JOURNAL OF MATERIALS SCIENCE 33 (1998) 3351–3359

Effects of the creep deformation on the fractal dimension of the grain boundaries in an austenite steel

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The change in the fractal dimension of the grain boundaries during creep was investigated using an austenitic SUS304 steel at 973 K. The fractal dimension of the grain-boundary surface profile (the fractal dimension of the grain boundaries, D, $1 < D < 2$) in the plane parallel to the tensile direction (in the parallel direction) and in the transverse direction, was examined on specimens deformed up to rupture (about 0.30 creep strain). Grain boundaries became serrated and the fractal dimension of the grain boundaries increased with increasing creep strain, because the density of slip lines which formed ledges and steps on grain boundaries increased as the creep strain increased. The increase in the fractal dimension due to creep deformation was slightly larger under the higher stress (118 MPa) than under the lower stress (98 MPa), while the increase of the fractal dimension with strain was a little larger in the specimens tensile-strained at room temperature (293 K) than in the crept specimens. These results were explained by the grain-boundary sliding and the diffusional recovery near grain boundaries, which lowered the increase of the fractal dimension with the creep strain. The fractal dimension of the grain boundaries in the parallel direction was slightly larger than that in the transverse direction in both creep at 973 K and tensile deformation at room temperature, especially at the large strains. This could be correlated with the shape change of the grains by creep or plastic deformation. Grain-boundary cracks were principally initiated at grain-boundary triple junctions in creep, but ledges, steps and carbide precipitates on serrated grain boundaries were not preferential nucleation sites for the cracks.

1. Introduction

The concept of fractal geometry introduced by Mandelbrot has been applied to the interpretation of many phenomena in natural science [1]. In materials science, the fractal geometry has been employed to describe complex but self-similar microstructures in metals and alloys. Hornbogen [2] has revealed that the grain-boundary configuration can be estimated by the fractal dimension of the grain-boundary surface profile in the two-dimensional section (the fractal dimension of the grain boundaries, D, $1 < D < 2$) and that grain boundaries become serrated and the value of D increases with hot work in a copper alloy. Nishihara [3] has also reported that the value of D increases with increasing amount of cold work in pure iron. However, Tanaka [4, 5] has shown that the value of D increases with cold work up to about 50%, but its increase levels off above about 50% cold work in pure iron, because not only the slip in the grains but also the rotation of the grains contributes to the plastic strain of the specimens at the larger amount of cold work. Streitenberger *et al.* [6] have studied the deformed specimens or the deformed and annealed ones of pure zinc and have suggested a correlation between the microstructure and the grain-boundary roughness.

The creep deformation may affect the grain-boundary configuration in metals and alloys, because the slip in the grains may cause ledges and steps on grain boundaries at which the slip lines meet, and may increase the fractal dimension of the grain boundaries during creep as well as in cold work [4, 5]. Ashby [7] and Ashby *et al.* [8–10] discussed the effects of ledges, steps, bumps and precipitates on grain-boundary sliding and grain-boundary fracture in creep. Their results indicate that the diffusional recovery reduces the stress concentration at these obstacles for grain-boundary sliding. Grain-boundary sliding and recovery by diffusion of atoms near grain boundaries may also affect the fractal dimension of the grain boundaries, D. However, there seem to be no reports on the quantitative estimation of the change in the grain-boundary configuration during creep.

In this study, the change in the grain-boundary configuration during creep has been investigated using an austenitic SUS304 steel at 973 K. The fractal dimension of the grain boundaries, D, was estimated on the crept specimens by the box-counting method [1, 11, 12]. The slip line spacing was also examined in the crept specimens. The results of the creep experiments were compared with those of the tensile tests at room temperature (293 K). Further, the effects of grain-boundary ledges, steps and precipitates on the crack initiation were also discussed.

2. Experimental procedure

2.1. Material and creep experiments

Table I shows the chemical composition of the commercial austenitic SUS304 steel used in this study. The specimens of about 80 mm length were cut out from the hot-forged round bars of 16 mm diameter. Table II shows the heat treatment, the grain diameter and the particle size of grain-boundary precipitates in the specimens of the SUS304 steel. The specimens were water-quenched after solution heating for 1.8 ks at 1323 K. The grain diameter, 24 µm, is the mean value of 187 grains in both planes parallel to and transverse to the longitudinal direction, because there was no difference in the grain diameter between these directions. The ageing for 360 ks at 1023 K was performed in order to mark grain boundaries with $Cr_{23}C_6$ carbide particles [13] for the fractal analysis of grain-boundary configuration and to avoid the microstructural change during creep. The size of grain-boundary precipitates was examined on 200 particles in the heat-treated specimens. These specimens were machined into test pieces of 30 mm gauge length and 5 mm diameter.

Creep experiments were carried out using these test pieces under the nominal stresses of 98 and 118 MPa at 973 K. The test pieces were strained using creep–rupture equipment of single-lever type to 0, 0.05, 0.10, 0.20 nominal creep strain or final rupture (about 0.30 creep strain). All the test pieces were loaded after heating for 7.2 ks at the test temperature (973 K). For comparison, some test pieces were tensile-loaded up to 0.30 plastic strain using the creep–rupture equipment (average strain rate was manually controlled to be in the range from about 1.5×10^{-4}–3.3×10^{-4} s^{-1}) at room temperature (293 K).

