Surface Roughening and Fractal Dimension during Plastic Deformation of Polycrystalline Iron*

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In order to investigate the relationship between surface roughening and deformation of respective grains, three-dimensional observation of the roughened surface of polycrystalline iron during uniaxial compressive deformation was carried out. The pattern of grain boundaries and the contour map of the surface roughening were superimposed on a personal computer monitor. The three-dimensional surface roughness data were also high-pass-filtered to obtain detailed figures of the surface. The fractal dimension was introduced to characterize the change in three-dimensional surface roughening during plastic deformation. The box-counting method was adopted to measure the fractal dimension. It was found that three-dimensional surface roughening showed fractal characteristics. The value of the fractal dimension was almost constant with increasing applied strain.

Key Words: Plasticity, Polycrystalline Iron, Surface Roughness, Fractal Dimension

1. Introduction

The free surface of polycrystalline metal becomes roughened after plastic deformation. The study of surface roughening is important to clarify the microscopic deformation behaviour of polycrystalline metals. It is also important in metal-forming processes. Namely, surface roughening directly affects the friction, lubrication, adhesion and surface finish of the products, and hence the control of surface roughening is one of the important subjects in metal forming.

Surface roughening is closely related to the inhomogeneous deformation of individual grains^{(1)~(6)}. Hence, in order to clarify the problem, it is important to study the relationship between surface roughening and the deformation behaviour of respective grains during plastic deformation. In the present study, three-dimensional measurement of roughened surface of polycrystalline iron during uniaxial compressive

plastic deformation was carried out using a system to measure the three-dimensional surface shape^{(7)~(10)}. Although the three-dimensional shape of roughened surface was measured at the intervals of 50 μm in the previous work⁽¹⁰⁾, measurement at the intervals of 10 μm became possible in the present study owing to some improvements in the system. The changes in the shape of the roughened surface with increasing applied strain, and the relationship between surface roughening and the deformation of grains were observed with this system.

In the study of surface roughening, the cut-off method (the cut-off of long wavelengths) is usually used in the instrument to obtain detailed surface figures by eliminating the components of long wavelengths. The cut-off method, however, is not applicable to the measurement of three-dimensional surface roughening. Therefore, the three-dimensional high-pass-filtering method was newly introduced instead of the conventional cut-off method, and detailed figures of the three-dimensional surface roughening were obtained.

The method to evaluate the characteristics of three-dimensional surface roughening is not fully

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established because the shape of a roughened surface is usually quite complex and difficult to deal with by simple analysis. Fractal geometry was introduced in the present study to evaluate the characteristic of the shape of the roughened surface^{(11)~(15)}. The shape of the roughened surface of polycrystalline metals seems to consist of waves of various wavelengths, and similar wave shapes are recognized under different magnifications. These characteristics are considered to show the essential feature of the fractal. Therefore, the fractal dimension of the shape of three-dimensional surface roughening was measured by means of the box-counting method, and the change in the fractal dimension with increasing applied strain was studied.

2. Experimental Method

2.1 Specimen and experimental method

The material used was polycrystalline iron⁽¹⁰⁾. The material was hot-rolled, so that the grain size of the specimen was relatively large and anisotropic. The large grain size is suitable for the present study. The initial shape of the specimen was a cube of 20 mm. The free surface of the specimen applied to the measurement was finished using abrasive papers and buffed to a specular finish until the initial center-line average roughness became less than $0.1 \mu\text{m } R_a$. Thereafter, the specimen was annealed in vacuum at 920°C for one hour to eliminate residual stress. The surface was etched in nitric acid to identify the grain boundaries. After these processes, the area of $3.0 \times 3.0 \text{ mm}$ surrounded by scrubbed lines was chosen on the free surface as the measuring area. The initial grain size in the measuring area was about $330 \mu\text{m}$ as determined by the Jeffries method.

The shape of the roughened surface was measured at the intervals of 0.05 of applied strain ϵ . Figure 1 shows the block diagram of the system for the measurement of the three-dimensional surface shape⁽¹⁰⁾. The following equipment was adopted in the system.

