Fractal Analysis of Fracture Surfaces in Materials Crept at High Temperatures or Fatigued by Repeated Bending

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1. Introduction

Fracture processes of materials can be known to some extent by detecting characteristic patterns such as striations or river patterns on the fracture surface with a scanning electron microscope (SEM). However, such characteristic patterns are not visible on the fatigue fracture surfaces of high-strength materials such as SUS631 steel as well as on the creep fracture surfaces of heat-resistant alloys. Fracture surface topography analysis (FRASTA), which relies on the matching of paired fracture surfaces on a computer monitor, is known to be useful for reproducing the fracture process in materials. Unfortunately, it is difficult to apply FRASTA to fatigue fracture surfaces when their morphology changes by cyclic compressive loading or to creep fracture surfaces that are severely oxidized at high temperatures. Therefore, it is necessary to develop a new fractography that is applicable to any fracture surface in materials.

In the fracture of SUS631 steel fatigued by repeated bending, the fractal dimension of the fracture surface (D), which is estimated in a length scale (r) range smaller than one grain-boundary length (1GBL) (r<1GBL) is associated with microcracks or dimples in the grains. The value of D estimated on small areas of the fracture surface increases with increasing distance from the site of crack initiation (the specimen surface), because the fracture surface formed earlier may be damaged more extensively and its complexity may be reduced to larger extent compared with that formed in later stages by cyclic compressive loading. In high-temperature creep of heat-resistant alloys, the value of D, which is evaluated at r>1GBL, represents fracture surface patterns involving grain-boundary microcracks on the fracture surface. Creep fracture is caused by growth of the main crack and linkage of the crack with grain-boundary microcracks in the surface notched specimens. In these specimens, the value of D, estimated on small areas of the grain-boundary fracture surface for r>1GBL, decreases with increasing distance from the site of crack initiation (the notch root). The growth of the main creep crack increases the net section stress in the specimens, which accelerates the crack growth rate and decreases the contribution of grain-boundary sliding to the total creep strain. As a result, the density of grain-boundary microcracks of which nucleation and growth are governed by grain-boundary sliding, decreases with growth of the main crack. This is why the value of D decreases with increasing distance from the site of crack initiation (the specimen surface). Thus, the change in the value of D is closely related to the physical fracture process and mechanism in materials.

The value of D estimated for r>1GBL is also expected to change with crack growth in fatigue fracture. However, the value of D for r>1GBL increases with decreasing magnification of images in fatigued specimens of SUS316 steel. This is attributed to the self-affine nature of the fracture surfaces, because the value of D approaches 2 in the fractal analysis by the box-counting method as the box size (r) increases to the maximum height in the analyzed area of the fracture surface.

2. Experimental Procedure and Fractal Analysis

The ruptured specimens of cobalt-based HS-21 alloy used in the present fractal analysis are the same as those used in a previous study. A specimen with serrated grain boundaries (fractal dimension of the grain-boundary surface profile D_gb=1.241) and the one with straight grain boundaries (D_gb=1.056) (grain diameter d=130 μm) were ruptured under a stress of 108 MPa at 1089 K. The rupture life and the elongation were respectively 235.7 h and 0.0503 for the specimen with serrated grain boundaries, and 146.1 h and 0.0254 for the one with straight grain boundaries. The main alloy composition is Co, 0.27 mass% C, 26.71 mass% Cr, 2.37 mass% Ni, 5.42 mass% Mo and 0.003 mass% B. Fatigue experiments by repeated bending were performed using thin-plate specimens (1.5 mm×10 mm×144 mm) of austenitic SUS316 steel (the main composition is Fe, 0.06 mass% C, 16.80 mass% Cr, 10.20 mass% Ni, 2.11 mass% Mo and 1.00 mass% Mn; d=13 μm) and ferritic 21Cr steel (the main composition is Fe, 0.007 mass% C, 20.65 mass% Cr, 0.45 mass% Co and 0.26 mass% Ti; d=17.4 μm) under fully reversed strain cycling conditions with bending fatigue equipment operating at 0.42 Hz. The maximum total strain range (Δε_t) at the specimen surface was 0.0168 for the SUS316 steel (the fatigue life was 2880 cycles) and 0.0127 for the 21Cr steel (the fatigue life was 3240 cycles). The value of 1GBL was calculated from the grain diameter in these specimens (1GBL=0.577d), assuming that the two-dimensional section of a grain is hexagonal.

Stereo pair photographs of a basic image of the fracture surface and an image tilted by 10 deg. were taken using a SEM equipped with a digital camera. The three-dimensional fracture surface was reconstructed to obtain an elevation map (height data) with 256 grayscale levels using stereo pair images by a computer-aided stereo matching method. The value of D was estimated by the box-counting method on concentric square areas on the elevation map ranging in size from 60 to 660 pixels. In the fractal analysis, the value of D was obtained by the regression analysis from the relationship between the number of boxes (N) covering the fracture surface and the box size (r), namely, \( N \approx r^{-D} \). The value of D was evaluated mainly for r>1GBL on the fatigue fracture surface and also estimated for r<1GBL for comparison. For simplicity, the maximum box size in the fractal analysis was set to be equal to the size of the analyzed area (N) in this study. The value of D was also calculated on small areas of fatigue fracture surface by shifting the analyzed area of 180×180 pixels (containing more than 150 grains) by 6 pixels in the vertical or horizontal direction.