TABLE I Chemical composition of the austenitic SUS304 steel used in this study (wt %)

Steel	C	Cr	Ni	Mn	Si	P	S	Fe
SUS304	0.06	18.28	8.12	1.00	0.49	0.033	0.021	bal.

TABLE II The heat treatment, the grain diameter and the particle size of grain-boundary precipitates in the specimens of the SUS304 steel

Heat treatment	Grain diameter (10^{-6}m)	Mean particle size of grain-boundary precipitates (particle-size range) (10^{-6}m)
1323 K – 1.8 ks → WQ[a] + 1023 K 360 ks → AC[b]	24	0.45 (0.11–1.3)

[a] WQ, water-quenched.
[b] AC, air-cooled.

2.2. Fractal analysis of grain boundaries

The strained test pieces were cut in parallel with or transverse to the tensile direction in order to obtain specimens for the fractal analysis. A small area which was strained to a nominal creep strain was examined on the crept specimens, because the necking was observed in those crept to strains above about 0.10. Optical micrographs of the specimens were taken at the magnification of ×1000. The specimens were lightly electrolytically etched with 10% chromic acid in water before microscopic observation [14].

In this study, the fractal dimension of the grain boundaries, D, means the fractal dimension of the grain-boundary surface profile in the two-dimensional section ($1 < D < 2$) averaged over twenty grain boundaries randomly oriented in the plane parallel to the tensile direction (i.e. in the parallel direction) or in that transverse to the tensile axis (i.e. in the transverse direction) in each specimen. The image analysis of grain-boundary configuration in micrographs and the calculation of the fractal dimension of the grain boundaries were performed by the box-counting method [1, 11, 12] using soft programs developed by the present authors or installed in a personal computer.

The procedure of image analysis employed in this study is similar to that developed by Li *et al.* [15]. Fig. 1 shows the schematic illustration of the box-counting method applied to the estimation of the fractal dimension of a grain boundary, D'. There is a relationship between the number of boxes, N, intersected by a grain boundary and the size of the boxes, r, to be expressed through the fractal dimension, D' [1, 11, 12]

$$N = N_0 r^{-D'} \quad (1)$$

where N_0 is a constant. The length of a grain boundary, L, can be correlated to the scale length of the

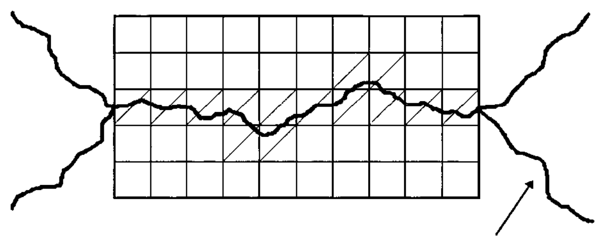

Figure 1 A schematic illustration of the box-counting method applied to the estimation of the fractal dimension of a grain boundary, D' (r is the size of boxes, and the number of the boxes, N, intersected by a grain boundary is 14 in this case).

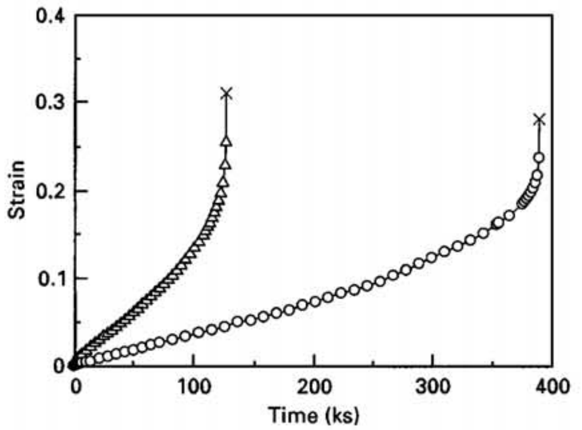

Figure 2 Creep curves in the specimens of the SUS304 steel tested at 973 K. (○) 98 MPa, (△) 118 MPa.

fractal analysis (the size of the boxes), r, by the fractal dimension, D', such that [1, 11, 12, 16, 17]

$$L = N r = L_0 r^{1-D'} \qquad (2a)$$

or in the logarithmic form

$$\log_{10} L = \log_{10} L_0 + (1 - D') \log_{10} r \qquad (2b)$$

where L_0 is a constant. The values of L and r were fitted to Equation 2a or Equation 2b to obtain the value of D'. The mean value of D' averaged over twenty grain boundaries is hereafter referred to as the fractal dimension of the grain boundaries, D, in this study.

The slip line spacing was also examined on the specimens crept at 973 K or on those tensile-strained at room temperature (293 K). Some specimens sectioned parallel to the tensile axis were deeply electrolytically etched with 10% chromic acid in water to reveal slip lines in the grains and the optical micrographs of the slip lines were taken at the magnification of × 1000.