- Stylus instrument : Surfcom 304 B
(Tokyo Seimitsu)
(Radius of stylus tip is $5 \mu\text{m}$)
- Analog-Digital converter : ANALOG-PRO II
(Canopus Electronic)
- Personal computer for the control of A-D converter and processing of data : PC 9801 VX (NEC)
- Personal computer to draw the three-dimensional pattern : PC-H 98 model 70 (NEC)
- The system for the trigger of A-D conversion
- Differential Transformer : LT 1-060 C
(Shinko Electronic)
- Indicator : GP-DMP-313 (Shinko Electronic)

Fig. 1 System for measurement of 3-dimensional surface shape

The conditions of the measurement with the stylus instrument and the sampling of data through the A-D converter were as follows.

- Interval of tracing : $10 \mu\text{m}$
- Tracing speed of stylus : 0.3 mm/s
- Magnitude of measurement : $\times 100 \sim \times 500$
- Sampling interval of A-D conversion : $0.6 \mu\text{m}$
- Sampling interval of three-dimensional pattern : $10 \mu\text{m}$

It became possible to compose the mesh-type data after the above processing. (Hereafter, the mesh-type data are called three-dimensional mesh data.) The obtained mesh data were used for following processes. The size of the three-dimensional mesh data at every step of the applied strain ϵ , that is, the number of data points for respective directions, is as follows.

(Direction of compression $\times$ Direction of surface roughness measurement ; points)

$\epsilon = -0.05 : 250 \times 289$	$\epsilon = -0.10 : 232 \times 304$
$\epsilon = -0.15 : 220 \times 313$	$\epsilon = -0.20 : 214 \times 325$
$\epsilon = -0.25 : 193 \times 334$	$\epsilon = -0.30 : 184 \times 361$
$\epsilon = -0.35 : 169 \times 361$	$\epsilon = -0.40 : 145 \times 364$

At every step of applied strain ϵ , grain boundaries on the measuring area were observed by an optical microscope and a scanning electron microscope (Hitachi, S-450). The optical microscope can distinguish the grain boundaries better than the scanning electron microscope when surface roughening is small. As surface roughening became large, however, the scanning electron microscope became more appropri-

ate to distinguish the grain boundaries because its depth of focus is deeper. The grain boundaries are photographed, and transformed into image data by a TV camera and an image processor (ADS, PIP 4000).

2.2 High-pass filter method

The cut-off method was defined in JIS-B 0601 for two-dimensional roughened surface to eliminate the components of long wavelength, but this is not adequate for three-dimensional surface roughening. Therefore, the neighborhood averaging method⁽¹⁶⁾ was adopted for the high-pass filter of three-dimensional roughened surface. Figure 2 shows the outline of this method, and the procedure is as follows.

(1) Set the frame of a filter around the point which is processed for filtering (the original value for the point is $z(x, y)$).

(2) Calculate the average value $\bar{z}(x, y)$ for the points included in the frame of the filter.

$$\bar{z}(x, y) = \frac{\sum_{i=1}^{n_x} \sum_{j=1}^{n_y} z(i, j)}{n_x \cdot n_y} \quad (1)$$

(3) The corrected value $z'(x, y)$ at the point is calculated by

Fig. 2 Neighborhood averaging method

$$z'(x, y) = z(x, y) - \bar{z}(x, y) \quad (2)$$

The components of short wavelength are more emphasized with smaller size of the filter. Two filters with different sizes were adopted in the present study. One was $350 \times 350 \mu\text{m}$ (hereafter referred to as Filter A), and the other was $170 \times 170 \mu\text{m}$ (Filter B). Meanwhile, the initial shape without filtering was referred to as Profile. These filter sizes were selected considering the initial grain size. Figure 3 shows the high-pass-filtered shape at $\varepsilon = -0.4$. Figure 3(a) shows the shape of Profile, (b) the shape of the neighborhood averaging, and (c) the high-pass-filtered shape (Filter A) obtained by subtracting the shape of (b) from that of (a). It is concluded from the comparison of these figures that the neighborhood averaging method is useful to eliminate the components of long wavelength.

The results obtained from the cut-off method and the neighborhood averaging method were compared in Fig. 4. Figure 4(a) shows the roughness curve of Profile, (b) cut-off shape (cut-off value is 0.8 mm), and (c) high-pass-filtered shape by the two-dimensional neighborhood averaging method. Here, the filter size of neighborhood averaging (c) is chosen as $786 \mu\text{m}$, so that the value of the average center-line roughness is the same as the case of (b). It is seen by comparing (c) with (b) that the positions of the mountains and the valleys are similar, though there are some differences in their heights.

