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STEREOSCOPIC FRACTURE ANALYSIS BY SEM USING STEREO MATCHING AND INTEGRATING SECONDARY ELECTRON SIGNALS

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ABSTRACT

Three-dimensional analysis of a fracture surface using a scanning electron microscope (SEM) is necessary to clarify the cause of the fracture. Stereo matching and the integration of the angles calculated based on the intensity of secondary electron signals are widely used methods because of their versatility and simplicity. The former method is advantageous because of its accuracy, and the latter method is advantageous because of its resolution; however, it is rather difficult to attain both accuracy and high resolution. In this paper, a new method is described to solve this problem, which is attained by the combination of these two methods. In this method, the profile heights of fracture surface calculated by stereo matching are revised with those correct inclinations measured by secondary electron signal intensity so as to lessen the error of stereo matching. The application of the developed method on several typical fracture surfaces of metals will be shown. In order to examine its precision, the accuracy of the proposed method was investigated and satisfactory results were obtained. A personal computer takes approximately only six minutes for 3 dimensional analysis of one picture, this results shows the developed method is practical. It also shows that the method will become a powerful tool to analyze fracture surface and understand fracture.

KEYWORDS

fractography, fracture surface, SEM, 3-dimensional measurement, fracture, stereo matching, secondary electron.

INTRODUCTION

In the field of fractography, three-dimensional analysis of a fracture surface is helpful when trying to clarify the cause of the fracture. At the nano-scale, it is valid to analyze the fracture surface with a scanning tunneling microscope (STM) or an atomic force microscope (AFM), but at the micro-meso scale region, especially at the scale of grain size and subgrain size, a scanning electron microscope (SEM) shows superior property to analyze the stereoscopic information of the fracture surface. As for the 3D analysis by SEM, the stereo matching and the integration of secondary electron signals are widely used [1]. Stereo matching is the process of taking a pair of stereo images at different inclination angles of a specimen and determining the height or depth by measuring deviations of corresponding points on the two images. This method is advantageous for measuring the height of edge points and has no accumulated error, but it is disadvantageous when measuring no characterized region, such as a smooth plane or a gentle curved surface. Because stereo matching can only calculate the height in every pixel unit, it is unavoidable to lead to the discretized error of the height, so the resolution of height is limited and a plane or a curved surface may appear as a jagged surface [2]. Another method for reconstructing a fracture surface profile is to use a pair of secondary electron detectors [3]. Using the system installed in a SEM, the surface profile is obtained by integrating secondary electron signals, whose intensity is in proportion to the inclination of the surface profile. This method is superior for measuring planes or gently curved surfaces, but the accuracy is not assured at the edge points or at the point where the inclination angle of the surface is more than 65 degree. Thus, the error accumulates along the integrating line and this problem is not solved yet.

In summary, neither stereo matching nor the integration of secondary electron signals satisfactorily can meet both accuracy and resolutions, which are requirements of micro-fractography for microscopic 3-dimensional measurements. Thus, in order to obtain real 3-dimensional fracture surface profiles, a new method is proposed, which is the combination of the two methods.

NEW METHOD OF MEASURING FRACTURE SURFACE PROFILES

In this method, the profile heights of fracture surface calculated by stereo matching are revised with those correct inclinations measured by secondary electron signal intensity so as to lessen the error of stereo matching. At first, using SEM stereo images (source image and oblique image) of fracture surface are taken. And in the meantime, the height data of surface profile for source image is also obtained by integrating secondary electron signals. It is necessary for stereo matching that the data interval of heights between neighboring points is not less than 8 pixels. Hereafter, the length between neighboring points is called as mesh and is shown in Figure 1. To ensure that the two methods can be combined, the position of point (i,j) reconstructed with stereo matching must correspond to the position determined by integrating secondary electron signals. Then, in order to lessen the error of stereo matching and obtain the real height H(i,j) of point (i,j), it is necessary to revise the height $H_m(i,j)$ of stereo matching with the inclination θ_s (namely clockwise $\theta_s(i,j-1)$, $\theta_s(i-1,j)$, $\theta_s(i,j+1)$, $\theta_s(i+1,j)$) which is between point (i,j) and neighboring 4 points. And here θ_s is measured by secondary electron signal detectors. In cases where each inclination θ_m (clockwise $\theta_m(i,j-1)$, $\theta_m(i-1,j)$, $\theta_m(i,j+1)$, $\theta_m(i+1,j)$) calculated by stereo matching is less than 65 degree, the degree θ_s detected by secondary electron signals is much more correct than that of stereo matching. So the revised height is the average of $H_m(i,j)$ and $H'_m(i,j-1)$, $H'_m(i,j+1)$, $H'_m(i-1,j)$, $H'_m(i+1,j)$. Here, $H'_m(i,j-1)$, $H'_m(i,j+1)$, $H'_m(i-1,j)$, $H'_m(i+1,j)$ are the heights calculated from neighboring points and their inclinations detected by secondary electron signals. For example:

$$H'_m(i,j-1) = H_m(i,j-1) + mesh \times \tan(\theta_s(i,j-1)) \qquad (1)$$

However, it is not appropriate to revise the height at the point where one of the inclinations calculated by stereo matching is more than 65 degree because the degree detected by secondary electron signals cannot be assured. For example, if $\theta_m(i,j-1)$ is less than 65 degree, the revised height of (i,j) will be the average of $H_m(i,j)$, $H'_m(i,j+1)$, $H'_m(i-1,j)$, $H'_m(i+1,j)$

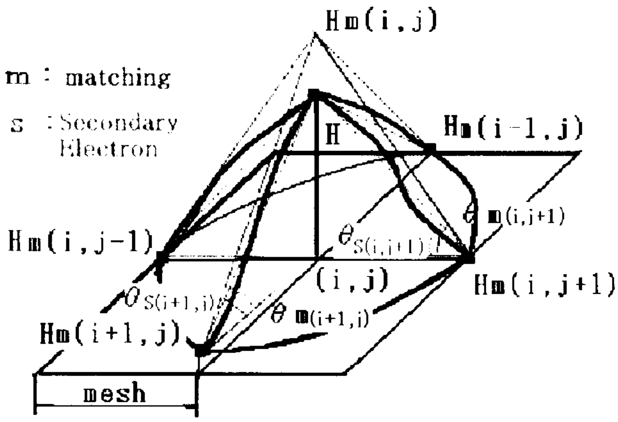
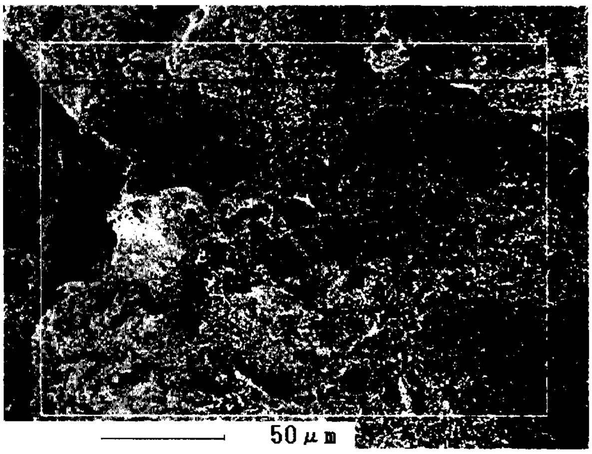


Fig. 1. Illustration of calculation for the height of point (i,j) revised with the heights and inclinations of neighboring points. The position of point (i,j) reconstructed with stereo matching is correspond to the position measured by integrating secondary electron. The interval (namely mesh) between the points is not less than 8 pixels. Hm(i,j) is the heights calculated by stereo matching.

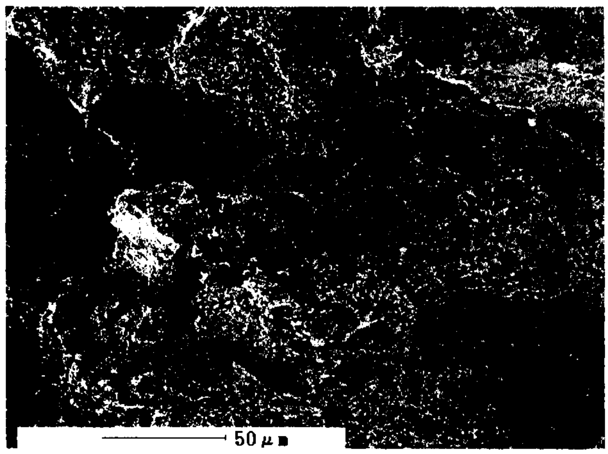
According to this concept, the revised height is also calculated for all points. The height of every point is revised the two times to lessen the discretized error of stereo matching.

APPLICTION OF THE METHOD TO FRACTURE SURFACES

The proposed method is applied to several fracture surfaces. Figure 2 shows the image of a ductile fracture surface on a Charpy V-notch specimen. The material used is steel JIS G3106 SM400B whose chemical composition is C =0.2%, Si=0.35%, Mn=0.60%, 0.14%, P<0.035%. The left side of the figure is a SEM photograph of the source image and the right side of the figure is the oblique image tilted by 5 degrees. These digital images are taken directly with a scanning electron microscope (ERA-8800, manufactured by Elionix Co. of Japan), with which the surface profile is also measured by integrating secondary electron signals. The area outlined by the white line of Fig. 2 (a) is reconstructed by the proposed method. In order to minimize the number of mismatching points, a modified template method of stereo matching is employed, in which the template size is varied from 51×51 to 7×7 pixels[4]. It takes about 5 minutes to process all the heights of 130×90 points in a workstation (SUNW, Axil-245) with a 245-MHz CPU, 64 M of memory, or about 6 minutes in a personal computer with a 233-MHz CPU and 64 M of memory. Thus, it is considered to be practical for the analysis.