3. Results and discussion

3.1. Microstructures of crept specimens

Fig. 2 shows creep curves in the specimens of the SUS304 steel tested at 973 K. The specimens exhibit typical creep curves under both stresses of 98 and 118 MPa, which are composed of transient creep, steady-state creep and tertiary creep regimes. The elongation was 0.283 in the specimen ruptured at 388.5 ks (98 MPa) and 0.311 in that ruptured at 126.7 ks (118 MPa), while the reduction in area was 0.645 in the former specimen and 0.698 in the latter one. Fig. 3 shows the examples of optical micrographs of the specimens of the SUS304 steel crept under a stress of 118 MPa at 973 K. Grain boundaries in the plane parallel to the tensile direction (in the parallel direction) are shown in Fig. 3a–c, and those in the plane transverse to the tensile axis are shown in Fig. 3d. The tensile direction is horizontal in Fig. 3a–c. Large $Cr_{23}C_6$ carbide particles are visible on the grain boundaries in the non-deformed specimen (Fig. 3a), and the shape and size of the precipitates seems almost the same in the crept specimens (Fig. 3b–d), indicating that the precipitation and coarsening of the grain-boundary precipitates is not significant during creep at 973 K. Very fine precipitates of $Cr_{23}C_6$ carbide were also formed in the grains in the heat-treated specimen [13]. Grain boundaries seem to become serrated as the creep strain increases, although it is not clear in these micrographs (Fig. 3b–d). The grains tend

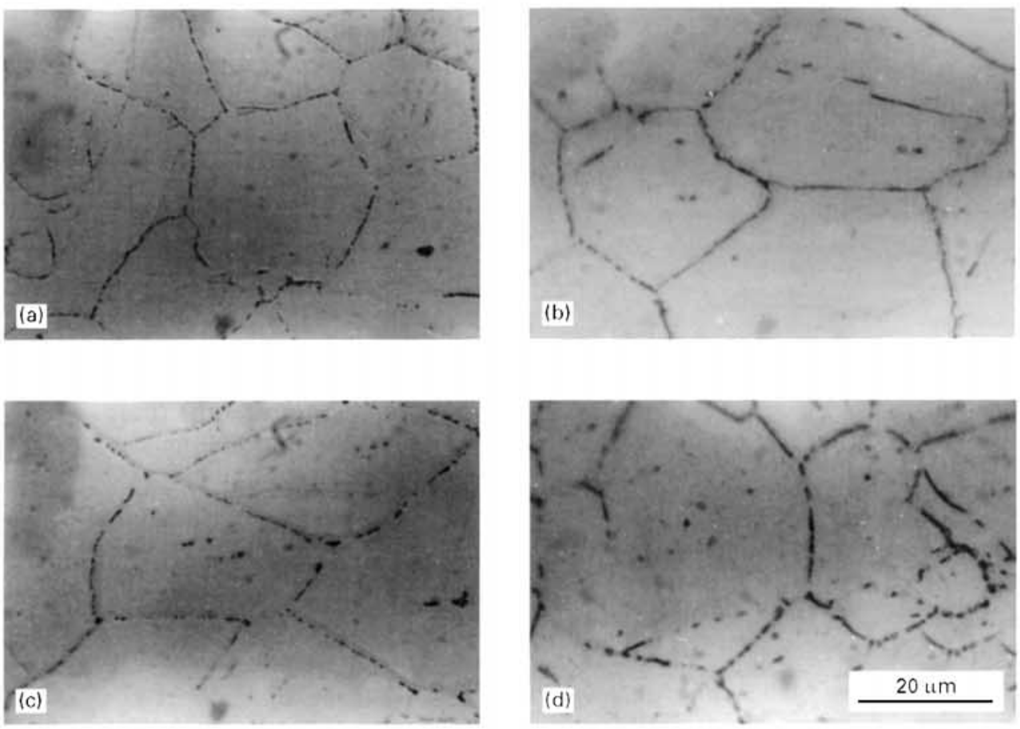

Figure 3 Examples of optical micrographs in the specimens of the SUS304 steel crept under a stress of 118 MPa at 973 K; creep strain is (a) 0, (b) 0.0996, (c) 0.311, (d) 0.311; (a–c) show grain boundaries in the parallel direction, and (d) shows those in the transverse direction.

to be elongated parallel to the tensile direction with increasing creep strain (Fig 3b and c), while the shape of grains is almost unchanged with strain in the transverse direction (Fig. 3d).

Fig. 4 shows examples of slip lines observed in the crept or tensile-strained specimens of the SUS304 steel. These specimens were sectioned parallel to the tensile axis. The tensile direction is horizontal in these micrographs. The slip lines within the grains are visible in the crept specimens and the slip-line spacing decreases with increasing creep strain (Fig. 4a and b). The slip line density in the crept specimen (Fig. 4b) seems to be a little lower than that in the specimen tensile-strained at room temperature (Fig. 4c). Table III lists the slip-line spacing in the specimens of the SUS304 steel crept at 973 K or tensile-strained at room temperature (293 K) of the SUS304 steel. The slip-line density increases with the creep strain, while the slip-line spacing in the crept or tensile-deformed specimens is almost in the range from about 4×10^{-7}–4×10^{-6} m. Both the size range and the mean value of slip-line spacing decrease with increasing creep strain or with increasing plastic strain. Both values are a little larger in the crept specimens than in the tensile-deformed specimens, while these values are slightly larger in the specimens crept under the lower stress.

