RAPID PUBLICATION

Fractal Analysis of Fractured Surfaces in Cu-9.7 mass% Zn Alloy

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Fracture surfaces of Cu-9.7 mass% Zn alloy have been analyzed in terms of the fractal dimension. Specimens with the average grain size of 130 μm were tensile tested on an Instron type testing machine from 300 to 973 K in Argon gas atmosphere. The initial strain rate was $3.5 \times 10^{-3} \text{ s}^{-1}$. Microstructure and fracture surfaces were observed by optical microscopy and scanning electron microscopy. The fractal dimension was determined from digitized images of the surfaces using the vertical section method. A ductility minimum appeared at 673 K. Cracks or voids were most frequently observed on grain boundaries of the specimen fractured at the temperature corresponding to the low ductility.

There are two kinds of dimension named D_1 and D_2 . D_1 represents the void formation and crack propagation, and D_2 represents the effect of grain boundary migration on the void formation. D_1 and D_2 increase with increasing test temperature and the difference between the two values decreases with increasing temperature.

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Fractured surfaces consist of many complicated zig-zag planes. Recently, a concept of the "Fractal dimension" has been applied to the analysis of these surfaces⁽¹⁾⁻⁽³⁾. The "fractal dimension" means self-similarity in mathematics and its value has been used to estimate the irregularity of fractured surfaces in materials science. These reports have dealt with some Al alloys tensile tested at room temperature, and the correlation between the fractal dimension and fracture strength has been studied.

In a high temperature deformation, grain boundary migration and sliding occur and the stress concentration at grain boundaries causes the formation of voids. The coalescence of these voids and crack propagation along grain boundaries lead to the intergranular fracture in the high temperature deformation. In this case, the complicated combination of these elementary processes may have great effects on the surface irregularity. Consequently, the fractured surfaces are more complicated than those of the specimens tested at low temperatures.

The effects of grain boundary behaviors on the high temperature fracture have been studied mainly by metallography such as optical microscopy and electron microscopy. Meanwhile, there are very few studies by fractography to quantitatively estimate the contribution of the grain boundary behavior in the high temperature deformation.

In the present work, the fractured surfaces were analyzed

in terms of the fractal dimension to estimate the contribution of the grain boundary behavior in the high temperature deformation.

A Cu-9.7 mass% Zn alloy was prepared in a high purity Ar gas atmosphere from electrolytic copper and pure zinc in a carbon crucible. The ingot was then hot rolled at 1073 K and cold rolled to a thickness of 1 mm. The tensile test was performed on an Instron type testing machine (TENSILON UTM-1) from 300 to 973 K in the Ar gas atmosphere. The initial strain rate was $3.5 \times 10^{-3} \text{ s}^{-1}$. The fractured surfaces and microstructure were observed with a SEM (JSM-840A) and an optical microscope. The fractured specimen was imbedded into resin and the side surface of the fractured specimen was observed with SEM and the image of the surface was digitized to calculate the fractal dimension. The fractal dimension (D) was calculated on the basis of a Vertical section method⁽¹⁾. When a straight distance from one end to the other of the surface profile is L and the profile is divided by a sectioning length of L/r , the dimension is defined as

$$D = \log(n) / \log(r),$$

where n is the number of divisions with a sectioning length L/r , and L is about 1.0 mm for each calculation. The D has only one value if the profile is made from a single mechanism such as the Koch curve⁽⁴⁾ in mathematics.

Temperature dependence of the ductility in Cu-9.7Zn alloy is shown in Fig. 1. The elongation to fracture shows a minimum at 673 K. In the specimen deformed at the temperature of ductility minimum, there existed large voids or cracks on grain boundaries⁽⁵⁾. These voids have

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Fig. 1 Temperature dependence of ductility in Cu-9.7 mass% Zn alloy.

been formed during deformation, and the amount of the voids was larger than that in specimens deformed under more ductile conditions. Thus, the formation of voids on grain boundaries plays an important role in the fracture process.

Fractured surfaces of these specimens changed their morphology with test temperature. At room temperature where ductile fracture was observed, the surface was of the knife edge type, while at 673 K of ductility minimum, the surface was irregular, i.e. the so-called grain boundary brittleness surface. However, at 973 K where the specimen showed fully ductile elongation, the surface still showed some brittle morphology.

Fig. 2 Full logarithm plot of r and n . The solid line is the referential line and the slope is unity. There are two parts which have a larger slope than the referential line.

The r and n plotted on a full logarithm scale are shown in Fig. 2. It is meaningless to divide the curve by a sectioning length which is much less than $1 \mu\text{m}$ or much larger than 1mm , because the slopes come to unity at these sectioning lengths.

