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Size distribution of creep cracks in materials showing a mixed mode fracture simulated by one-dimensional crack growth model

M. TANAKA, R. KATO
Department of Mechanical Engineering, Faculty of Engineering and Resource Science, Akita University, 1-1 Tegatagakuen-cho, Akita 010-8502, Japan
E-mail: tanaka@mech.akita-u.ac.jp

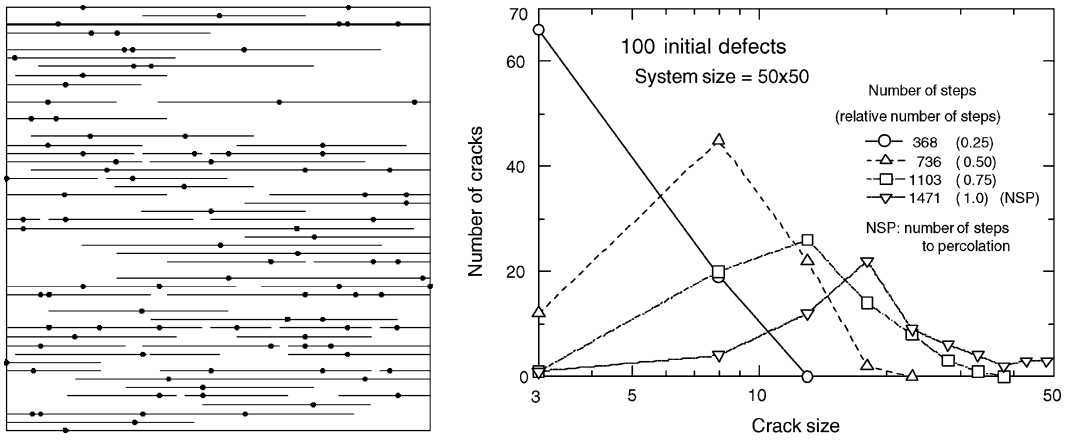
The size distribution of creep cracks has been simulated by a logarithmic normal distribution [1, 2] or a normal distribution [3]. Evans [4] summarized the experimental data and concluded that the crack size distribution can be approximated quite well by a logarithmic normal distribution. In the previous study [5], the growth and linkage of grain-boundary cracks was simulated by a two-dimensional multicrack growth model similar to the random walk model proposed by Nishiuma *et al*. [6, 7]. In the simulation, the crack size distribution could be approximated by a logarithmic normal distribution, and the number of the cracks (N) of the size (x') equal to or larger than a given size (X) (the ranking of the crack size) could be approximated by a power law relationship ($N(x' \geq X) \propto X^{-a}$, a: scaling exponent) at the larger crack sizes [5]. The results of the simulation could explain the crack size distribution characteristics on the crept specimens of the austenitic 21Cr-4Ni-9Mn steel, in which creep fracture of specimens is governed by grain-boundary fracture [8, 9]. However, a mixed mode of grain-boundary fracture and transgranular fracture is often observed on the ruptured specimens of materials such as the austenitic SUS304 steel [10]. The difference in the fracture mechanisms may be correlated with the difference in the growth and linkage of cracks and may affect the size distribution of creep cracks in materials. In this study, the simulation of growth and linkage of cracks was made using one-dimensional crack growth model that is similar to the (two-dimensional) multicrack growth model in the previous study [5].

The principal rules in the simulation using the present model are as follows:

1. A crack may grow in the horizontal direction from the initial defects randomly distributed on the nodal points of the square lattice (a crack has two growth points).
2. A growth point of a crack may reach an adjacent crack (crack linkage) or an edge of the square lattice (edge relaxation).
3. Some cracks may stop to grow on the square lattice (crack arrest) and may not link up with other cracks, even if they are very close to other cracks.