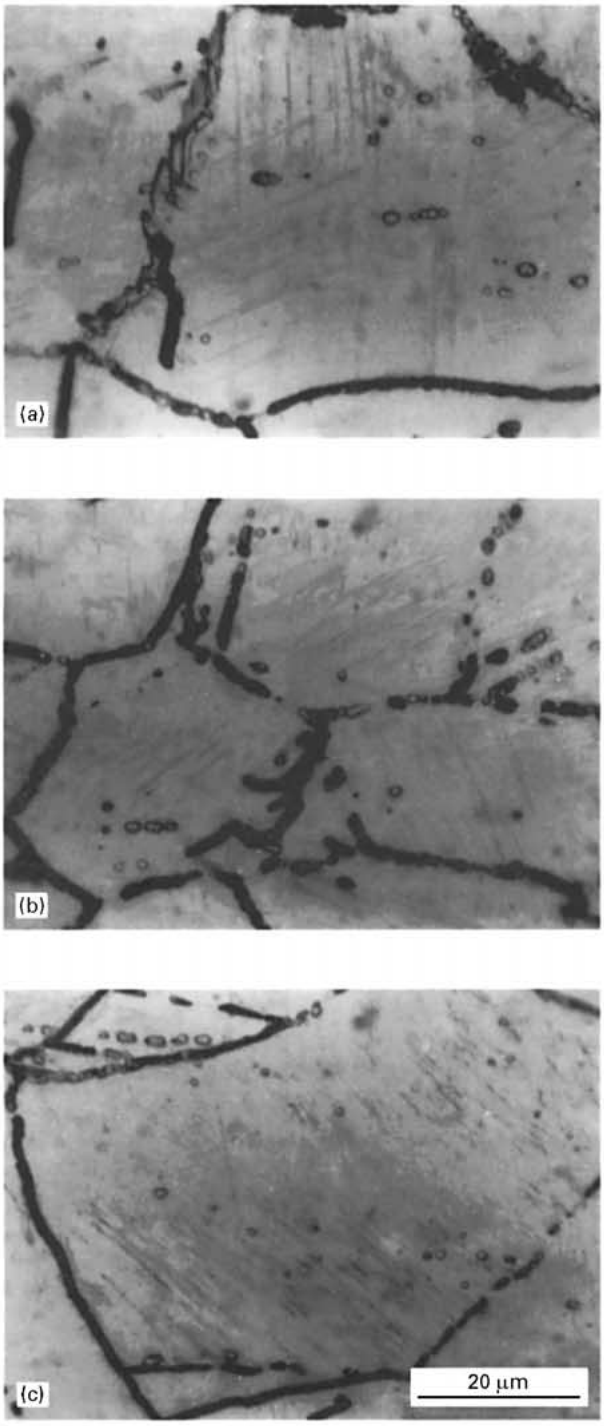

Figure 4 Examples of slip lines observed in the specimens crept under a stress of 118 MPa or in the specimen tensile-strained at room temperature of the SUS304 steel; creep strain is (a) 0.0518, (b) 0.311, and plastic strain is (c) 0.296.

3.2. Scale dependence of grain-boundary length

Fig. 5 shows the relationship between the length of a grain-boundary, L, and the scale length of the fractal analysis, r, in the specimens (in the parallel direction) of the SUS304 steel crept under a stress of 118 MPa at 973 K. The value of L decreases with increasing values of r in these specimens. The fractal dimension of a grain boundary, D', in each specimen (the slope of the solid line) is also shown in the figure. As described in section 2, the fractal dimension of the grain boundaries, D, in this study is the mean value of the fractal dimension, D, averaged over twenty grain boundaries in each specimen. The scale range of the fractal analysis, r, $4 \times 10^{-7}\,\mathrm{m} \leqslant r \leqslant 4 \times 10^{-6}\,\mathrm{m}$, which is chosen for the fractal analysis in this study, is similar to that employed in the previous study on the cold-worked specimens of pure iron [4, 5], because this scale range is correlated to the slip-line spacing in the crept specimens of the SUS304 steel (Section 3.1). As reported in the previous study [4, 5], the slip lines in the grains form ledges and small steps on grain boundaries at which these slip lines meet, and the grain boundaries become serrated as a result. It is considered that the similar mechanism also works in the creep deformation of the SUS304 steel in this study. A large dependence of the grain-boundary length, L, on the scale length, r, can be observed in the scale range less than 4×10^{-7} m (indicated by the dotted lines in the figure), irrespective of creep strain. Tentative evaluation of the slopes gave a value more than about 1.3. The scale, r, dependence of the grain-boundary length, L, is attributed to the pre-existing grain-boundary $Cr_{23}C_6$ precipitates which also contribute to the grain-boundary serration, because the size of these carbide particles was in the range from 1. 1×10^{-7}–1.3×10^{-6} m in these specimens (Table II).

3.3. Change in the fractal dimension of the grain boundaries by creep deformation

Fig. 6 shows the relationship between the fractal dimension of the grain boundaries, D, in the parallel direction and the creep or plastic strain in the specimens of the SUS304 steel. The value of D increases with increasing strain in both specimens crept at

TABLE III The slip-line spacing in the specimens of the SUS304 steel crept at 973 K or tensile-strained at room temperature (293 K)

Nominal value of plastic strain	Tensile deformed at 293 K		Crept at 973 K, 118 MPa		Crept at 973 K, 98 MPa	
	Size range of slip-line spacing (10^{-6}m)	Mean slip-line spacing (10^{-6}m)	Size range of slip-line spacing (10^{-6}m)	Mean slip-line spacing (10^{-6}m)	Size range of slip-line spacing (10^{-6}m)	mean slip-line spacing (10^{-6}m)
0.05	0.58–4.1	0.94	0.63–4.7	1.0	0.63–5.1	1.5
0.10	0.47–2.9	0.82	0.53–3.2	0.89	0.53–4.0	1.2
0.20	0.42–1.9	0.62	0.47–2.2	0.66	0.42–2.6	0.89
0.30	0.37–1.5	0.48	0.42–1.5	0.52	0.37–2.4	0.65