This locus has three parts of different slopes named D_1 , D_2 and the transition region. As D_1 and D_2 lie in the ranges of r from 10 to 30 and 80 to 150, these values correspond to the ranges of sectioning length from $30 \mu\text{m}$ to $100 \mu\text{m}$ and $6 \mu\text{m}$ to $12 \mu\text{m}$, respectively. Taking into account the fact that the average grain size of the specimen is $130 \mu\text{m}$, we consider D_1 to reflect the effect of grain size or crack propagation. The larger region of r is comparable to the wave length of grain boundary migration or the dimples caused by the formation of voids on grain boundaries. Hence, D_2 is thought to reflect the grain boundary migration or void formation on the grain boundaries. Therefore, these fractured surfaces are not made from a single mechanism.

Figure 3 shows the relationship between the value of D_1 and the test temperature. Each datum was taken from various parts of the specimens. The value is 1.05 at 300 K. The D_1 value increased with increasing test temperature up to 673 K, but remained almost constant from 673 to 973 K.

The D_1 is from 1.05 to 1.10 when calculated on the assumption that a crack propagates along the shortest path, i.e., the homogeneous void formation on grain boundaries. However, D_1 is about 1.10 to 1.19 for the specimen tested above 573 K in this study. This suggests that the crack propagation is complicate and the void formation is heterogeneous in this alloy. The strength of grain boundary is connected to the void formation and affected by grain boundary structure⁽⁶⁾. The coincidence grain boundaries have higher fracture stresses than random grain boundaries. On the other hand, the relationship between the fracture stress of grain boundaries and the character of grain boundaries changes with the deformation conditions such as test temperature and strain

Fig. 3 Relationship between D_1 and test temperature.

Fig. 4 Relationship between D_2 and test temperature.

rate⁽⁷⁾. Thus, the heterogeneity of the void formation or crack propagation reflect the grain boundary character distribution. The fractal analysis of these brittle fractured surfaces may be useful to discuss the effect of grain boundary character distribution on the fracture process as well as the degree of the irregularity of the fractured surface.

Figure 4 shows the relationship between the value of D_2 and the test temperature. The D_2 value also increased with increasing test temperature, and the difference between D_1 and D_2 tended to decrease with increasing test temperature. The D_2 value was almost equal to the D_1 at 973 K. Hornbogen⁽⁸⁾ reported the changes of the dimension during annealing of a cold-rolled Cu-Zn alloy; the fractal dimension increased with increasing degree of rolling. In the present work, grain boundary migration occurred frequently above 673 K. Since the grain boundary migration releases concentrated stresses on grain boundaries caused by the pile-up of dislocations, stationary grain boundaries are preferential sites for the void forma-

tion. On the other hand, the grain boundary migration changes the shape of the boundary and makes it possible that the void formation occurs at the wavy grain boundary⁽⁹⁾. Thus the profile of the fractured surface resulting from these processes is characterized by the dimension (D_2) calculated from a smaller sectioning length which is comparable to a size of the dimple or a wave length of wavy grain boundaries. As for the crack propagation, the cracks arising from these stationary grain boundaries may propagate along the wavy grain boundaries which migrated during deformation. Then the profile of fractured surface shows the trace of wavy grain boundary.

Thus D_2 reflects the effect of grain boundary migration on the void formation or crack propagation, and D_2 increases with increasing test temperature because of the enhanced grain boundary migration.

In summary, the fractal analysis of the fractured surfaces of the specimen deformed at high temperature gives some information on the effects of grain boundary behavior and of grain boundary character distribution on the void formation during deformation.

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REFERENCES

- (1) B. B. Mandelbrot: *Nature*, **308** (1984), 721.
- (2) C. S. Pande, L. E. Richards, N. Louat, B. D. Dempsy and A. J. Schwoeble: *Acta Metall.*, **35** (1987), 1633.
- (3) E. E. Underwood and K. Banerji: *Mater. Sci. Engng.*, **80** (1986), 1.
- (4) B. B. Mandelbrot: *The Fractal Geometry of Nature*, Freeman, San Francisco, (1982).
- (5) T. Shibayanagi, S. Saji and S. Hori: *Supple. Trans. JIM, Grain Boundary Structure and Related Phenomena*, (1986), p. 473.
- (6) T. Watanabe: *Metall. Trans.*, **14A** (1983), 531.
- (7) T. Shibayanagi, A. Yoshimoto and S. Hori: *J. Japan Inst. Metals*, **54** (1990), 9.
- (8) E. Hornbogen: *Z. Metallk.*, **78** (1987), 622.
- (9) R. Raj and M. F. Ashby: *Metall. Trans.*, **2** (1971), 1113.