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Effects of surface morphology on fatigue behavior of reduced activation ferritic/martensitic steel

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Abstract

Depending on the pulse lengths, the operating conditions, and the thermal conductivity, oscillating temperature gradients will cause elastic and elastic–plastic cyclic deformation giving rise to (creep-)fatigue in the structural first wall and blanket components of fusion systems. In order to perform an accurate fatigue lifetime assessment for the international thermonuclear experimental reactor-test blanket module (ITER–TBM) and advanced systems utilizing the existing data base, mechanical understanding of fatigue fracture is mandatory. In this work, the low cycle fatigue (LCF) properties of F82H IEA heat were examined for three kinds of surface morphology with miniaturized hourglass-type fatigue specimens (SF-1). The assumed fatigue lifetime of cooling channels for ITER-TBM was also compared and assessed by correlating the results of LCF tests performed with SF-1 type specimens. Fracture surfaces and crack initiation sites were investigated by scanning electron microscopy (SEM).

1. Introduction

Reduced activation ferritic/martensitic (RAFM) steel is the primary near-term candidate for the blanket structural material of nuclear fusion reactors. Although vanadium alloys and SiC/SiC composite are other potential candidates, their blanket design is more complex and poses many more technological challenges [1,2]. RAFM steel has been developed for a water-cooled solid breeder blanket system, where JLF-1 steel (9Cr–2W) and F82H steel (8Cr–2W) have been extensively studied. Loading of the structural materials in a fusion reactor is, besides the plasma surface interactions, a combined effect of high heat fluxes and neutron irradiation. Depending on the pulse lengths, the operating conditions, and the thermal conductivity, oscillating temperature gradients will cause elastic and elastic–plastic cyclic deformation giving rise to (creep-) fatigue in the structural first wall and blanket components.

Low cycle fatigue (LCF) damage of metals and alloys is known to occur through extended micro-cracking, which is often described as a purely superficial phenomenon not only with respect to crack nucleation but also with respect to crack growth during the major part of the fatigue life [3]. LCF micro-cracks nucleate at the metal surface in the initial stage of LCF tests, generally between 5% and

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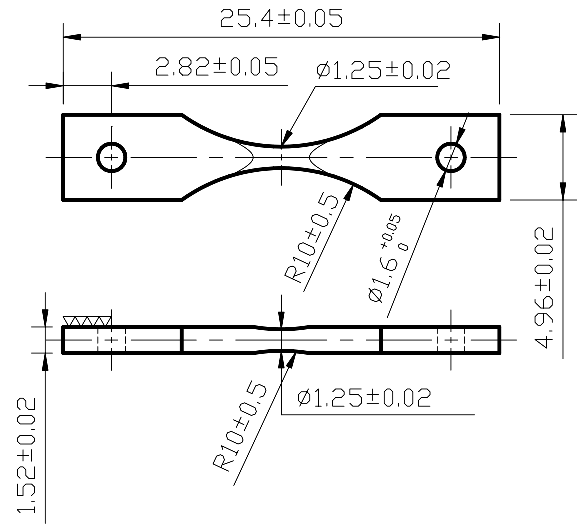

Fig. 1. Dimension of miniaturized hourglass-shaped fatigue specimen.

25% of failure cycles to failure (N_f) [3,4], and the fatal crack is considered to propagate in the bulk within the last 5–10% N_f only [3]. Thus, the major part of fatigue life consists in generalized multi-cracking.

This paper examines the possible relation between surface roughness and fatigue life. Surface heterogeneities resulting from either finishing or polishing processes or by corrosive agents such as fluoridated solutions can negatively affect fatigue life. The surface morphology of cooling channels made from F82H steel is related to service performance under fatigue stress. Also, polishing of the fabricated cooling channels is difficult, and an accepted polishing protocol has not been established. Therefore, this study evaluated and compared the lifetime of cooling channels and correlated the results with LCF testing performed with miniaturized hourglass-type fatigue specimens (SF-1). Fracture surfaces and crack initiation sites were also investigated by scanning electron microscopy (SEM).