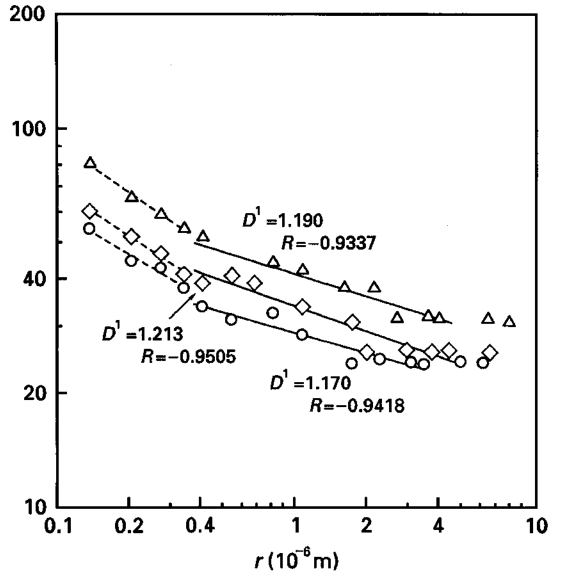

Figure 5 The relationship between the length of a grain boundary, L, and the scale length of the fractal analysis, r, in the specimens (in the parallel direction) of the SUS304 steel crept under a stress of 118 MPa at 973 K. Creep strain: (○) 0, (△) 0.099, (◇) 0.311. D' is the fractal dimension, R the correlation factor.

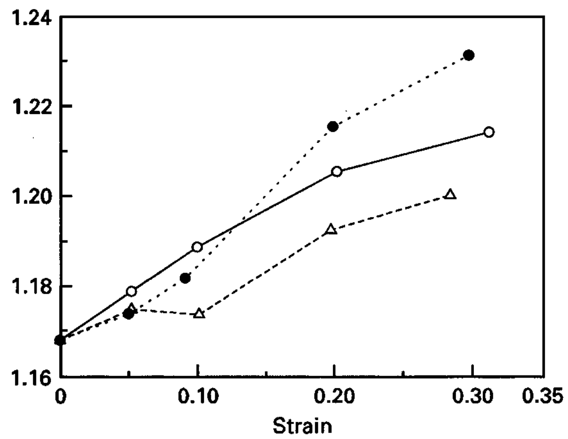

Figure 6 The relationship between the fractal dimension of the grain boundaries, D, in the parallel direction and the creep or plastic strain in the specimens of the SUS304 steel. (△) 973 K, 98 MPa, creep; (○) 973 K, 118 MPa, creep; (●) tensile test at 293 K.

973 K and those tensile-strained at room temperature (293 K). For example, the value of D increases from about 1.17 to about 1.22 on increasing the creep strain up to about 0.30. The value of D is slightly larger in the specimens crept under the higher stress (118 MPa)

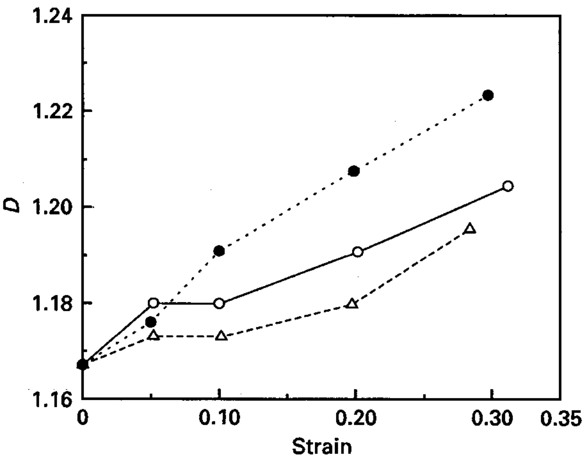

Figure 7 The relationship between the fractal dimension of the grain boundaries, D in the transverse direction and the creep or plastic strain in the specimens of the SUS304 steel. (▲) 973 K, 98 MPa, creep; (○) 973 K, 118 MPa, creep, (●) tensile test at 293 K.

than in those crept under the lower stress (98 MPa), whereas the value of D is largest in the specimens tensile-strained at 293 K at the larger strains. Fig. 7 shows the relationship between the value of D in the transverse direction and the creep or plastic strain. The value of D in the transverse direction also increases with increasing strain. The value of D in the non-deformed specimen of the SUS304 steel, about 1.17, is a little larger than that in the corresponding one of pure iron, about 1.07, in the previous study [4, 5], because the pre-existing precipitates on grain boundaries also affect the value of D in the specimen of the SUS304 steel.

Hinojosa *et al.* [18] reported on the AISI 316L steel that the fractal dimension of the grain boundaries in the transverse direction decreases with increasing tensile strain, although the grain boundaries exhibit a fractal nature in the specimens strained up to 20%. However, very different results have been reported by many investigators. Hornbogen [2] revealed that the fractal dimension of the grain boundaries increases with increasing plastic deformation in the hot-worked specimens of a copper alloy. Nishihara [3] and one of the present authors [4, 5] also showed that the fractal dimension of the grain boundaries increases with increasing amount of cold work in pure iron. The increase of the fractal dimension with cold work is associated with slip in the grains [4, 5]. In the crept specimens of SUS304 steel, the increase of the fractal dimension with creep strain can also be correlated to the increase of slip-line density, which leads to the increase in the density of ledges and steps on grain boundaries where the slip lines meet (Table III).