2.3 Measurement of fractal dimension

The shape which possesses statistical self-similarity can be analyzed with fractal geometry having non-integer dimension, that is, the fractal dimension^{(11)–(15)}. The complex shape of three-dimensional roughened surface is expected to be classified and evaluated quantitatively with fractal geometry.

Although numerous methods have been proposed to measure the fractal dimension, the box-counting method^{(11)–(15)} was adopted in the present study. The box-counting method is easily applicable to the evalu-

Fig. 3 Example of neighborhood averaging method (Filter A, $\varepsilon = -0.4$)

ation of the shape of roughened surface. Hereafter, the fractal dimension measured by the box-counting method is called the box dimension. The procedure of

(a) Roughness curve (Profile)

(b) Cut-off shape (cut-off : 0.8 mm)

(c) Shape after neighborhood averaging
(filter size : 786 μm)

Fig. 4 Comparison between cut-off method and neighborhood averaging method

the box-counting method is given as follows.

(1) Make a rectangular parallelepiped (box) which completely covers the three-dimensional mesh data.

(2) Divide the sides of the initial box into n partitions, so that the total number of similar boxes is n^3 . Count the number of the boxes (N) which contain data.

(3) Draw a graph whose abscissa is the logarithm of $\delta (=1/n)$ and ordinate is the logarithm of N . If the mesh data have statistical characteristics of the fractal, the plotted points are expected to show a linear relation. Then, the box dimension is obtained as the absolute value of the slope of the line.

The value of the box dimension, which shows the geometrical characteristics of the shape of surface roughening, is basically independent of the dimensions of the shape. Here, the limit of the number of divisions was chosen as the smaller number of measuring points in the two directions of the three-dimensional mesh data (Section 2.1).

The range in which the points show a linear relationship is limited, because the mesh data are of discrete type. In the present study, the box dimension is obtained as the slope of the line calculated by the least squares method from the points in a limited range. Hence, the box dimension varies by about ± 0.05 with slight difference in the choice of the range. Accordingly, a standard procedure is adopted to determine the range suitable for obtaining correct values of the box dimension. The following requirements were considered.

(1) The points on the graph which show linear relations over the region of $10^{1/2}$ of δ are chosen.

(2) The following decision function is used :

Fig. 5 Relationship between $\log \delta$ and $\log N$ of box-counting method ($\epsilon = -0.3$)

Fig. 6 Shape of 3-dimensional surface roughening (Profile)

$$r^2 = \frac{\sum(\hat{y} - \bar{y})^2}{\sum(y - \bar{y})^2}, \quad (3)$$

where y is measured data, $\hat{y}$ is value on the regression line and $\bar{y}$ is mean value of y (when all measured data are on the regression line, $r^2=1$; otherwise, $r^2=0$, $\hat{y} = \bar{y}$). The value of r^2 is chosen as $r^2 \geq 0.9995$ in the present analysis.

The box dimension is given as the mean value of the box dimension measured for all ranges which satisfy (1) and (2).

Figure 5 shows the logarithmic plots of δ and N for the mesh data of $\varepsilon = -0.3$. Figure 5(a) shows the result for Profile, (b) for Filter A, and (c) for Filter B. Since all three figures show linear relations within a certain range, it is concluded that the shape of three-dimensional roughened surface has the characteristics of a fractal.

3. Experimental Results and Discussion

3.1 Observation of three-dimensional shape of surface roughening

Figures 6~8 show the change in the three-dimensional shape of the roughened surface with increasing applied strain. Figures 6, 7 and 8 show the data of Profile, Filter A and Filter B, respectively.

The mountains and the valleys shown in Fig. 6 are

composed of 5~10 grains. It is also seen that the amplitude of the roughened surface grows with increasing applied strain. That is, the mountains which appear at the initial stage of deformation become higher with the applied strain, while the valleys become deeper. Their location, however, does not appreciably change. The mountains and the valleys elongate in the direction normal to loading, and shrink in the loading direction. Hence, it is considered that the deformation behaviour of polycrystalline metals is affected by the deviation of flow stresses resulting from crystallographic orientations of respective grains.

