Automated Image Processing and Analysis of Fracture Surface Patterns Formed during Creep Crack Growth in Austenitic Heat-Resisting Steels with Different Microstructures

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(Received on May 10, 2002; accepted in final form on August 23, 2002)

A computer program of automated image processing was developed for fractal analysis of creep fracture surface profiles in this study. Change in the creep fracture surface patterns during crack growth was examined by the computer-aided image processing and analysis. Fractal analysis was then made using software on the processed images. Creep crack growth experiments were carried out on the surface notched specimens of the austenitic 21Cr–4Ni–9Mn steel at 973 K. Creep crack growth rate was lower in the specimens with serrated grain boundaries than in those with straight grain boundaries. The fractal dimension of the grain-boundary fracture surface profiles was larger in the former specimens than in the latter ones. The fractal dimension was larger in the specimens tested under the lower stress, and decreased with increasing distance from notch root. Effects of grain-boundary microstructures and stress on the fracture patterns were correlated to the microstructure and stress dependence of the density of grain-boundary microcracks linked to the fracture surface. Quantitative evaluation of fracture surface patterns may give an important information about the fracture origin or crack growth direction.

KEY WORDS: automated image processing; image analysis; fracture surface patterns; austenitic heat-resisting steels; creep crack growth; grain-boundary microcracks; fractal dimension.

1. Introduction

Grain-boundary fracture is the dominant fracture mechanism in commercial heat-resistant alloys at high temperatures. However, usual fractography does not give any information about fracture origin or crack growth direction on the grain-boundary fracture surface of high-temperature components, since fracture surfaces are generally covered with oxide layer. On the fracture surfaces created at high temperatures, there are usually no such characteristic patterns as striations in fatigue and river patterns in brittle fracture.

Two-dimensional fracture surface analysis can reveal microstructures such as “debris” and “overhang” on the fracture surface and microcracks linked to the fracture surface, which cannot be detected by three-dimensional fracture surface analysis. Mandelbrot et al. first applied the concept of fractal geometry to the quantitative description of self-similarity of fracture surface morphology in steels. Grain-boundary fracture surfaces also have a self-similarity, and their morphological feature can be estimated by the fractal dimension in the creep-ruptured specimens of heat-resistant alloys. There is a correlation between the fractal dimension of the grain-boundary fracture surface profiles \( D_f \) and the creep-rupture properties. The fractal dimension \( D_f \) estimated in the scale range larger than about one grain-boundary length is larger in the specimens tested under the lower stress, and decreased with increasing distance from notch root. Effects of grain-boundary microstructures and stress on the fracture patterns were correlated to the self-similarity of the grain-boundary fracture surface profiles (\( D_f \)). Grain-boundary fracture pattern may change during creep crack growth at high temperatures. Computed crack growth at high temperatures. Computer-aided image analysis has been widely applied to the quantitative evaluation of fracture surface patterns and microstructures in materials. Image processing is usually carried out in order to extract characteristic patterns of images before image analysis. It is favourable to employ automated image processing and analysis for quantitative description of fracture surface profiles, since difference in manual image processing or manual operation may affect the result of fractal analysis. In this study, a computer program was developed for automated image processing. The fractal dimension of grain-boundary fracture surface profiles was estimated on the automatically processed images in the surface notched specimens of the austenitic 21Cr–4Ni–9Mn steels with different grain-boundary microstructures ruptured at 973 K. Change in the fractal dimension during creep crack growth was examined by the fractal analysis of the grain-boundary fracture surface profiles. Effects of grain-boundary microstructure and stress on the creep crack growth were also examined using the surface notched
specimens at 973 K. Effects of grain-boundary microstructures and creep stress on the fracture patterns were then discussed in connection with the density of grain-boundary microcracks linked to the fracture surface.