The increase of the fractal dimension, D, with creep strain is slightly smaller in the specimens tested under the lower stresses, while the value of D is a little smaller in the crept specimens than in the specimens tensile-strained at room temperature. The change in the fractal dimension of the grain boundaries with creep strain cannot solely be explained by the change in the slip-line density. Not only the slip in the grains but also the grain-boundary sliding contributes to the total creep deformation [19–21]. It has been reported that the ratio of the strain contribution, ε_{gb}, due to grain-boundary sliding to the total strain, ε, $\varepsilon_{gb}/\varepsilon$, is in a wide range between 0.8% and 93%, but a typical value would be upto 20% [20]. In general, the value of $\varepsilon_{gb}/\varepsilon$ increases as the applied stress level decreases. Therefore, the increase in the fractal dimension of the grain boundaries with creep strain may be slightly smaller under the lower creep stresses, because the relative amount of creep deformation in the grains is a little smaller under the lower stresses. The grain-boundary sliding is accompanied with accommodation processes, such as the slip in the grains and the diffusion of atoms near grain boundaries [20, 21]. Ashby [7] and Ashby *et al.* [8–10] also reported that the grain-boundary sliding is affected by ledges, steps, bumps and precipitates on grain boundaries and that the stress concentration at these obstacles can be relaxed by the diffusion of atoms near grain boundaries. The effect of the diffusional relaxation is generally more remarkable under the lower stresses (at the lower strain rates). The diffusional relaxation may decrease the height or the width of ledges and steps on the grain boundaries [8, 9], and may also decrease the fractal dimension of the grain boundaries.

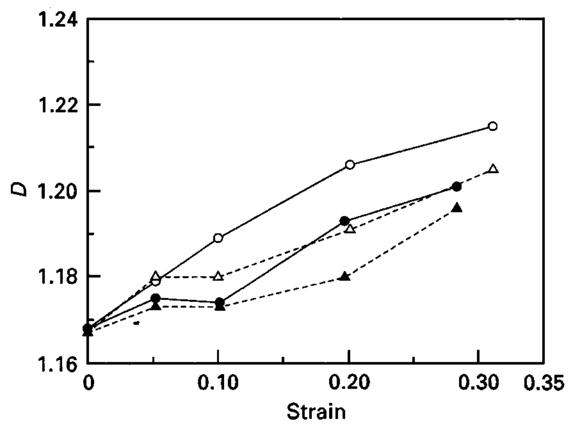

Figure 8 The relationship between the fractal dimension of the grain boundaries, D, and the creep strain in the specimens of the SUS304 steel crept at 973 K, (●, ○) parallel direction, (▲, △) transverse direction, for (●, ▲) 98 MPa stress and (○, △) 118 MPa stress.

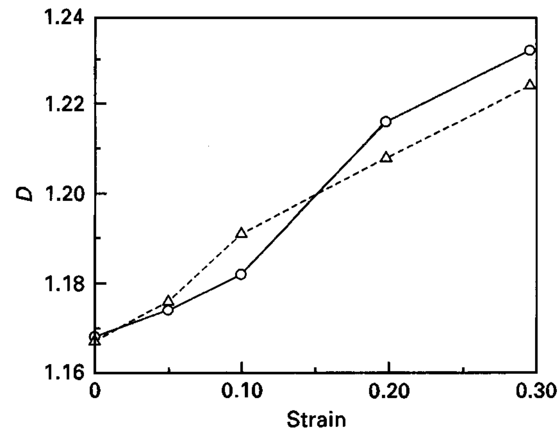

Figure 9 The relationship between the fractal dimension of the grain boundaries, D, and the plastic strain in the specimens of the SUS304 steel tensile-strained at room temperature (293 K): (○) parallel direction, (△) transverse direction.

3.4. The fractal dimensions of the grain boundaries in two directions

Fig. 8 shows the relationship between the fractal dimension of the grain boundaries, D, and the creep strain in the specimens of the SUS304 steel crept at 973 K. The value of D in the parallel direction is almost the same as that in the transverse direction (about 1.17) in the non-deformed specimen. As described in Section 3.2, the value of D increases with increasing creep strain, while it is lower in the specimens crept under the lower stress (98 MPa). The value of D is a little smaller in the transverse direction than in the parallel direction especially at the large strains. Similar results were obtained in the specimens tensile-strained at room temperture (293 K).

Fig. 9 shows the relationship between the fractal dimension of the grain boundaries, D, and the plastic strain in the specimens of the SUS304 steel tensile-strained at room temperature (293 K). The value of D is also slightly smaller in the transverse direction than in the parallel direction at the larger strains. As shown in Fig. 10, these results may be explained by the difference in the shape change of grains due to creep or plastic deformation in two directions. If the uniform creep or plastic deformation ($\varepsilon_{33} = \varepsilon$, $\varepsilon_{11} = \varepsilon_{22} = -\varepsilon/2$) is assumed, the principal creep or plastic strain is ε for the tensile direction (x_3 direction) and $-\varepsilon/2$ for two perpendicular directions (x_1 and x_2 directions). Thus, the shape change of grains occurs in the plane parallel to the tensile direction ($x_3 - x_1$ plane), while it does not occur in that transverse to the tensile axis ($x_1 - x_2$ plane) (Figs 3 and 10). This may be one the reasons why the fractal dimension of the grain boundaries is slightly smaller in the transverse direction.