2. Experimental procedures

2.1. Material

The material used was F82H-IEA heat, which was normalized at 1313 K for 40 min, air-cooled

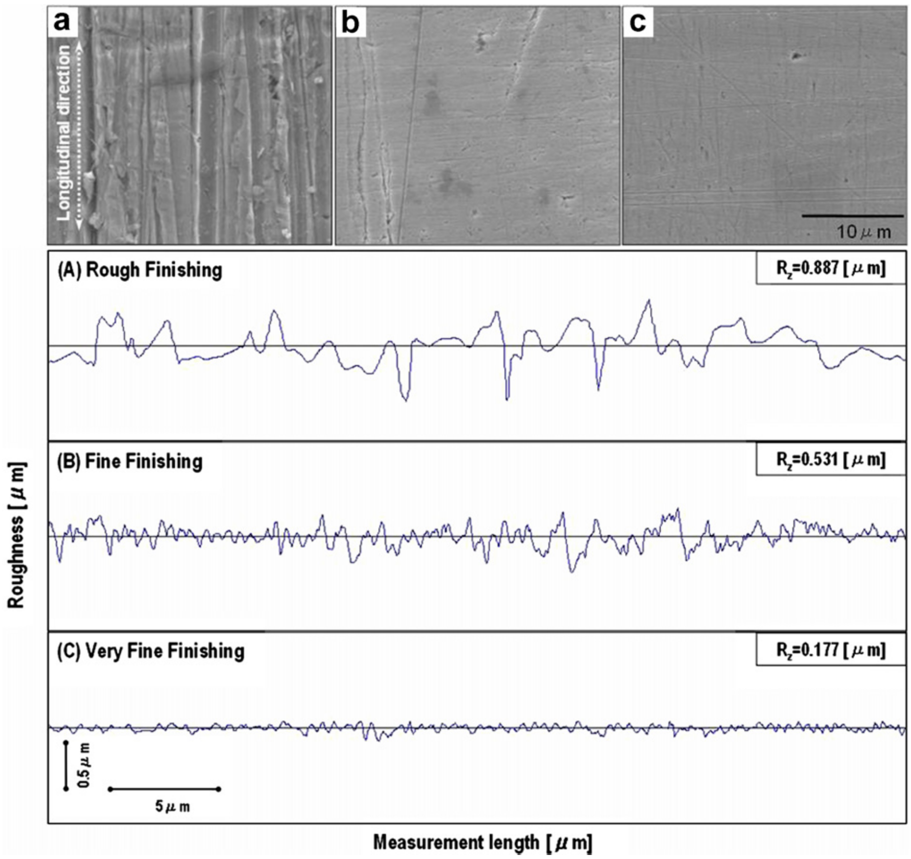

Fig. 2. Surface profiles of SF-1 types of LCF test specimens.

and tempered at 1023 K for 60 min followed by air-cooling. The size of prior austenitic grains was about 200–300 μm. Further details on its chemical composition and characterization can be found elsewhere [5].

The shape and dimensions of the specimens are presented in Fig. 1. It is well known that the hourglass-type specimen has good resistance to buckling, which is a very important issue in miniaturize specimens for push–pull tests. Mini-sized hourglass-type