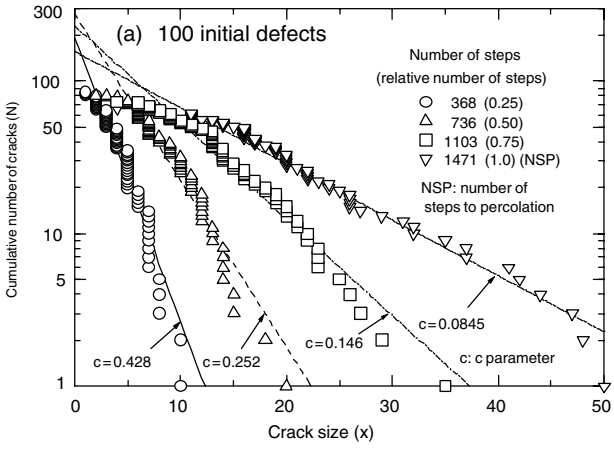
One segment (one step) length in the lattice corresponds to the increment of the crack length in a single step of the simulation. The crack size (cluster size) was defined by the number of segments forming a cluster on the square lattice. The system size of the square lattice used in the simulation was 50×50 and the total number of nodal points on the lattice was $51^2 = 2601$ in this study. Percolation in the lattice corresponds to fracture of materials. Computer simulation was made five times each for 100 initial defects (the initial defect density, IDD, is 0.0384) and for 200 initial defects (IDD is 0.0769) to percolation. The number of the initial defects (or IDD) was determined according to the observation of creep cracks on the ruptured specimens of the SUS304 steel [10]. The probability that a growth point of a cluster does not link up with a growth point of other clusters is 0.250 in the one-dimensional crack growth model, while the probability is about 0.167 in the (two-dimensional) multicrack growth model. The cluster size does not exceed the length of 50 steps (the length of a percolation cluster) in the present one-dimensional crack growth model. Further, percolation occurs only in the horizontal direction in the present model. A cluster formed in the simulation is hereafter referred to as "crack".

Fig. 1a shows a result of simulation using one-dimensional crack growth model (100 initial defects and the initial defect density, IDD, is 0.0384 in this case). Solid circles show 100 initial defects in the lattice. A bold line in the figure indicates a percolation crack (percolation cluster). Many cracks are formed on the lattice. Fig. 1b shows the crack size distribution in the simulation result of Fig. 1a. The number of steps in the figure may correspond to the creep deformation after crack initiation, which drives the growth and linkage of creep cracks. The crack size distribution seems to be approximated by a logarithmic normal distribution except early stage of simulation. Similar results were obtained on other four simulations for IDD = 0.0384 and on five simulations for IDD = 0.0769. These results of simulation are also similar to those obtained on the (two-dimensional) multicrack growth model [5]. Fig. 2 shows the cumulative number of cracks in the simulation using the one- dimensional crack growth model. Almost linear relationship is observed between the cumulative number of cracks, N, and the crack size, x, in the semi-logarithmic scale for both IDD = 0.0384 and IDD = 0.0769 at each step of the simulation. This indicates that the cumulative number of cracks (N) can be approximated by an exponential law relationship with a parameter c for all crack sizes (x), namely, $N = B_0 \exp(-cx)$, where B_0 is a constant. The value of c parameter decreases with increasing relative number of



(a) lattice image at the stage of percolation (b) crack size distribution in the simulation

Figure 1 A result of simulation using one-dimensional crack growth model (100 initial defects and the initial defect density, IDD, is 0.0384 in this case).



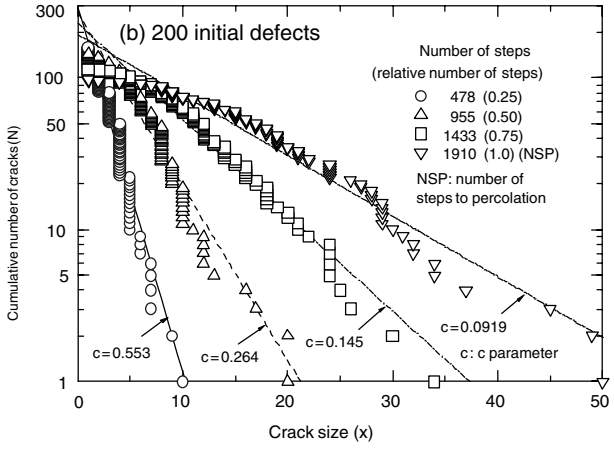


Figure 2 Cumulative number of cracks in the simulation using one-dimensional crack growth model: (a) 100 initial defects (IDD = 0.0384) and (b) 200 initial defects (IDD = 0.0769).

steps in the simulation. The value of c is a little larger in the simulation for IDD = 0.0384 at the same relative number of steps. Fig. 3 shows the cumulative size distribution of cracks in five simulations for IDD = 0.0384 (100 initial defects) at the stage of percolation (fracture of materials). Each set of the datum points can be better approximated by an exponential law relationship rather than a power law relationship, although there are some differences in the number of steps to

