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General paper

Stereoscopic Fracture Surface Analysis by SEM Using Advanced Stereo Matching

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Abstract: Three-dimensional analysis of fracture surface by SEM (Scanning Electron Microscope) is inevitable to clarify the cause of fracture. It is effective to analyze with stereo matching. However, conventional template matching method to measure 3-dimensional profile of fracture surface usually employs fixed template size and has deficiencies such as mismatching and consuming much processing time. Therefore, in this paper, a new stereo matching algorithm is developed, which cannot only save processing time but assure accuracy. In this new template matching method, template size is varied to assure accuracy and lessen mismatching points. In order to shorten processing time greatly, when calculating the correlation coefficient of image template pixels to search the matching templates, all the pixels in templates are not employed, but it is proposed that one pixel is chosen every 2 or several pixels in the same positions of the two templates. In order to investigate the precision and the usefulness of the proposed method, two examples of reconstructing fracture surfaces are successfully shown. It is practically realized to measure three-dimensional profile of fracture surface in personal computer.

Key words: *Fractography, 3-dimensional measurement, SEM, Stereo matching, Algorithm, Fracture surface, Fracture*

1. INTRODUCTION

Three-dimensional analysis of a fractured 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), however, at the micro-meso scale region, especially at the scale of crystal grain size and subgrain size, a scanning electron microscope (SEM) is still needed to analyze the stereoscopic information of the fracture surface [1]. Popular methods for such analysis include the method of integrating secondary electron signals and stereo matching. The former is superior for applying to planes or gently curved surfaces, but the accuracy is not assured when it is used to reconstruct the fracture surface which has complex shapes [2-9].

In fractography, stereo matching is a valid method to reconstruct 3-dimensional fracture surface. 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. Although stereo matching method cannot be performed in real-time, because it is advantageous for measuring the height of edge points and has no accumulated error, it is widely employed in the analysis of complex fracture surface. However, conventional stereo matching method has two disadvantages, namely the tendency to produce mismatching and the amount of calculation time needed [5-9].

In this research, compared with conventional method, it is attempted to develop a stereo matching algorithm which is improved for both speed and accuracy. This efficient algorithm is proposed and its validity is examined, and finally the examples of application to fracture surface are also shown.

2. THE PROBLEM OF COVENTIONAL STEREO MATCHING METHOD

Similar to a human being's vision, stereo matching is a method for reconstructing 3-dimensional surface shape by a pair of images, namely "source image" and "oblique image". In this method, it is fundamentally important for stereo matching to search a matching point between stereo images and many kinds of algorithm have been developed. Matching methods are roughly divided into structure matching and template matching [10-18]. The former is a feature-based method and makes a match on the feature structure extracted from the images, i.e., the edge lines. This method is effective in especially automatic detection and reconstruction of a building from stereo aerial photograph. But, since characters need to be detected or be judged subjectively, it is difficult to reconstruct the shape in which there are no character points such as edges [16]. Template matching method is an area-based method and makes a match on template areas in images. In order to search correspondent points or areas on two images, a window area (template) is set on both source image and oblique image. The candidate of template is scanned on the search area of oblique image by computer until the best matching template is found. The typical measures used for evaluating the matching are SSDA (sequential similarity detection algorithm) or MCC (mutual correlation coefficient) methods.

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Although the algorithm of " Coarse and Fine Search"[5-6] is employed to save processing time, it is difficult to improve the accuracy by conventional matching method. Since the template size is usually fixed in conventional matching method, when a big template is employed, the accuracy cannot be assured and much processing time is necessary. On the country, a small template is employed, the accuracy can be assured if matching is correct, but it is easy to lead to mismatching. To lessen mismatching, GA (Genetic algorithms) was also developed [9]. Since template size is also fixed in GA method, it is necessary to find the appropriate template size and to take much processing time [11]. By using GA method, super-computer was usually employed in the past.

Moreover, a pyramid template matching method is also popular recently. It is a type of multi-resolution image representation in which an image at level I is obtained from the image at level I-1 by smoothing and sampling. The base of the pyramid, level 0, is the original image. The resolution of both template and image by creating an image is reduced and a small template is matched against a small image to identify locations of strong matches. Then, by iterating on higher and higher resolution images, the image and template is expanded and higher resolution template selectively is matched to higher resolution image. The issue is how to decide the number of levels and how to choose detection thresholds at each level: too low level will lead to too much cost; too high level will miss match. So, in order to attain high accuracy, this method requires much experience and processing time [10-18].

