Application of a Fractal Method to Quantitatively Describe Some Typical Fracture Surfaces

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By using a vertical sectioning method (VSM) or secondary electron line scanning method (SELSM), the fractal dimension \( D_s \) for surface, \( D_s \) for scanning profile were measured quantitatively on some typical fracture surfaces, namely cleavage fractures, dimple fractures and fatigue fractures of composite materials. It was shown that the measured value of \( D_s \) relates differently to the impact energy values of materials for cleavage or dimple fractures. The microstructure of materials should be considered comprehensively when relating \( D_s \) to the mechanical properties of materials. It is found that the correlation between the fractal dimension and the impact energy obtained by SELSM and VSM methods appears to be quite similar. Moreover, the quantitative measurements on the fatigue fracture surfaces of SiC/Al composite materials showed that SiC volume fraction has a strong effect on fractal dimension \( D_s \), and that there is an obvious difference in the \( D_s \) values for fatigue fractures which are due to different fracture mechanisms. These results show that it is possible to reflect the fracture mechanism using \( D_s \) and relate it to the fracture properties of materials.

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1. Introduction

The original concept of fractal geometry developed by Mandelbrot et al.\(^1\) has been actively applied to the field of materials science, for example, quantitative description of microstructures such as grain boundaries\(^2,3\) and dislocation patterns,\(^4\) as well as of fracture surface with different features.\(^5-8\) Fracture surface roughness, which is a major object of study in "Quantitative Fractography", has been attracting substantial interest.\(^9-11\) Based on the classical stereological principles and verified with the aid of computer simulations, Gokhale and Underwood\(^12,13\) proposed an assumption-free method for estimating the fracture surface roughness by vertically sectioning the fracture into three parts at an angle of 120° to each other. In our previous work,\(^6\) based on this kind of vertical sectioning method (VSM), an indirect method for measuring the fractal dimension \( D_s \) for fracture surface was presented. It was shown that \( D_s \) is a better quantitative indicator of the roughness of a fracture surface. In the present study, the fractal dimension measured by VSM would be adopted to describe some typical fracture surfaces.

Secondary electron line scanning method (SELSM), which acts as an effective and convenient way of describing the fracture surface quantitatively, has been also investigated and used extensively. Pande et al.\(^14,15\) and Huang et al.\(^16\) measured the fractal dimension successfully using SELSM. Here, the method of sectioning the fracture surface at 120° suggested by Gokhale and Underwood\(^12,13\) will be induced into SELSM for obtaining a more effective fractal dimension \( D_s \) for scanning profile from a fracture surface.

2. Experimental Procedures

0.02 mass% carbon iron and 26 mass%Mn-5 mass%MAl

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stainless steel were chosen in the present work. After being annealed at different temperatures, the iron and steel bars were machined into charpy V-notch specimens, which were impacted at liquid-nitrogen temperature to obtain a series of cleavage or dimple fractures with different impact values.

The SiC/Al composite investigated in the present study was made by powder metallurgy. The SiC particulate with a size of 10 μm was mechanically mixed with 14 μm aluminum powder. The mixture was then hot compacted at 893 K and subsequently extruded to bars. The unreinforced aluminum matrix was produced in the same process except for mixing. The fatigue specimens were machined from the as-extruded bars with the loading axis parallel to the extrusion direction. The gauge length and diameter of the specimens were 14 and 16 mm, respectively. The low-cycle fatigue tests were performed under fully reversed plastic strain control using a mechanical servo-controlled testing system. The tests were conducted in air at room temperature and the cycling frequency was 0.125 Hz.

Quantitative measurements were performed on these fractures by the VSM, the detailed procedure of which can be found in Ref. 6). As for SELSM, it will be introduced in Section 3.3.

3. Experimental Results and Discussion

3.1 Characterization of cleavage and dimple fracture surfaces by VSM

As the low-temperature impact fractures for iron are almost purely brittle cleavage (see Fig. 1(a)), the total energy of fracture, i.e. impact energy, will approximately transfer into the surface energy needed for the formation of the fracture surfaces. Therefore, fracture surface roughness is expected to be proportional to impact energy \( \alpha_K \), leading to a monotonous increase in \( D_s \) with \( \alpha_K \) as shown in Fig. 2. 26 mass%Mn-5 mass%MAl steel possesses a superior impact toughness at different temperatures,\(^16,17\) and its low-temperature impact fracture surface has dimpled morphology shown in Fig. 1(b). Its...
impact energy is closely related to the grain size and the solid solubility of carbonitrides.\textsuperscript{16,17} When the annealing temperature is below 1100°C, which is higher than that used in the present experiment, the effect of grain size on impact energy value is more pronounced than that of the solid solubility of carbonitrides. With increasing the annealing temperature, the solid solubility of carbonitrides increases, causing an increase in the impact energy value, although the higher annealing temperature leads to coarse grain size. However, fracture surface roughness is related primarily to the grain size $D$. The larger $D_L$, the larger dimple size and the smaller fracture surface roughness. Accordingly, Fig. 3 exhibits an opposite relationship between $\alpha_K$ and $D_S$, \textit{i.e.}, $D_S$ decreases instead with increasing $\alpha_K$. The results above indicate that the measured $D_S$ value may relate differently with the mechanical properties of materials for different types of fractures. The microstructures of materials must be considered comprehensively when relating $D_S$ to the mechanical properties of materials.