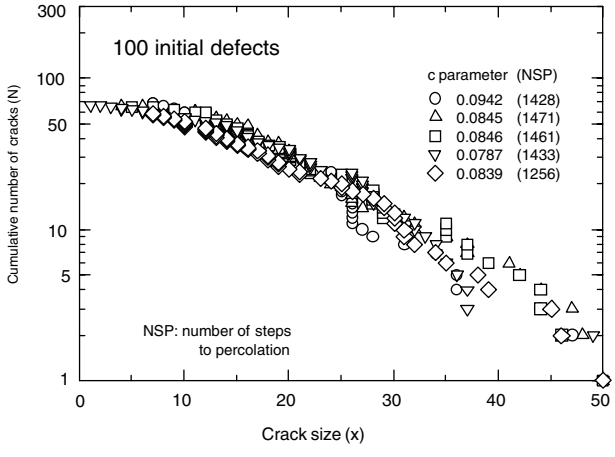


Figure 3 Cumulative size distribution of cracks in five simulations for 100 initial defects (IDD = 0.0384) at the stage of percolation.

percolation (NSP) and in the values of c parameter between five simulations. These results are different from those obtained in the simulation using the two-dimensional multicrack growth model [5], in which the cluster size distribution could be approximated by a logarithmic normal distribution but the cumulative number of the clusters (N) could be fitted to a power law relationship ($N(x' \geq X) \propto X^{-a}$) at the larger crack sizes. Thus, different cumulative size distribution of cracks observed in the present simulation may be attributed to more restricted growth and linkage of cracks in the one-dimensional crack growth model compared with the (two-dimensional) multicrack growth model.

Steel bars of 16 mm diameter and 90 mm length of the austenitic SUS304 steel (Fe-0.06 wt%C-16.80 wt%Cr-10.20 wt%Ni-2.11 wt%Mo) were water-quenched after solution heating for 14.4 ks at 1473 K and then aged for 360 ks at 1023 K [10]. The heat-treated bars (the average grain diameter was 200 μm) were machined into creep-rupture specimens of 5 mm diameter and 30 mm gauge length. The creep experiments were carried out at 973 K. The size distribution of creep cracks initiated in a given area (5 mm $\times$ 2 mm) on the specimen surface were examined on the crept specimens. The

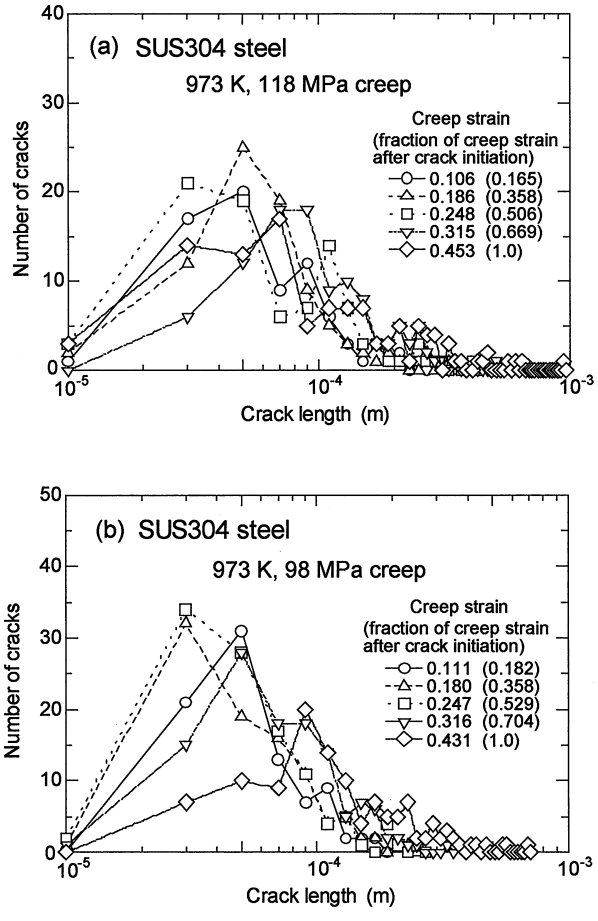


Figure 4 Crack size distribution in the aged specimens of the SUS304 steel crept at 973 K: (a) 118 MPa and (b) 98 MPa.