Generally speaking, in order to realize practical analysis in a personal computer, it is necessary to develop the method of satisfying all these characteristics: short processing time, high accuracy and correct matching.

3. THE PROPOSAL OF EFFICIENT STEREO MATCHING METHOD ALGORITHM

As the conventional template matching method, there are two ways to lessen processing time:

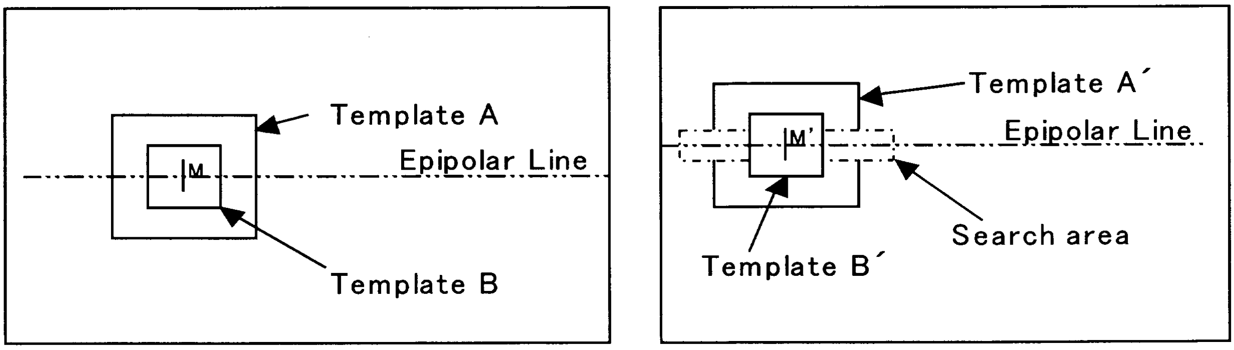
(1) Coarse and Fine Search: In this case, the maximum mutual correlation coefficient, point A, is first searched by the coarse search. Then the maximum is searched in the eight neighborhoods of point A, which give the solution, i.e. point B.

(2) Utility of epipolar geometry [15]. If the constraints of epipolar geometry are satisfied fully, when searching the matching points, a 1-dimensional search along epipolar line is theoretically sufficient. Because of the displacement accompanied with tilting specimen stage, matching point is not necessarily fit for epipolar geometry. So the search area of corresponding candidate points should be limited to the epipolar line and two lines of the adjoining upper and lower sides as shown in Fig.1.

Besides, as an algorithm of raising analysis speed without spoiling analysis accuracy, the following two items are newly proposed:

(1) Make template size variable. Figure 1 shows the principle. In order to find M' on the oblique image which is the correspondent point of position M on the source image, big template A centering on M point is set, and rough analysis is performed. By mutual correlation coefficient method, mating template A' is determined in oblique image and central point P is also determined as a mating point. However, because of coarse research, P is not correct correspondent point M', but M' must be near the P point. Therefore, smaller template B is set up to search by limiting about 2 pixels near the P points similarly, and point Q is determined as a central point of matched template B'. In most cases, this point of Q is thought to be the correct correspondent point M', but when M' points are near the ridgeline or the boundary of a template faces across a ridgeline, or when there is image noise, or when correspondent point is masked, the maximum correlation coefficient is so small that Q may be not M' and exact matching is still difficult by this step. So, a threshold value of correlation coefficient (for example, 0.8) is set. If less than threshold value, the correlation coefficient of template B and B' is compared with that of template A and A'. The central point of the larger one is determined as a corresponding point. In this way, mismatching can be prevented and the error can be controlled to the minimum extent. As the level of template size, there is usually no problem on accuracy just using two layers of template.