3.2 Characterization of fatigue fracture surfaces of SiC/Al composite materials by VSM

The materials adopted in this study were the unreinforced aluminum matrix and SiC/Al composite with two SiC volume fractions of 6 and 25%. The fatigue tests were carried out under a plastic strain amplitude of $5.0 \times 10^{-3}$. The three fatigue fractures are given in Fig. 4. It is obvious from Fig. 4 that there is a quite difference in the features of the three fracture surfaces. From the measurements in Fig. 5 it was found that with increasing SiC volume fraction, the fatigue life $N_f$ decreases and the fractal dimension $D_S$ increases. For the composite that has less ductility than the unreinforced matrix it is relatively easy to initiate micro-cracks under high fatigue strain either by interface cracking or by particle fracturing. Furthermore, the ductility of the composite is reduced more with increasing SiC volume fraction so that the fatigue life $N_f$ decreases. As to the unreinforced aluminum matrix, many fatigue striations were observed on the fracture surfaces and the fatigue-crack propagation path is comparatively even and smooth. Therefore, the corresponding $D_S$ value is small. In the case of composite it was hard to see fatigue striations, but a population of unequiaxed dimples appears on the fracture surfaces. In the center of most dimples there were broken or detached SiC particles. On propagation, the crack encounters SiC particles and will pass by or through the particles and its propagation path becomes more tortuous. This trend is more evident with increasing SiC volume fraction. The measured value of $D_S$ thus increases.

It was found from Fig. 5 that there is a corresponding relation between $D_S$ and $N_f$, showing that it is possible to relate the fractal dimension $D_S$ with the fatigue life $N_f$. Certainly, to be exact, the fatigue life should be divided into the initiation life and propagation life. Here, $D_S$ was only related with
the total fatigue life, which might be incomplete. Moreover, Fig. 5 also shows that the measured $D_S$ value of pure aluminum differs significantly from those obtained for the composites due to different fracture mechanisms. It is thus possible to reflect the fracture mechanism to some extent by using the fractal dimension $D_S$.

3.3 Introduction of developed secondary electron line scanning method (SELSM)

As it is well known, the profile obtained by SELSM is not the presentation of the real fracture profile, which reflects only the variation of the tilt angle $\theta$ of the fracture surface to the incident electron beam at the scanning position. The variation of $\theta$ relevant to the different positions of the fracture surface reflects exactly the degree of roughness of a fracture surface. Therefore, the fractal dimension $D_L$ for scanning profile measured by SELSM can be used to characterize fracture surface roughness quantitatively. A critical problem is how to select appropriately the scanning positions and ensure the measurements for a high accuracy and efficiency. The sectioning method suggested by Gokhale and Underwood is induced into the present study for solving this problem.

Three representative fields of view at an angle of 120° to each other from each fracture surface were taken by the secondary electron image of scanning electron microscopy (SEM). The images were then sent to an IPS-500 image analyzer and line scanning was carried out mutually at 120° on each image (see Fig. 6) to get three scanning profiles. Because the change of grey values of image relevant to different positions along the scanning direction is discontinuous, the obtained scanning profile is actually composed of some scattered points (see Fig. 7(1)). Therefore, the treatments of linear interpolation are made between adjacent points in order to obtain a smooth scanning profile (see Fig. 7(2)). Subsequently, the yardstick method was adopted to measure the fractal dimension $D_L$ for the scanning profile. The fractal dimension for each field of view was based on the average taken from three scanning profiles at an angle of 120° to each other. Finally, the fractal dimension $D_L$ corresponding to the whole fracture was obtained by averaging over the values for three representative fields of view mutually at 120°.

By using the developed SELSM above, quantitative measurements were also performed on a series of cleavage frac-

![Fig. 4 SEM images of the morphology of fatigue fractures of pure Al and composites with different volume fractions of SiC. (a) pure Al (0%), (b) 6% and (c) 25%.

![Fig. 5 Fractal dimension $D_S$ and Fatigue life $N_f$ versus SiC volume fraction.](image)

![Fig. 6 Determination of the scanning position on one field of view selected from the whole fracture surface.](image)
tures with different impact values, which is identical to that used by VSM. The results are also shown in Fig. 2. Comparing the results of SELSM with those of VSM, it is found that the correlation between the fractal dimensions \( D_S \) and \( D_k \) and the impact energy \( \alpha_K \) obtained by the two methods appears to be quite similar. The results further confirm the effectiveness and consistency of the two methods in application to quantitative description of fracture surfaces.

4. Conclusions

Based on the experimental results and discussion above, the following conclusions can be drawn:

1. Fractal dimension \( D_S \) for fracture surface might have different relationships with the mechanical properties of materials for different types of fractures. The microstructures of materials must be considered in the case of relating \( D_S \) to the mechanical properties of materials.

2. The SiC volume fraction has an effect on the fractal dimension \( D_S \) for SiC/Al composite fracture surfaces. The measured \( D_S \) is closely related to the fatigue-crack propagation path and may correspond to the fatigue life. It is possible to reflect the fracture mechanisms to some extent using \( D_S \).

3. The method of sectioning the fracture surface at 120° can be induced into secondary electron line scanning method (SELSM) efficiently. The correlation between the fractal dimensions (\( D_S \) and \( D_k \)) and the impact energy \( \alpha_K \) obtained by VSM and SELSM appears to be quite similar.

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