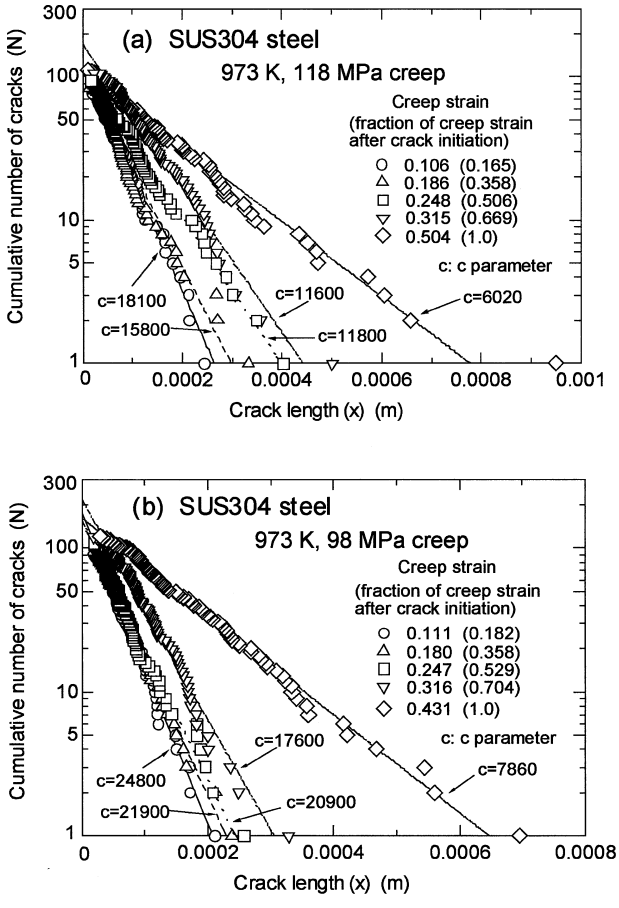


Figure 5 Cumulative number of cracks in the specimens of the SUS304 steel crept at 973 K: (a) 118 MPa and (b) 98 MPa.

creep strain to crack initiation was in the range from 0.0375 to 0.0400, and decreased slightly with increasing creep stress [10]. Fig. 4 shows the crack size distribution in the specimens of the SUS304 steel crept at 973 K. The size distribution of creep cracks can be approximated by a logarithmic normal distribution for both stresses of 98 and 118 MPa. The number of cracks is larger in the specimen crept under the lower stress (98 MPa), suggesting that the initial defect density (IDD) is larger in this specimen. Fig. 5 shows the cumulative number of cracks in the aged specimens of the SUS304 steel crept at 973 K. The cumulative number of cracks (N) seems to be approximated by an exponential law function of the crack length (x) in the SUS304 steel under both stresses (Fig. 5a and b). The slope of straight line gives the c parameter of the exponential law relationship ($N = B_0 \exp(-cx)$). The value of c decreases with increasing creep strain, although the value of c parameter in the experiments is much larger than that in the simulation (Fig. 2). The value of c is a little larger in the specimen crept under the lower stress at the same fraction of creep strain after crack initiation. These results were different from those obtained on the 21Cr-4Ni-9Mn steel [5] and the HS-21 alloy [11], in which the cumulative number of cracks could be approximated by a power law relationship at the larger crack sizes. Difference in the cumulative crack size distribution should be attributed to the difference in the fracture mechanism between these materials.

Creep cracks may extend not only on grain boundaries but also in the grains in the specimens of the SUS304 steel, especially when the crack length exceeds about one grain-boundary length (about 1.2×10^{-4} m), whereas these cracks are nucleated on grain boundaries [10]. A mixed mode of grain-boundary fracture and transgranular fracture was observed in the SUS304 steel [10], although grain-boundary fracture occurred in the 21Cr-4Ni-9Mn steel [8, 9] and the HS-21 alloy [11]. Occurrence of transgranular fracture may lead to a decrease in the crack growth rate, namely, an increased difficulty of the growth and linkage of cracks [10]. A mixed mode fracture may result in a different type of cumulative size distribution of cracks approximated by an exponential law relationship. Both the size distribution and the cumulative size distribution of cracks in the crept specimens of the SUS304 steel can be reproduced also in the simulation using one-dimensional crack growth model in this study.

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