2. Image Processing and Fractal Analysis

Visual Basic was used for programming of automated image processing. Figure 1 shows the procedure of image processing employed in this study. The resulting images are also shown in the figure. In the program, a red line with one pixel width is drawn on images (bitmap files) of 256 grey scale levels for fractal analysis in the following process:

(1) The threshold value \( T \) of brightness for binarization was automatically obtained by the mode method from the brightness histogram of images. In the binarization of images, all pixels whose brightness \( C \) is equal to or larger than \( T \) (\( C \geq T \)) should be converted to white pixel (\( C = 255 \)), and others (\( C < T \)) should be changed into black pixel (\( C = 0 \)).

(2) A binary image processing is employed to eliminate “isolated points” of one pixel size in both white and black regions. The fracture surface profile is detected by the border following. A red line with one pixel width is then drawn in order to trace the fracture surface profile between white and black regions in the manner that one pixel is at least connected with one of neighbouring eight pixels (8-neighbours).

(3) Final binary image processing is carried out to eliminate “islands”, and the red line of the fracture surface profile is then converted to the four-connective one in which one pixel is at least connected with one of nearest four pixels (4-neighbors).

The procedure (3) can be neglected or a little manual processing may be necessary in some cases.

Automated fractal analysis of processed images on the creep fracture surfaces profiles was made using a computer program, which was developed in our laboratory. The fractal dimension of the grain-boundary fracture surface profiles was estimated in the length scale range larger than about one grain-boundary length.

3. Materials and Experimental Procedure

Creep crack growth experiments were carried out at 973 K using surface-notched round bar specimens of the austenitic 21Cr–4Ni–9Mn steels with different grain-boundary configurations. Details of the heat-treatments were described in the reference.\(^1\)\(^2\) Figure 2 shows the microstructures of the heat-treated specimens of the steel. The specimens have the same hardness (about 320 Hv, Hv: Vickers hardness number) and grain diameter (about 9.9×10^{-3} m) but different grain-boundary configurations. The fractal dimension of the grain boundaries (\( D_{gb} \)) is larger in the specimen with serrated grain boundaries (\( D_{gb} = 1.233 \)) than in that with straight grain boundaries.

Fig. 1. Procedure of automated image processing in this study.

Fig. 2. Optical micrographs of the heat-treated specimens in the 21Cr–4Ni–9Mn steel. (a) Specimen with straight grain boundaries (\( D_{gb} = 1.094 \)), (b) specimen with serrated grain boundaries (\( D_{gb} = 1.233 \)), (\( D_{gb} \): fractal dimension of the grain boundaries).
Both grain-boundary and matrix precipitates are M₂₃C₆ type carbide in these specimens. Heat-treated specimens were then machined into the surface notched test pieces of 5 mm diameter and 30 mm gauge length for creep crack growth experiments at 973 K. The gross section stresses in the experiments were 167, 196 and 245 MPa.

Figure 3 shows the schematic illustration of crack geometry and the locations of sampling of fracture surface profiles for the image processing and analysis in the surface notched specimens ruptured at 973 K. Figure 4 shows the increment of the crack depth with time in the surface notched specimens of the 21Cr–4Ni–9Mn steels crept at 973 K. Creep crack growth rate is lower in the specimens with serrated grain boundaries than in those with straight grain boundaries under constant stress intensity factor (Kᵢ). Creep crack growth rate is very low at the small values of Kᵢ, and the threshold value of Kᵢ below which creep cracks do not grow is larger in the specimens with serrated grain boundaries.

4. Experimental Results

4.1 Creep Crack Growth in Materials

Figure 4 shows the increment of crack depth with time during creep at 973 K. Grain-boundary cracks initiated at the notch root and grew into inside of the specimen. The crack growth period is longer in specimens with serrated grain boundaries than in those with straight grain boundaries. Only grain-boundary fracture was observed on both specimens ruptured at 973 K. Many grain-boundary microcracks that are linked to or in the vicinity of the main crack are visible in both specimens with serrated grain boundaries and those with straight grain boundaries in the 21Cr–4Ni–9Mn steels. The length of surface crack is given by dθ/2 (θ: the open angle), and can be experimentally determined by using an optical microscope. Therefore, calculating value of θ based on this relationship, one can obtain the crack depth a by a geometrical consideration. The stress intensity factor (Kᵢ) was calculated using the following equation proposed by Kiuuchi et al.:

\[
Kᵢ = \sigma_s (\pi a)^{1/2} \{1.12 + 0.30(d - 1.85/R)a \quad - 6.63/d^2 - 10.25/(Rd)a^2 + 23.13/d^3 - 18.75/(Rd^2)a^3 \} \quad (a/d \leq 0.4 \quad \text{and} \quad R \geq 0.5d) \quad (1)
\]

where \(\sigma_s\) is the gross section stress. The number of grain-boundary microcracks linked to the fracture surface was also examined on the ruptured specimens with an optical microscope.

4.2 Effects of Microstructures and Stress on Fracture Patterns

Figure 6 shows the relationship between crack growth rate and stress intensity factor (Kᵢ) in the surface notched specimens of the 21Cr–4Ni–9Mn steel.7 Creep crack growth rate is lower in the specimens with serrated grain boundaries than in those with straight grain boundaries under constant stress intensity factor (Kᵢ). The crack growth rate is very low at the small values of Kᵢ, and the threshold value of Kᵢ below which creep cracks do not grow is larger in the specimens with serrated grain boundaries.

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A red line is originally drawn between the white and the black regions in the automatically processed images (Figs. 7(d), 7(e) and 7(f)). Characteristic patterns of each fracture surface profile seem to be preserved after automated image processing. The number of the microcracks seems to decrease with increasing distance from notch root ($x$) (for example, Figs. 7(a) and 7(b)). The number of the microcracks is larger in the specimen with serrated grain boundaries ($D_{gb}/H_{11005}=1.233$) than in that with straight grain boundaries ($D_{gb}/H_{11005}=1.094$) at the same distance from notch root ($x=0.3$ mm). The fractal dimension of the grain-boundary fracture surface profiles was estimated on various locations (Fig. 2) in the scale length range larger than about one grain-boundary length (about $6\times10^{-5}$ m).

Figure 8 shows the change in the fractal dimension of the grain-boundary fracture surface profiles ($D_{gb}$) with the distance from notch root ($x$). The fractal dimension decreases with increasing distance ($x$) from notch root, and is larger in the specimens with serrated grain boundaries ($D_{gb}=1.233$). The fractal dimension also decreases with increasing gross section stress ($\sigma_s$). These results can be correlated with the grain-boundary microcracks linked to the fracture surface.

Figure 9 shows the change in the density of the grain-boundary microcracks, $N_c$, linked to the fracture surface with the distance ($x$) from notch root. The density of the microcracks ($N_c$) decreases with the distance from notch root, and also decreases with increasing gross section stress ($\sigma_s$). The value of $N_c$ is larger in the specimens with serrated grain boundaries ($D_{gb}=1.233$). Creep fracture mechanism in the steels is associated with the dependence of fracture patterns on the crack growth, the grain-boundary microstructures and the gross section stress. This will be discussed in the next chapter.

5. Discussion

5.1. Effects of Crack Growth, Gross Section Stress and Grain-boundary Microstructures on Creep Fracture Pattern

Figure 10 shows schematic illustration of the intensely creeping region ahead of the growing main crack. At the early stage of creep crack growth, many grain-boundary microcracks can initiate and grow ahead of the main crack owing to stress concentration induced by both main crack...
and notch during relatively long period. The main crack gradually passes through the intensely creeping region under the lower net section stress (Fig. 10). Some grain-boundary microcracks would link up with the main crack in creep fracture process (Fig. 9), and the fracture surface (and the crack surface) is rugged or tortuous in the early stage of the growth of the main crack (Figs. 5 and 7(a)). The growth of the main crack becomes accelerated owing to the increase in the net section stress as a result of the crack growth (Fig. 4), and there may not be enough time for initiation and growth of the microcracks ahead of the main crack, although the size of intensely creeping region increases with the growth of the main crack. This results in the smaller number of the microcracks linked to the fracture surface and less complicated fracture surface patterns (Figs. 5 and 7(b)).

