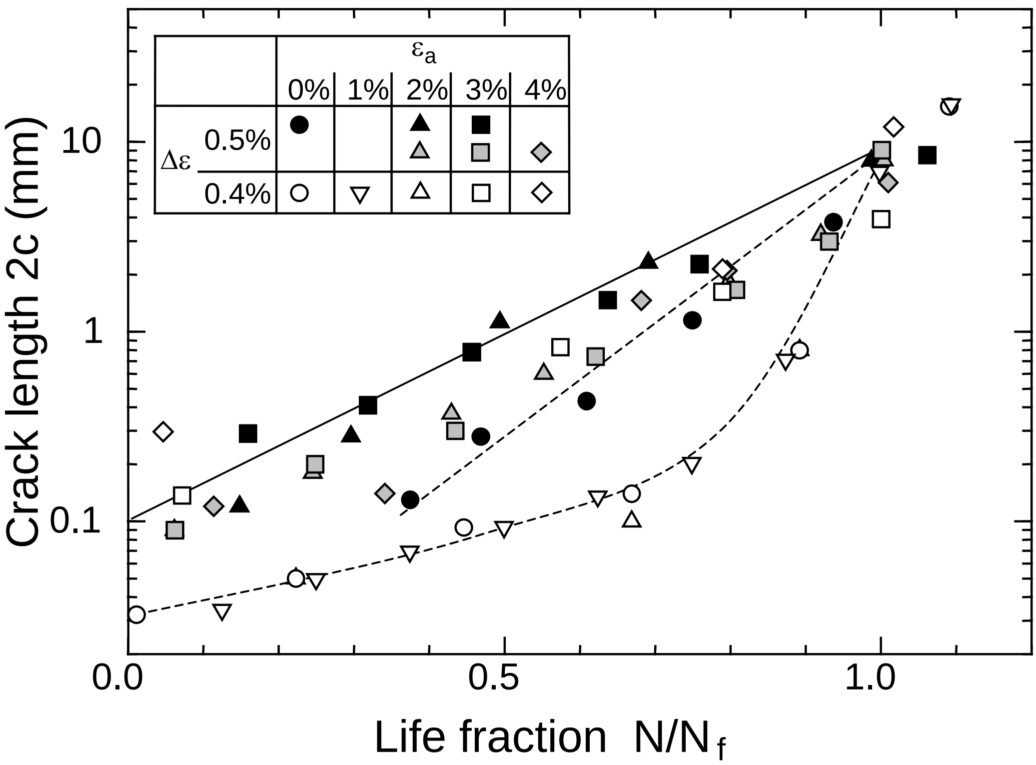
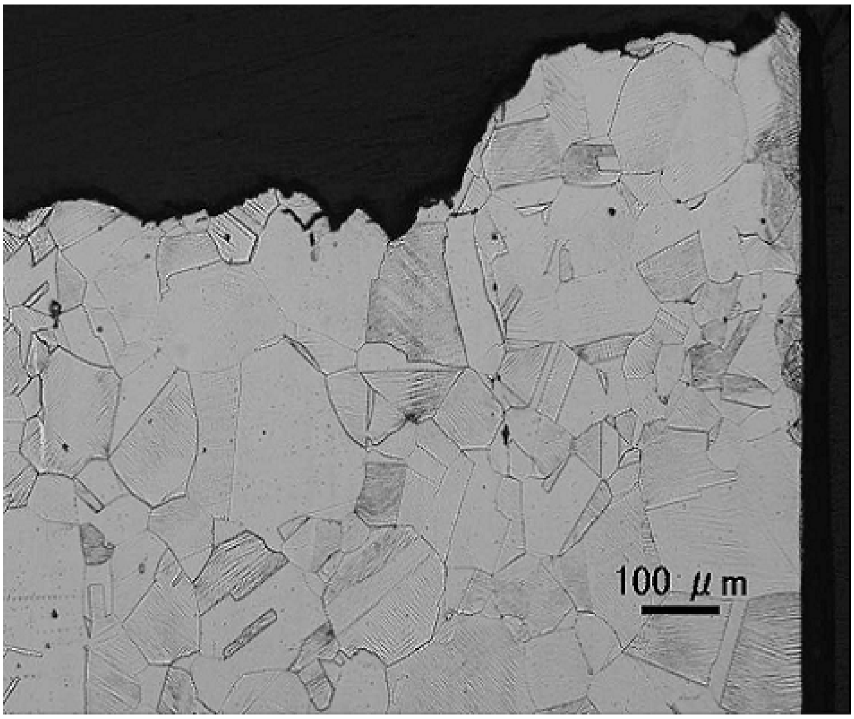
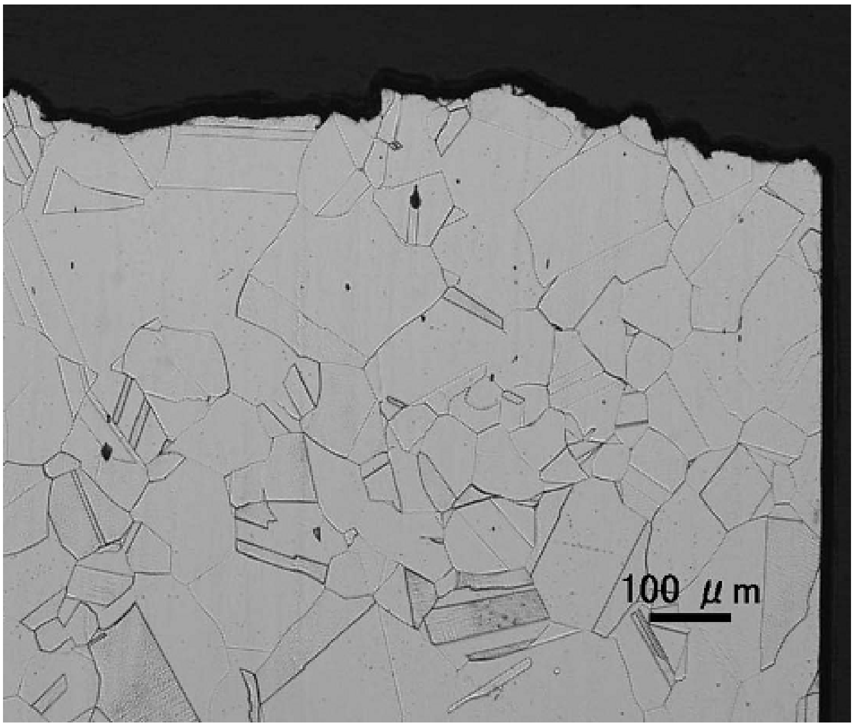


Figure 12. Relationship between crack length and life fraction.



(a)Low cycle fatigue test (failure life: 47580)



(b) Ratcheting fatigue test of 3 % accumulated strain (failure life: 9420)

Figure 13. Microstructure of cross section around crack initiation site.

4. CONCLUSIONS

Damage tolerance limits for ratcheting fatigue and its life reduction mechanisms were investigated in order to improve the structural design methodology of fast reactors. As a result of the present investigation, the following conclusions were obtained;

1) Fatigue life reduction is negligible for 316FR steel when the accumulated strain is less than 2 % at the ratchet expired cycle, N_0=1000. The stain limit of 2 % in the present design standard is effective to ratcheting fatigue since the condition of N_0=1000 is considered as conservative to the operational condition of fast reactors.
2) Mean stress and stress range were increased accompanying with the strain accumulation and the maximum value of them through the life was proportional to the accumulated strain and also depend on the ratchet-expired cycle. Life reduction was negligible when the maximum mean stress was less than 25 MPa.
3) Initiation life of micro-cracks reduced in ratcheting fatigue when the accumulated strain was greater than 3 %. Failure life can be divided into micro-crack initiation and propagation stage and ratchet deformation mainly affects to the initiation life.

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