(a) Source image (0 degree)



(b) Oblique image (5 degree)

Fig. 2. SEM photographs of the ductile fracture surface on a Charpy impact specimen of JIS SM400B (Image size: 1200×900 pixels)

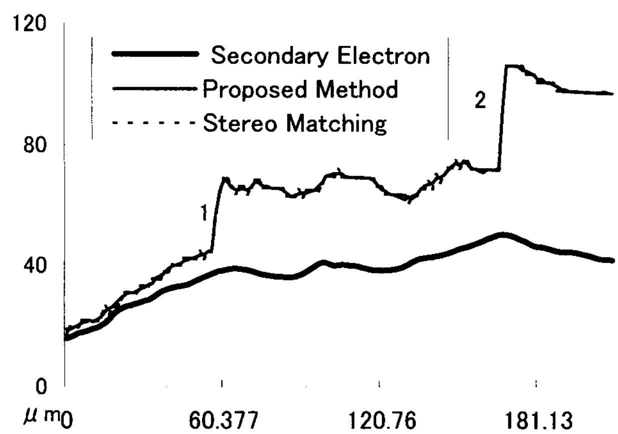


Fig. 3. Profile height of one line in the source image of Fig.2 measured by proposed method. The results calculated with stereo matching and integrating

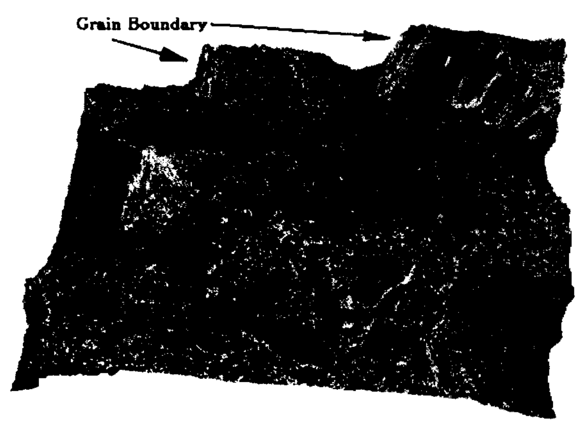
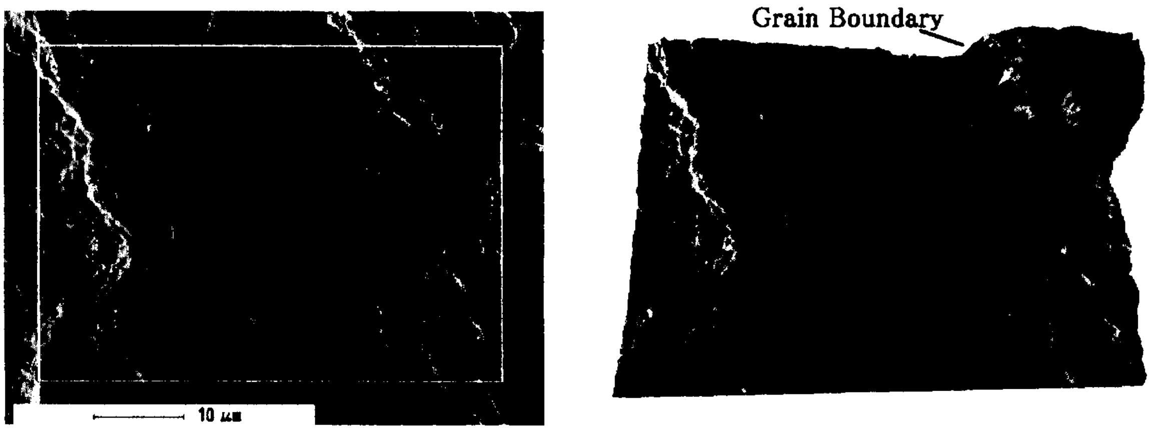