(2) Choose one pixel every several pixels to match. When calculating the correlation coefficient of image



(a) Source Image (b) Oblique Image

Fig. 1. Illustration of stereo matching by varying template size.

template pixels to search the matching templates, all the pixels of template are employed in the conventional method. With increase of template size, the calculation time of correlation coefficient increases remarkably. In order to shorten processing time, when calculating the correlation coefficient of large templates, all the pixels in templates are not used to calculate the correlation coefficient, but one pixel is chosen every 2 or 3 pixels in the same positions of the two templates so that the processing time can be saved and become 1/4 (or 1/9) but it does not lead to a difference in the results of matching.

4. EXPERIMENTAL

The proposed method is applied to two 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 compositions are C=0.20%, Si=0.35%, Mn=0.60%, S<0.14%, P<0.035%. The left side of the figure is on SEM photograph of the source image and the right one is the oblique image tilted by 5 degrees. The image sizes are 1200x900 pixels and each pixel is 8 bits (256 gray levels) in intensity.

These digital images are taken directly with a scanning electron microscope (ERA-8800, manufactured by Elionix Ltd. Co., 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. It takes about 6 minutes to process all the heights of 130×90 analyzing points in a workstation (SUNW, Axil-245) with a 245-MHz CPU(central processing unit), 64 MB of memory, or about 7 minutes in a personal computer with a 233-MHz CPU and 64 MB of memory. Thus, it is considered to be practical for the analysis.

5. RESULTS AND DISCUSSION

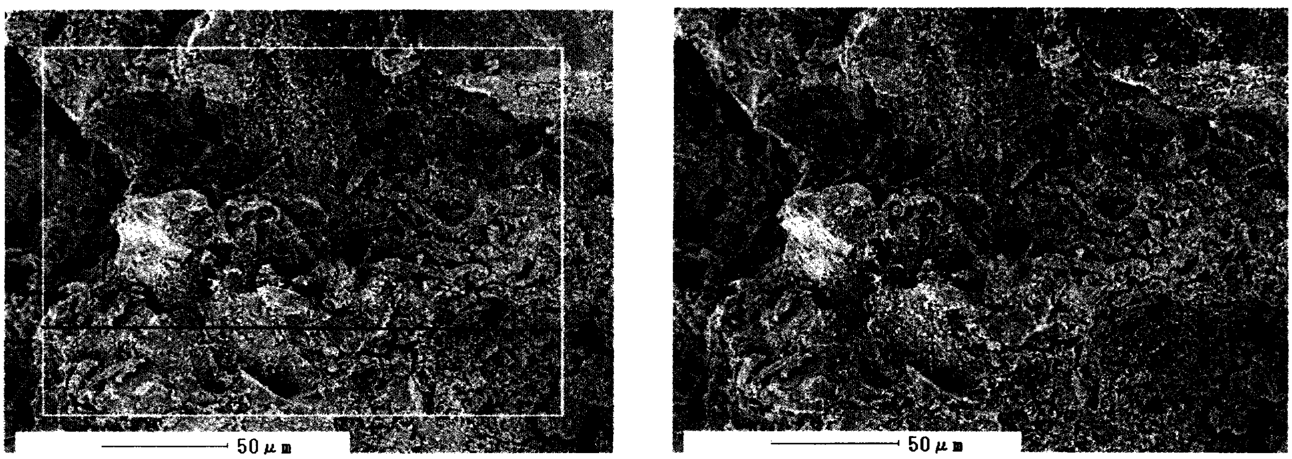
The result of the conventional method, in which the template size is fixed, is compared with that of the proposed method.

Template size in the proposed method was made variable from 51x51 to 7x7, and performance comparison was performed for calculation time, number of mismatching points, and the mean correlation coefficient.

The mismatching points were judged as clearly irrational points by stereovision. For fracture surface A

Table 1. Comparison between proposed and conventional method for two fracture surfaces (A and B). The result was calculated in a workstation.