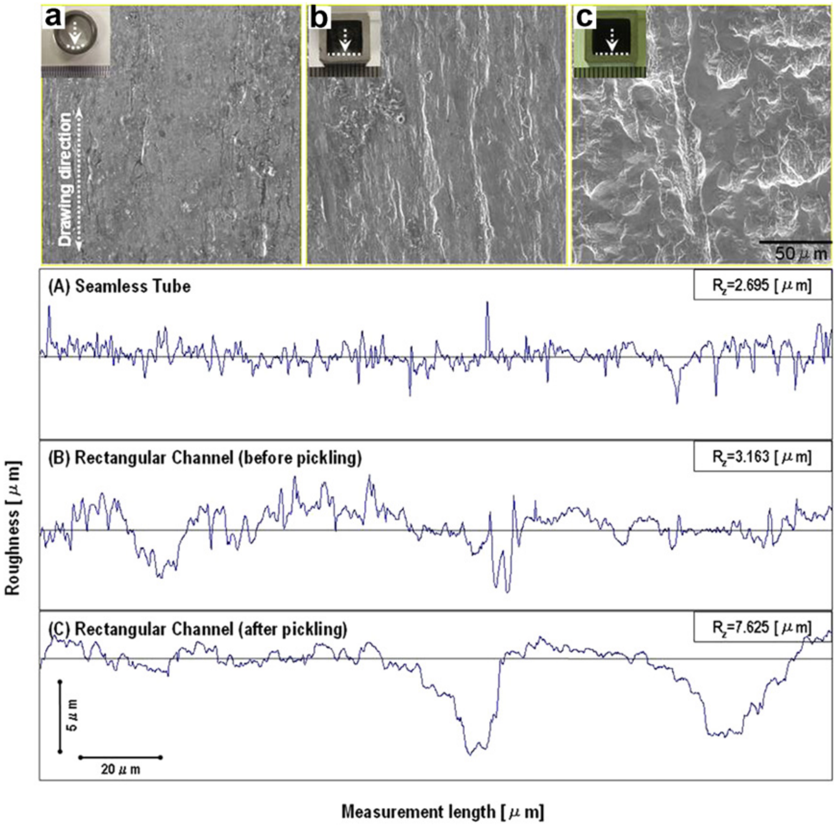

Fig. 3. Surface profiles of cooling channels for the ITER-TBM.

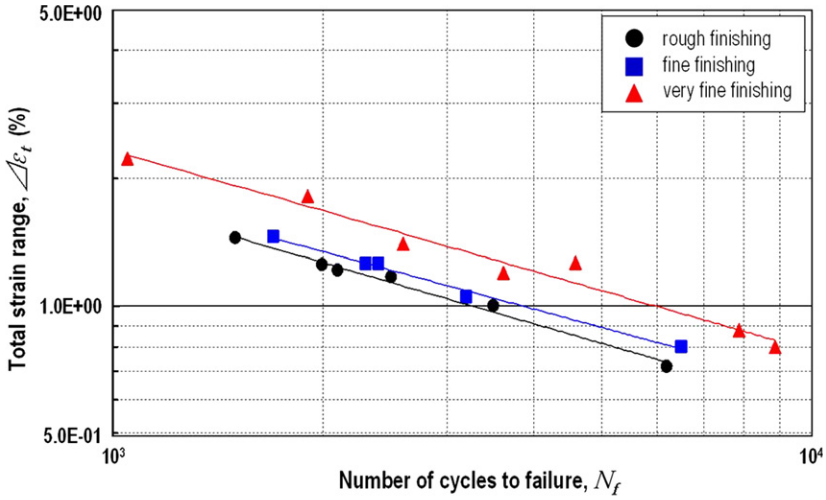

Fig. 4. Results of LCF test controlled by diametral strain.

specimens were machined from the 25^t mm × 320^w mm × 500^l mm plate oriented in the rolling longitudinal direction. In order to reduce stress concentration, the root radius to minimum diameter

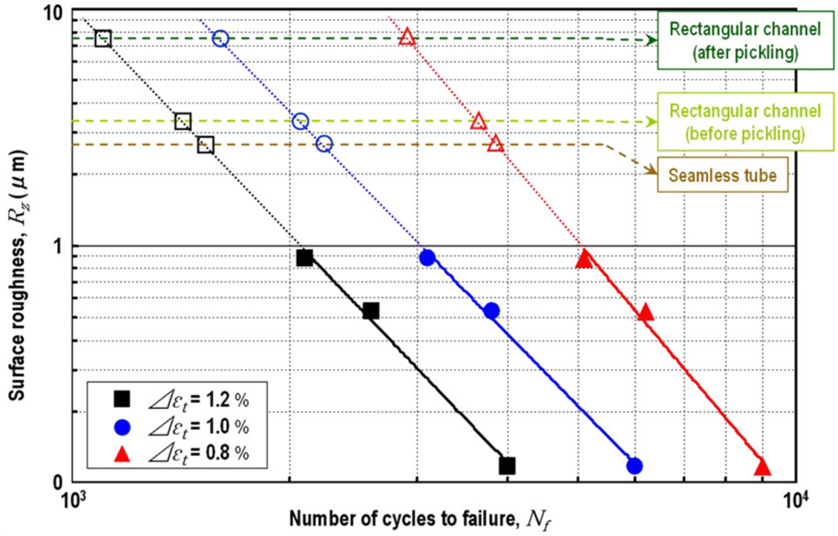

Fig. 5. Surface roughness versus fatigue cycles to failure for F82H steel.