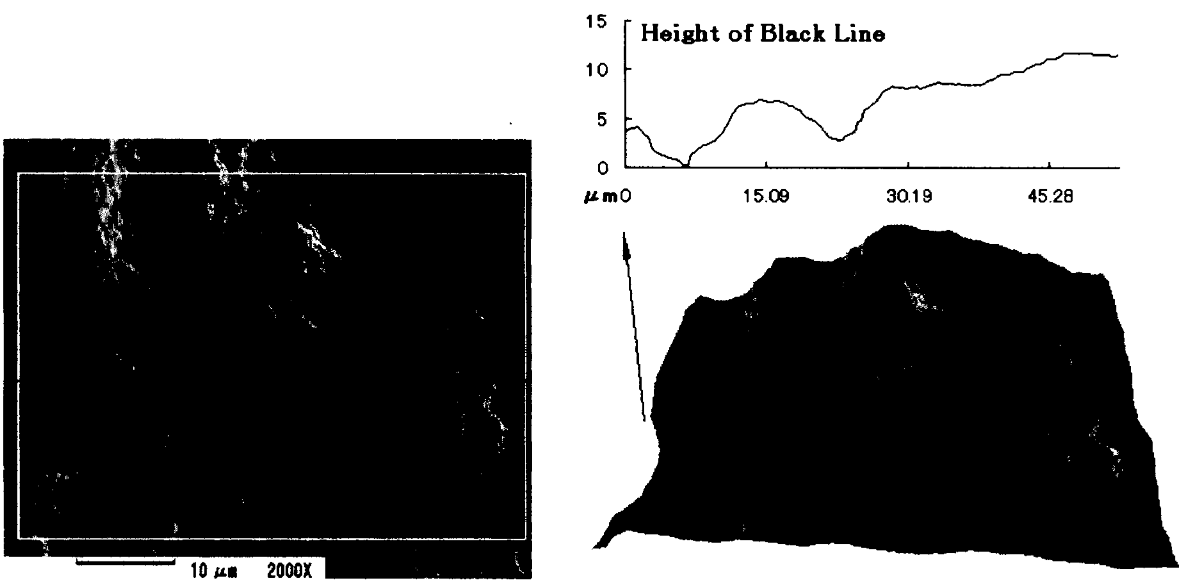
Fig. 4. Bird's-eye view of the fracture surface of the object in Fig. 2

Figure 3 shows the profile heights along the black line in the source image of Figure 2. The profile is measured by three methods: the proposed method, stereo matching and integrating secondary electron signals. The lowest height of the measured area is set to 0 μm. On the one hand, the grain boundary or edge points 1, 2 shown in the figure can be found from the result of stereo matching, stereo matching gives poor resolution and the results are jagged. Although, the result of integrating secondary electron signals gives good resolution and one can obtain a gentle curve, but the edge point where the inclination is more than 65 degree cannot be found from the curve. On the other hand, the proposed method doesn't have the disadvantages of these two methods. Namely, using the proposed method, not only the grain boundary can be easily judged but also the resolution is high. It's shown that the results of three methods are similar except the edge points and the edge points yield a huge accumulated error of integrating secondary electron signals. Figure 4 shows the reconstructed 3-dimensional bird's-eye view whose area is



(a) SEM photograph of the fracture surface (b) Bird's-eye view of the fracture surface

Fig. 5. Creep-fatigue fracture surface on a specimen of 2 ¼ Cr-1Mo failed in vacuum



(a) SEM photograph of the fracture surface (b) Bird's-eye view of the fracture surface

Fig. 6. Creep-fatigue fracture surface on a specimen of 2 ¼ Cr-1Mo failed in vacuum

corresponding to the zone enclosed with white line in Figure 2, and the fracture surface is displayed in texture mapping of a VRML (Virtual Reality Modeling Language) file. The fracture surface is complicated, and it is difficult to find the grain boundary from just a 2-dimensional SEM image. From a 3-dimensional reconstructed image, however, the grain boundary can be easily found, where the surface is acute.

Figure 5 (a) shows an SEM photograph of the creep-fatigue fracture surface on a specimen of 2¼ Cr-1Mo failed in vacuum at 500 ℃. Figure 5 (b) is the 3-dimensional bird's-eye view of the area inside the white line of Figure 4 (a), which is reconstructed with the proposed method. Most of the fracture surface is shown to be gentle intragranular surface. The grain boundary in the fracture surface can be easily found. It can also be concluded that this fracture is a fracture surface of transgranular fracture.

Figure 6 shows the fracture surface on another area of the same specimen of 2¼ Cr-1Mo. Figure 6 (b) is the bird's-eye view of the area inside the white line of Figure 6 (a). Two cavities can be seen in the fracture surface. From the height of the black line, the average depth of the cavities is about 6 μm and the diameter is about 10 μm.

CONCLUSIONS

Conclusions would be summarized as follows:

1. Neither the stereo matching method nor the method of integrating the angles detected by the intensity of secondary electron signals is completely adequate for making a 3-dimensional measurement of a fracture surface.
2. A new method by combining stereo matching and integrating secondary electron signals has been developed.
3. The proposed method was applied to several typical fracture surfaces of metals. The accuracy of the proposed method is examined and satisfactory results are obtained.
4. The processing time for 3-dimensional analysis in personal computer was short enough to make the method practical. It shows that the method will become a powerful tool to analyze fracture surface and understand fracture.

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