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horizontal direction on the elevation map, and the averaged value of $D$ over 84 data points was obtained to examine the change in the fractal dimension of the fracture surface during fatigue fracture.\textsuperscript{1)}

3. Results and Discussion

3.1. Creep Fracture Surfaces

Figure 1 shows the optical microstructures, analyzed areas and elevation maps of the fracture surfaces in the ruptured specimens of HS-21 alloy. Fractral analysis of the fracture surface was performed on specimens with different grain-boundary microstructures (Figs. 1(a) and 1(b)). The concentric square areas for fractal analysis are set in the central part of the fracture surface (Figs. 1(c) and 1(d)). Brighter areas on the elevation maps are higher parts of the fracture surface (Figs. 1(e) and 1(f)). The fracture surface of the specimen with serrated grain boundaries is more complex than that of the specimen with straight grain boundaries. This is because the former involves more grain-boundary microcracks and steps, which form characteristic fracture patterns in the grain-boundary fracture.\textsuperscript{2)} The value of $D$, which was estimated for $r$>1GBL (1GBL is about 75 $\mu$m), decreases with increasing size of the analyzed area (increasing maximum box size) in the fractal analysis (Fig. 2). However, note that the value of $D$ for $r$>1GBL is always larger in the specimen with serrated grain boundaries than in the one with straight grain boundaries for the same analyzed area. This is attributed to the fact that the fracture surface of the former has a complex morphology with a higher density of grain-boundary microcracks compared with that of the latter.\textsuperscript{21} The larger value of $D$ is also correlated with a longer rupture life and larger creep ductility in the specimens with serrated grain boundaries (Fig. 1). Furthermore, the value of $D$ for $r$>1GBL may depend on the grain size of the specimen (d).\textsuperscript{11–13} Because the grain size generally affects the creep fracture mechanism including initiation and growth of cracks. Therefore, when the value of $D$ is examined in materials with different grain sizes, it should be estimated in almost the same range of scale length ($r$) or in almost the same $r$/$d$ range for almost the same size of analyzed area ($R$) or for almost the same $R$/$d$. The value of $D$ for $r$<1GBL was not estimated in the ruptured specimens of HS-21 alloy because severe oxidation masked the fracture surface patterns.

3.2. Fatigue Fracture Surfaces

Figure 3 shows the analyzed areas, the elevation maps and an example of fractal analysis on the fatigue fracture surfaces of steels. Fatigue cracks initiated at the specimen surface and grew from right to left in specimens of SUS316 (Fig. 3(a)) and 21Cr (Fig. 3(b)). Elevation surfaces and grew from right to left in specimens of HS-21 alloy because severe oxidation masked the fracture surface patterns.

Fracture patterns in the grain-boundary fracture.\textsuperscript{2)} The value of 1GBL decreases with increasing size of the analyzed area ($R$) or with increasing maximum box size in the fractal analysis of the fatigue fracture surfaces of steels (1GBL is about 7.5 $\mu$m for SUS316 steel and about 10 $\mu$m for 21Cr steel) (Figs. 4(a) and 4(b)). The value of $D$ for $r$>1GBL is associated with large river-like steps on the fatigue fracture surface in both steels and is larger in SUS316 steel at the same value of $R$/$d$. The fatigue fracture process may be somewhat different in these steels, even if the fracture mechanisms are similar. In contrast, the value of $D$ for $r$<1GBL is almost independent of the size of the analyzed area, because this value is associated with microstructures such as slip steps or striations in the grains.\textsuperscript{23} The averaged value of $D$ estimated for $r$>1GBL on small areas of the fracture surface increases with increasing distance from the specimen surface (the site of crack initiation) up to about

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Optical microstructures, analyzed areas and elevation maps of the fracture surfaces in specimens of HS-21 alloy ruptured under a stress of 108 MPa at 1089 K. (a, c, e) Specimen with serrated grain boundaries ($D_{\text{GB}}$=1.241, $t_r$=235.7 h, $e_r$=0.0503). (b, d, f) Specimen with straight grain boundaries ($D_{\text{GB}}$=1.056, $t_r$=146.1 h, $e_r$=0.0254). (a) and (b) are optical micrographs. Squares enclosed by white lines on the fracture surfaces of (c) and (d) are the analyzed areas (in pixels), and (e) and (f) are elevation maps (779x675 pixels) corresponding to the reconstructed areas in (c) and (d). ($D_{\text{GB}}$: the fractal dimension of the grain-boundary surface profile; $t_r$: rupture life; $e_r$: elongation).}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Dependence of the fractal dimension of the fracture surface ($D$) on the size of the analyzed area in specimens of HS-21 alloy ruptured under a stress of 108 MPa at 1089 K.}
\end{figure}
In ruptured specimens of HS-21 alloy, the fractal dimension of the fracture surface \( D \) for \( r>1 \text{GBL} \) was always larger in the specimen with serrated grain boundaries than in the one with straight grain boundaries for the same analyzed area, while the value of \( D \) decreased with increasing size of the analyzed area (increasing maximum box size) in the fractal analysis. Similar fractal analysis results were obtained on the fracture surfaces of SUS316 and 21Cr steels fatigued by repeated bending. The value of \( D \) for \( r>1 \text{GBL} \) estimated on small areas of the fracture surface increased with increasing distance from the specimen surface (the crack initiation site) to the location of the final fracture. If the value of \( D \) is examined in materials with different grain sizes \( d_0 \), the value of \( D \) should be estimated in almost the same range of scale length \( r \) (or almost the same \( r/d \) range) for almost the same size of analyzed area \( R \) (or almost the same \( R/d \)). The fracture process of materials can be known by detecting the change in the value of \( D \) with crack growth, irrespective of the presence of characteristic patterns, if parameters for fractal analysis are properly chosen. Thus, it is possible to develop a new fractography on the basis of fractal analysis of fracture surfaces.

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