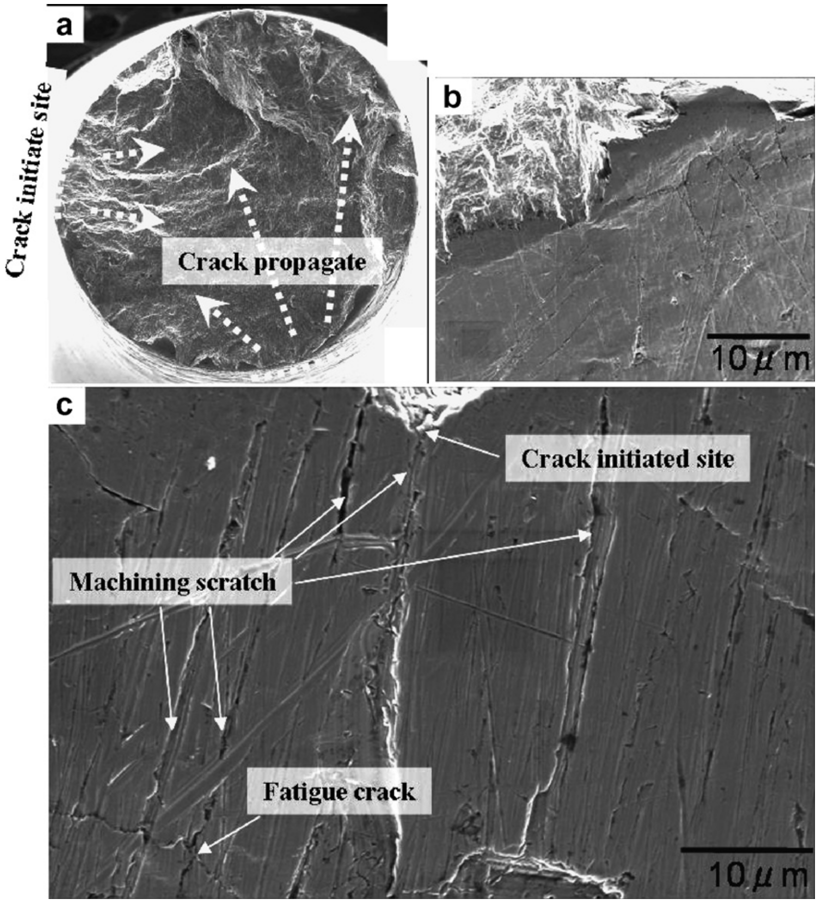

Fig. 6. SEM micrographs of fatigue fracture surface of rough finished specimen ($\Delta\varepsilon_t = 1.17\%$, $N_f = 2469$ cycle).

ratio (R/d) of specimens was selected to be 8, which is the upper limit of the ASTM E-606 recommendation of 6–8. The minimum diameter of mini-sized specimens was 1.25 mm. The mini-sized specimens called SF-1 are proposed for use in accelerator-driven D-Li stripping reaction neutron sources, such as IFMIF [6].

2.2. Test condition

For the LCF test using SF-1 specimen, an electromotive testing machine with a 200 kg load cell was used. Diametral strain controlled fatigue tests were carried out with a triangular stress waveform and a total diametral strain range, $\Delta\varepsilon_d$, of 0.4–1.0%. A laser extensometer was used for monitoring the diametral deformation; it enabled the measurement without any contacts on the specimen surface [7]. A completely push–pull condition was applied, and the total strain range was controlled with diametral strain rate 0.04%/s. The $\Delta\varepsilon_d$ was converted to total axial strain range, $\Delta\varepsilon_a$, using the following formula [8]:

$$\Delta\varepsilon_a = (\sigma/E)(1 - 2\nu_e) - 2\Delta\varepsilon_d, \tag{1}$$

where σ is applied stress, E the elastic modulus, and ν_e is the elastic Poisson's ratio.

According to this formula, the converted axial strain range, $\Delta\varepsilon_a$, was about 0.8–2%. The number of cycles to failure, N_f, was defined at a point where a peak tensile stress decreased by 25% from an extrapolated curve of the peak tensile stress against number of cycles.