Figure 11 shows schematic illustration of the effects of

![Figure 7](image1)

Examples of original images (a, b, c) and processed ones (d, e, f) of the grain-boundary fracture surface profiles in the specimens of the 21Cr–4Ni–9Mn steel ruptured under a gross section stress of 196 MPa at 973 K (arrows indicate grain-boundary microcracks). (a, b, d, e) Specimen with serrated grain boundaries ($D_{gb}=1.233$), (c, f) specimen with straight grain boundaries ($D_{gb}=1.094$). (a, c, d, f): $x=0.3$ mm; (b, e): $x=0.7$ mm; $x$: the distance from notch root.

![Figure 8](image2)

Change in the fractal dimension of the grain-boundary fracture surface profiles ($D_f$) with the distance from notch root ($x$).

![Figure 9](image3)

The relationship between the number of the grain-boundary microcracks, $N_c$, linked to the unit projected length of the fracture surface profile and the distance from notch root, $x$, in the surface notched specimens ruptured at 973 K.

![Figure 10](image4)

Schematic illustration of crack growth process in the surface notched specimens.
about one grain-boundary length is an increasing function linked to the fracture surface, such that:

As the fractal dimension decreases with increasing distance from notch root (x) and increasing gross section stress ($\sigma_g$), the function $D_f(N_c)$ can be written as

$$D_f(N_c)=g(x)h(\sigma_g) ......................(3)$$

where $g(x)$ is a decreasing function of $x$ and $h(\sigma_g)$ is a decreasing function of $\sigma_g$.

It is known that in commercial heat-resistant alloys including the 21Cr–4Ni–9Mn steel the creep ductility is larger and the rupture life is longer in the specimens with serrated grain boundaries than in those with straight grain boundaries.$^{2-4,12,15-17}$ There is a relationship between the creep ductility, $\varepsilon_c$ (and the rupture strength, $\sigma_r$), and the fractal dimension of the grain-boundaries, $D_{gb}$, and the value of $\varepsilon_c$ and $\sigma_r$ increases with increasing value of $D_{gb}$.$^{2,3}$ The value of $D_f$ is also larger in the specimens with the larger values of $D_{gb}$ in the heat-resistant alloys.$^{5-7}$ Therefore, $D_f(N_c)$ is a function of the value of $D_{gb}$ to be expressed as

$$D_f(N_c)=f(D_{gb}) ......................(4)$$

where $f(D_{gb})$ is an increasing function of $D_{gb}$. Combining Eqs. (3) and (4), one obtains finally the following equation:

$$D_f(N_c)=F(D_{gb})G(x)H(\sigma_g) ......................(5)$$

where $F(D_{gb})$, $G(x)$ and $H(\sigma_g)$ are functions similar to $f(D_{gb})$, $g(x)$ and $h(\sigma_g)$, respectively. If an increasing function of the creep ductility ($\varepsilon_c$), $F'(\varepsilon_c)$ is chosen instead of $F(D_{gb})$, one obtains

$$D_f(N_c)=F'(\varepsilon_c)G(x)H(\sigma_g) ......................(6)$$

If the functional form of $F(D_{gb})$ (or $F'(\varepsilon_c)$), $G(x)$ and $H(\sigma_g)$ is known on any fracture surface profile, Eq. (5) or (6) can give exact information about the fracture origin, the crack growth direction or the fracture mechanism. The functions $F(D_{gb})$ (or $F'(\varepsilon_c)$), $G(x)$ and $H(\sigma_g)$ may also involve the effect of oxidation on the creep fracture process,$^{39}$ although it is not clear in this study. Thus, quantitative estimation of fracture surface patterns can give an important information about the initiation and growth of the main crack or the fracture mechanism in high-temperature fracture by tracing the fracture surface profiles from simpler morphology to more complicated one. This method is also applicable to three-dimensional analysis of fracture surfaces.