Fig. 11 shows an enlarged optical micrograph of the specimen of the SUS304 steel ruptured under a stress of 118 MPa at 973 K (in the plane parallel to the tensile axis). The tensile direction is horizontal in the micrograph. Some grain boundaries bulge out between the grain-boundary carbide particles (indicated by arrows in the figure). Streitenberger *et al.* [6] suggested the correlation between the microstructural changes and the serrated grain boundaries in the

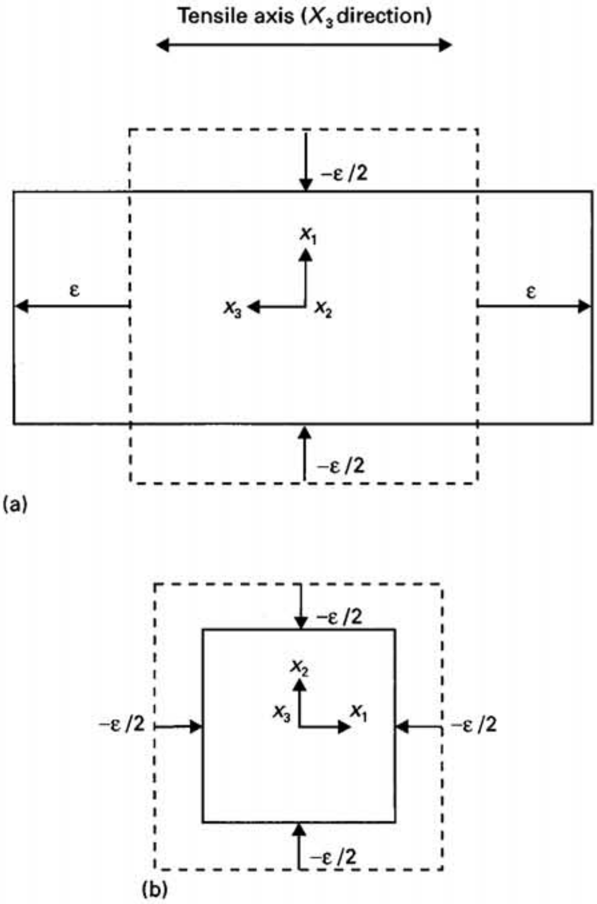

Figure 10 Schematic illustration of principal creep or plastic strains in two directions: (a) the plane in the tensile direction (x_1–x_3 plane); (b) the plane in the tensile direction (x_1–x_2 plane).

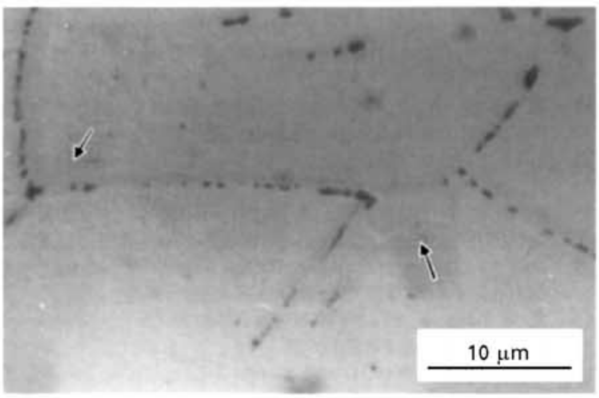

Figure 11 Enlarged optical micrograph of the specimen of the SUS304 steel ruptured under a stress of 118 MPa at 973 K (arrows indicate grain-boundary migration).

deformed specimens or the deformed and annealed ones of pure zinc. Subgrains of a few micrometres in size are generally observed in the specimens of the SUS304 type steels [22, 23] and the bulged grain boundaries may be formed as a result of the grain-boundary migration caused by the formation of subgrains near the grain boundaries. However, the bulged grain boundaries were hardly observed in the transverse direction in the same specimen and in the specimens ruptured under a stress of 98 MPa. Therefore, the effect of grain-boundary migration on the increase of the fractal dimension may be relatively small in the SUS304 steel in this study, probably because the grain-boundary precipitates of $Cr_{23}C_6$ carbide inhibit the grain-boundary migration during creep.

3.5 Effects of grain-boundary serration on creep fracture

Fig. 12 shows the optical micrographs of the specimens ruptured at 973 K. The tensile direction is