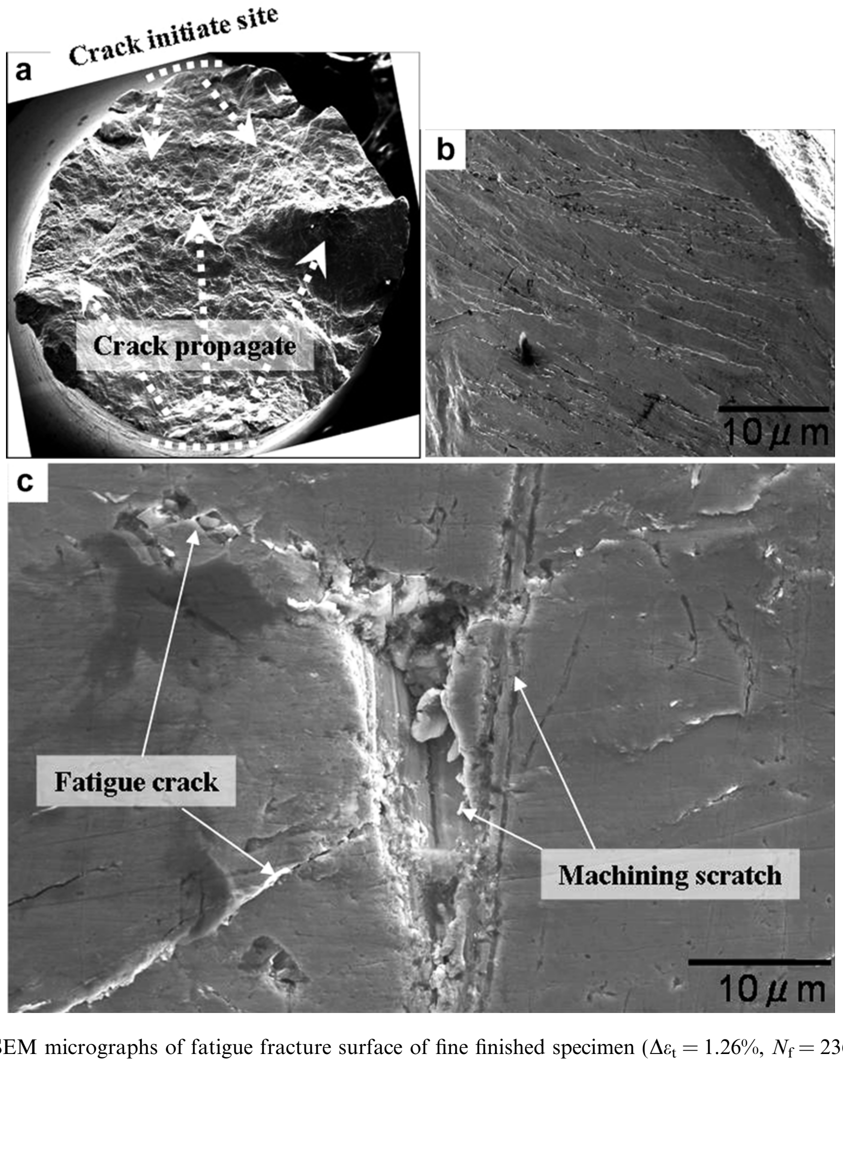

Fig. 7. SEM micrographs of fatigue fracture surface of fine finished specimen ($\Delta\varepsilon_t = 1.26\%$, $N_f = 2367$ cycle).

3. Results and discussion

3.1. Surface roughness

The surface morphologies and a representative profile of the 10 point average surface roughness (R_z) of rough finishing, fine finishing, and very fine finishing LCF specimen are shown in Fig. 2. The baseline of rough finished specimen has a surface roughness value of 0.89 μm. The surface roughness of a very fine finished specimen was less than 0.2 μm. This is a considerably lower roughness than the rough finished specimen.

In this work, the surface roughness profiles in seamless tube and rectangular channels for international thermonuclear experimental reactor-test blanket module (ITER-TBM) were measured with a laser microscope. The variation of surface morphologies and roughness for ITER-TBM cooling channels are shown in Fig. 3 – (a) shows the seamless tube of 15.9 mm diameter, and (b) and (c) show the rectangular channel before and after pickling, respectively. The seamless tube has a surface roughness (R_z) of 2.70 μm, and the rectangular channel before and after pickling has a surface roughness (R_z) of 3.16 μm and 7.63 μm. The surface roughness traces show a large difference between the surface of the rectangular tube, before pickling and after pickling.

3.2. Effects of surface roughness on LCF

The continuous LCF lifetimes of the specimens after rough finishing, fine finishing, and very fine finishing process are shown in Fig. 4. The fatigue lifetime of fine finished specimens ($R_z = 0.53$ μm) was