The shape shown in Fig. 7 is obtained after processing by the neighborhood averaging method (Filter A). The shape is mainly composed of shorter waves, where the wavelength is nearly equal to the grain size. The shorter waves cannot be distinguished in the shape of Profile, because the amplitudes of these waves are much lower than those of longer waves which dominate Profile. The mountains and valleys in Fig. 7 seem to correspond to the grain boundaries.

Figure 8 shows the surface shape obtained with Filter B. Here the shape is composed of waves shorter than those in Fig. 7. The shape of these figures is considered to show the deformation inside grains. It is

Fig. 7 Shape of 3-dimensional surface roughening (Filter A)

interesting that the locations of mountains and valleys of the high-pass-filtered shapes are also unchanged with increasing applied strain.

3.2 Change in surface roughness with applied strain

In the present paper, the average roughness R_a and the maximum height R_{max} were obtained from the

three-dimensional mesh data. That is, R_a was calculated from the central plane determined by the least squares method. Figure 9 shows the changes in R_a and R_{max} with the applied strain. The results for another specimen (Specimen 2) are also plotted in Fig. 9 (the initial grain size of Specimen 2 was $360\text{ }\mu\text{m}$).

The values of R_a and R_{max} increase proportionally

Fig. 8 Shape of 3-dimensional surface roughening (Filter B)

Fig. 9 Change in 3-dimensional surface roughness with applied strain

Fig. 10 Change in box dimension with applied strain

with the applied strain. R_a corresponds to the change in the average height in the entire measuring area, that is, global deformation. Meanwhile, R_{max} corresponds to the change in the height of peaks, that is, local deformation. The tendencies of the two changes are almost the same. These results seem to support the previous observation that only the amplitude of the roughened surface increases with applied strain.

The values of R_a and R_{max} decrease with decrease in filter size, which results from the elimination of long wavelengths.

3.3 Change in box dimension with applied strain

Figure 10 shows the relationship between the box dimension (fractal dimension) calculated from the three-dimensional mesh data and the applied strain. The values of the box dimension are nearly constant with increasing applied strain. This result is also in accordance with the previous observation that the locations of mountains and valleys on the roughened surface are unchanged, whereas the amplitude increases with applied strain. That is, the fractal characteristics of the shape of surface roughening are almost unchanged during the increase of applied strain.

The results shown in Fig. 10 indicate that the box dimension increases with decrease in filter size. This corresponds to the changes in the surface shape shown in Figs. 3 and 6~8 where the shape becomes very wavy with decrease of filter size. Two possibilities may be considered as to the influence of the filter method. One is the characteristics of the mathematical operations in the neighborhood averaging method. Although the neighborhood averaging method was used to eliminate the components of long wavelength, its influence on the box dimension has not been

clarified yet. Since the aspect ratio of boxes in the box-counting method is altered by the filtering method, it may affect the value of the box dimension^{(14),(15)}. (The resolution upon measurement of the surface asperities normal to the surface is about 1 : 6 for Profile and Filter B).

The second possibility is that different physical mechanisms of deformation may result in different values of the box dimension. Surface roughening may be caused by various mechanisms such as deformation and rotation of grains or microscopic slips in a grain. Therefore, if the filtered shape and Profile shape show the effects of different physical mechanisms of deformation, the values of the box dimension may be varied.

Further investigation, however, is necessary to clarify the effect of the above two possibilities.

4. Conclusions

The three-dimensional shape of the roughened surface of polycrystalline iron was measured with a specially designed measuring system, and the changes of the shape with increasing compressive plastic strain were observed. The neighborhood averaging method was introduced to eliminate the components of long wavelength. Fractal geometry was introduced to evaluate the characteristics of the three-dimensional shape of surface roughening. The changes in the box dimension (fractal dimension) measured from the surface shape with the increase of applied strain were investigated. The main conclusions are summarized as follows.

(1) The amplitude of waves of surface roughening increases with increasing applied strain, but the location of mountains and valleys of the waves are almost unchanged.

(2) The average roughness R_a from the central plane and the maximum height R_{max} of the measured surface increase nearly in proportion to the applied strain.

(3) The roughening of the free surface of polycrystalline iron shows the characteristic feature of the fractal.

(4) The values of the box dimension are almost constant during compressive strain. This is considered to indicate quantitatively the characteristic of the surface roughness waves of polycrystalline iron.

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