6. Conclusions

Creep crack growth at 973 K and change in the fracture patterns during creep were investigated on the surface notched specimens of the austenitic 21Cr–4Ni–9Mn steel with different grain-boundary microstructures. A computer program was developed for automated image processing of the creep fracture surface profiles. The fractal dimension of grain-boundary fracture surface profiles was then estimated on the automatically processed images of the creep-ruptured specimens. The results obtained were summarised as follows.

(1) The fracture surface patterns were complex at the early stage of creep crack growth, and became simpler with the crack growth, as indicated by the decrease of the fractal dimension of the grain-boundary fracture surface profiles
that was estimated in the scale range larger than about one grain-boundary length. The fractal dimension was larger in the specimens under the lower stresses.

(2) The fractal dimension of the grain-boundary fracture surface profiles was larger in the specimens with serrated grain boundaries than in those with straight grain boundaries. Crack growth period was longer and creep crack growth rate was lower in the former specimens than in the latter ones.

(3) The fracture surface patterns formed during crack growth and the dependence of the fractal dimension on grain-boundary microstructure and stress were correlated to the density of grain-boundary microcracks linked to the fracture surface, that is, the initiation and growth of the microcracks in the intensely creeping region ahead of the main crack.

(4) Quantitative estimation of fracture surfaces can give an important information about the fracture initiation and growth of the main crack or the fracture mechanism, if the fracture surface pattern is defined as a function of grain-boundary microstructures, applied stress and crack growth process.

Acknowledgements

The authors thank The Iron and Steel Institute of Japan for financial support (Tekkou-Kenkyu-Josei [b]).

REFERENCES

1) B. B. Mandelbrot, D. E. Passoja and A. J. Paullay: Nature (London), 308 (1984), 721.
2) M. Tanaka and H. Iizuka: Z. Metallkd., 82 (1991), 442.
3) M. Tanaka: J. Mater. Sci., 27 (1992), 4717.
4) M. Tanaka: J. Mater. Sci., 32 (1997), 1781.
5) M. Tanaka: Z. Metallkd., 84 (1993), 697.
6) M. Tanaka: J. Mater. Sci., 28 (1993), 5753.
7) M. Tanaka: Z. Metallkd., 88 (1997), 217.
8) T. Nishihara: J. Jpn. Inst. Met., 57 (1993), 209.
9) P. Streitenberger, D. Foerster, G. Kolbe and P. Veit: Scr. Metall. Mater., 33 (1995), 541.
10) X. W. Li, J. F. Tian, Y. Kang and Z. G. Wang: Scr. Metall. Mater., 33 (1995), 803.
11) M. Tanaka, A. Kayama, Y. Sato and Y. Ito: J. Mater. Sci. Lett., 17 (1998), 1715.
12) M. Tanaka, O. Miyagawa, T. Sakaki, H. Iizuka, F. Ashihara and D. Fijishiro: J. Mater. Sci., 23 (1988), 621.
13) M. Tanaka, H. Iizuka and F. Ashihara: J. Mater. Sci., 23 (1988), 3827.
14) A. Kiuchi, M. Aoki, M. Kobayashi and K. Ikeda: Tetsu-to-Hagané, 68 (1982), 1830.
15) H. Iizuka and M. Tanaka: Tetsu-to-Hagané, 71 (1985), 727.
16) M. Tanaka, H. Iizuka and M. Tagami: J. Mater. Sci., 24 (1989), 2421.
17) M. Tanaka, H. Iizuka and F. Ashihara: Tetsu-to-Hagané, 76 (1990), 113.
18) F. Garofalo: Fundamentals of Creep and Creep Rupture in Metals, translated by M. Adachi, Maruzen Book Co., Tokyo, (1968), 124.
19) T.G. Langdon and R.B. Vastava: Mechanical Testing for Deformation Model Development, eds. by R.W. Rohde and J.C. Swearengen, ASTM STP765, ASTM, Philadelphia, (1982), 435.
20) M. F. Ashby, R. Raj and R. C. Gifkins: Scr. Metall., 4 (1970), 737.
21) R. Raj and M. F. Ashby: Metall. Trans., 2 (1971), 1113.
22) M. F. Ashby: Acta Metall., 20 (1972), 887.