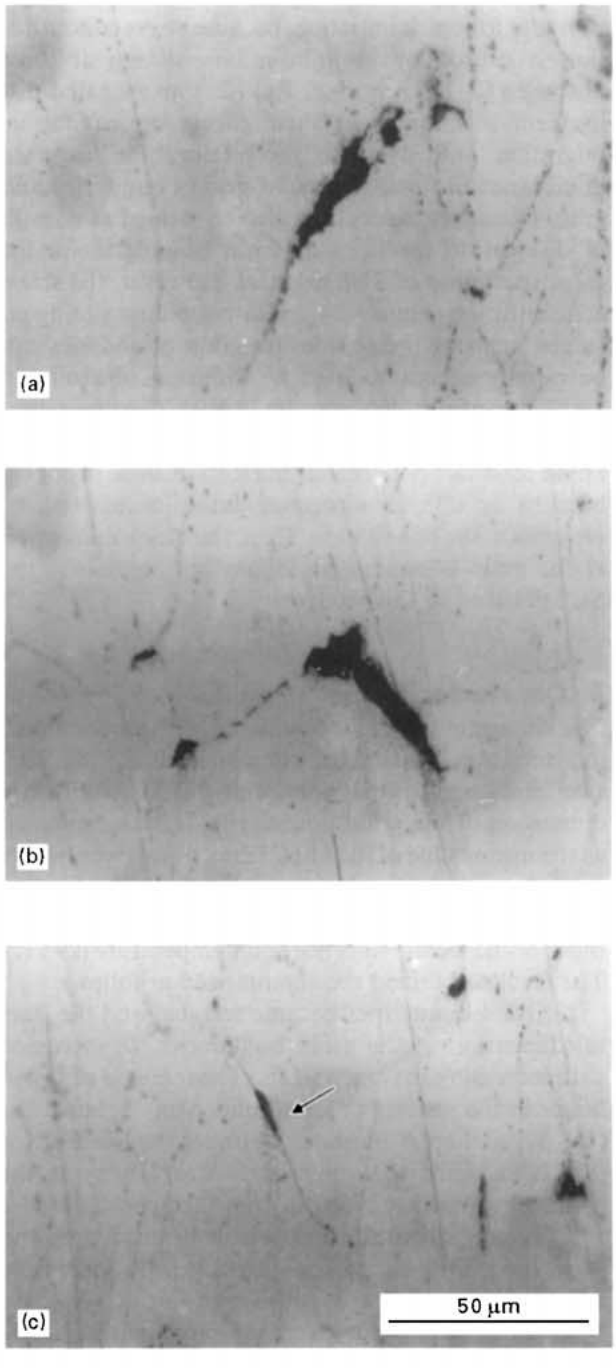

Figure 12 The optical micrographs of the specimens ruptured at 973 K; creep stress is (a) 98 MPa (t_r = 388.5 ks, ε_r = 0.283), (b, c) 118 MPa (t_r = 126.7 ks, ε_r = 0.311). t_r is the rupture life; ε_r the elongation (the arrow indicates a crack on a serrated grain boundary).

vertical in these micrographs. Most of the grain-boundary cracks are nucleated at grain-boundary triple junctions under both stresses of 98 MPa (Fig. 12a) and 118 MPa (Fig. 12b), while only a few cracks are initiated on the serrated grain boundaries (indicated by an arrow in Fig. 12c). As described in the previous section (Section 3.3), ledges and steps are formed on grain boundaries where the slip lines in the grains meet, and grain boundaries become serrated as a result. It is known that serrated grain boundaries are effective in improving creep–rupture properties by retarding the grain-boundary sliding which results in the nucleation and growth of the grain-boundary cracks [24–27]. On the other hand, ledges, steps and precipitates on grain boundaries which are obstacles for grain-boundary sliding, may also be potential nucleation sites for crack initiation, because stress concentration is caused by grain-boundary sliding at these obstacles [7–10]. Lim and Raj [28] investigated dislocation reactions and their effects on cavitation, migration and dynamic recrystallization at grain boundaries in detail. Serrated grain boundaries and grain-boundary cracks may also be formed as a result of dislocation reactions at grain boundaries in the crept specimens of SUS304 steel. However, the stress concentration caused by grain-boundary sliding at ledges, steps or precipitates on grain boundaries can be rapidly accommodated by diffusion of atoms in high-temperature deformation [8–10]. The present results imply that these obstacles on grain boundaries are at least not preferential nucleation sites, probably because the diffusional accomodation occurs around serrated grain boundaries. Thus, the crack nucleation at the grain-boundary triple junction prevails in the SUS304 steel in this study.

4. Conclusion

The change in the grain-boundary configuration during creep was investigated using an austenitic SUS304 steel crept up to final rupture at 973 K. The fractal dimension of the grain boundaries, D, was estimated as the mean value of the fractal dimension over twenty grain boundaries in each case by the box-counting method. The experimental results were compared with those of the tensile tests at room temperature (293 K). The results obtained are summarized as follows.

1. Grain boundaries became serrated and the fractal dimension of the grain boundaries, D, increased with increasing the creep strain. The increase of D was larger in the specimens tested under the higher stress (118 MPa) than in those tested under the lower stress (98 MPa), while the value of D was largest in the specimens tensile-strained at room temperature.

2. The density of slip lines which formed ledges and steps on grain boundaries increased with increasing creep strain, and the fractal dimension of the grain boundaries increased with creep strain as a result. The grain-boundary sliding and the diffusional recovery near grain boundaries lowered the increase in the fractal dimension of the grain boundaries with creep strain especially under the lower stress. The grain-boundary migration observed in the specimens crept at the higher stress (118 MPa) had a minor contribution to the increase of D.

3. The value of D estimated in the plane parallel to the tensile direction (in the parallel direction) was slightly larger than that measured in the plane transverse to the tensile axis (in the transverse direction) in both the crept specimens and the tensile-strained ones, especially at the large strains. The difference in the value of D was associated with the difference in the shape change of grains due to tensile creep or deformation between these directions.

4. Grain-boundary cracks were principally nucleated at grain-boundary triple junctions. Ledges, steps and carbide precipitates on serrated grain boundaries were not preferential nucleation sites for grain-boundary cracks.

Acknowledgements

The present authors are grateful to Mr S. Sawada, Sumikin Bussan Co. Ltd, for supplying SUS304 steel used in this study. They also thank Mr T. Okayama for his assistance in the creep experiments.

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Received 27 February 1997
and accepted 2 April 1998