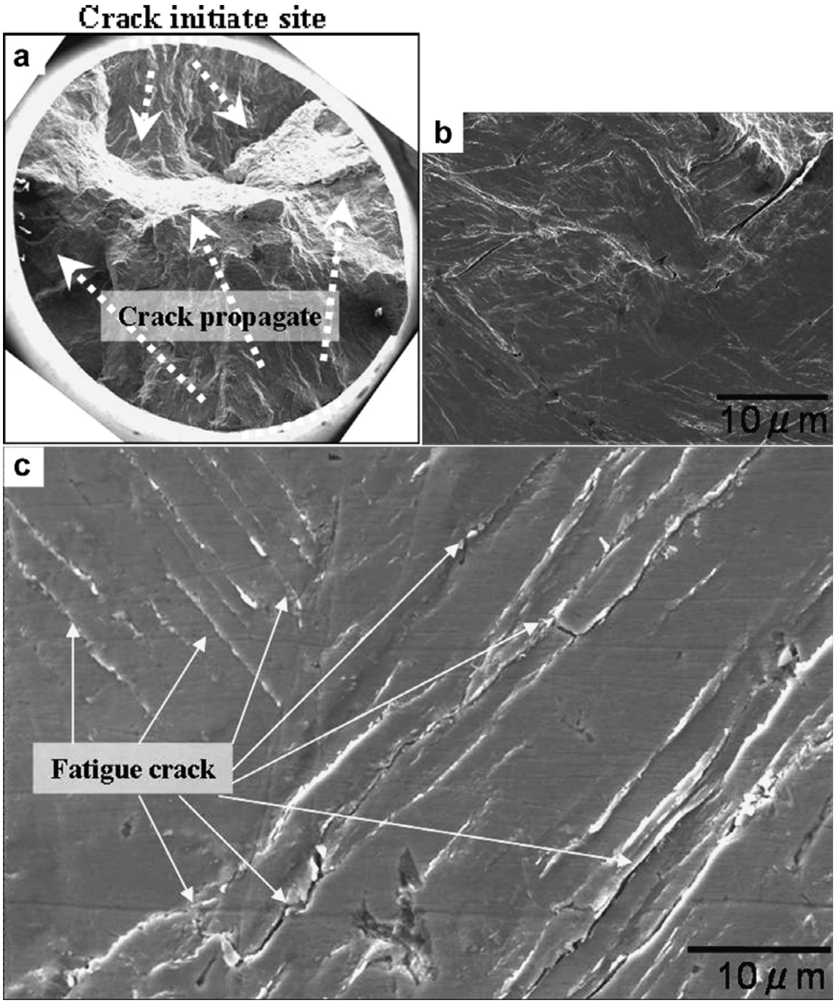

Fig. 8. SEM micrographs of fatigue fracture surface of very fine finished specimen ($\Delta\varepsilon_t = 1.38\%$, $N_f = 2563$ cycle).

slightly longer than those of rough finished specimens. In the meantime, the fatigue lifetime of very fine finished specimen ($R_z = 0.18$ μm) increased significantly, 61.3%. Therefore, the fatigue lifetimes should be dependent on the surface conditions. From these results, surface roughness of the various LCF specimens tested from the rough finished, fine finished, and very fine finished specimens were characterized and recorded. Fig. 5 shows the surface roughness as a function of the number of cycles. Linear regression of the data shown in this figure demonstrates the trend for the fatigue lifetime to decrease with increasing surface roughness. From these results, it can be concluded that the surface roughness affects the fatigue lifetime significantly. It can be assumed that the fatigue lifetime of cooling channels for ITER-TBM might be decreased significantly more than the fatigue life of a test specimen.

3.3. Fracture surface

SEM micrographs of the fracture surface on the LCF tested specimens are shown in Figs. 6–8. From these micrographs, it is seen that the fracture started from the region denoted by the dotted line on the micrograph (a), and this crack penetrated in the direction denoted by the dashed arrows on this specimen. The fatigue cracks preferentially initiated at the site of surface scratches from machining, as shown in Fig. 6(c). In the case of fine and very fine finished specimens, many sub-cracks were observed with extrusion on the side where the fracture initiated, and the cracks propagated along a prior austenitic grain boundary as shown in Figs. 7(b) and 8(b). For the fine finished specimen, however, crack initiation also occurred at the site of machining scratches as shown in Fig. 7(c). From these results, it can be inferred that cracks are preferentially initiated at machining scratches where the surface roughness (R_z) is more than 0.5 μm.

4. Summary

This study has explored the effect of surface morphology on LCF behavior of RAFM steel. The results are summarized as follows:

(1) A strong surface roughness effect on fatigue lifetime was clearly observed. The results indicate that the fatigue lifetime of cooling channels for ITER-TBM might be significantly lower than measured on laboratory test specimens as a result.
(2) Cracks initiated preferentially on scratches remaining from machining, and the cracks propagated along prior austenitic grain boundary. Many sub-cracks were observed with extrusion on the side where fracture initiated.

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