Method	Template Size (L×W)	Comparison of Performance: Total Processing Time (min.)		Mismatching Points Number		Average Correlation Coefficient	
		A	B	A	B	A	B
Coventional	51×51	33		0	0	0.822	0.829
	41×41	20		6	2	0.815	0.832
	31×51	12		8	6	0.756	0.796
	51×31	12		10	8	0.802	0.819
	21×21	5		>15	>15	0.683	0.714
	7×7	1		>15	>15	0.612	0.625
Proposed	51×51 & 21×21	7		0	0	0.837	0.852
	51×51 & 7×7	6		0	0	0.833	0.850



(a) Source Image (b) Oblique Image

Fig. 2. SEM images of the fracture surface on a Charpy impact specimen of JIS SM400B (Inclination $\theta=5°$, Image size: 1200×900 pixels).

and B, the result obtained for 130×90 analyzing points is shown in Table 1. By the conventional method, the result of Table 1 shows that mean correlation coefficient becomes smaller when the template size is smaller. This phenomenon can be explained as follows: That is, as described in Section 3, when the boundary of template faces across a ridgeline or image noise exists, a corresponding point will not be able to be discovered correctly so that the correlation coefficient will become remarkably small. Since this influence is larger when the template size is smaller, the mean correlation coefficient becomes smaller. The conventional method is difficult for the character of all the three items, but the proposed method has given the good result, namely that it does not have a mismatching point, and the mean correlation coefficient is high, also it needs little calculation time. Especially the calculation time of the proposed method is only 6 minutes in a workstation. In addition, the calculation time which analyzes the same domain using the personal computer of 233MHz CPU and 64M memory is 7 minutes. By using the conventional method in which the template size is set to 21×21 and 51×51 pixels, the reconstructed bird's-eye view of fracture surface A is shown in Fig. 3 and Fig. 4 respectively. The bird's-eye view of the same area reconstructed by the proposed method is shown in Fig. 5.

Contrasted with the stereovision of Fig. 2, the clear mismatching points exist in Fig. 3. The discontinuous height of mismatching point calculated by proposed method cannot be found in Fig. 5. From the comparison of Fig. 3 and Fig. 5, the discontinuous mismatching point of the height is not visible in Fig. 5 by the proposed method. It can be concluded that analysis accuracy of proposed method is improved. Moreover, although the mismatching points decrease with the bigger template size in Fig. 4, many level differences of height exist. As compared with the profile of smooth fracture surface shown in Fig. 5, it is clearly unnatural for fracture surface. So there is no mismatching point and the profile height of fracture surface changes smoothly in Fig. 5, therefore the proposed method considered to have high measurement accuracy. In addition, unevenness — acute grain boundary — can be judged clearly from Fig. 5.

The height section on the black line of the source image in Fig. 2 is shown in Fig. 6. By the conventional method which made template size small and is set to 21×21, two mismatching points exist in the place of 50 μm in horizontal coordinates. Moreover, when template size is enlarged and is set to 51×51, a mismatching point does not appear in the analysis result. It will become a level straight line in the place of 180～200 μm of horizontal coordinates, and the accuracy is thought to fall.

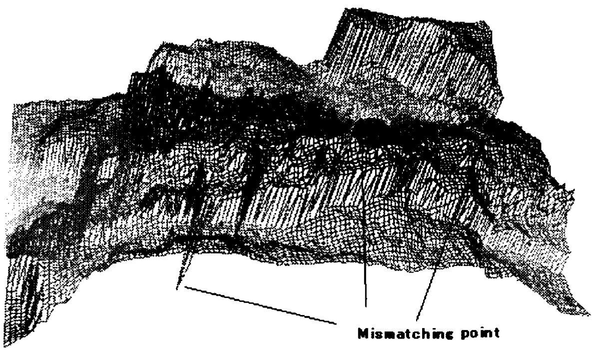


Fig. 3. Bird's-eye view for reconstructed surface profile on specimen A in Fig. 2. Template size is 21×21 pixels.

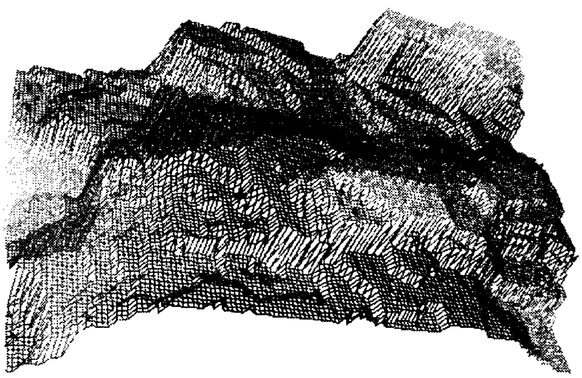


Fig. 4. Bird's-eye view of fracture surface in Fig. 2 by using template size 51×51 pixels.

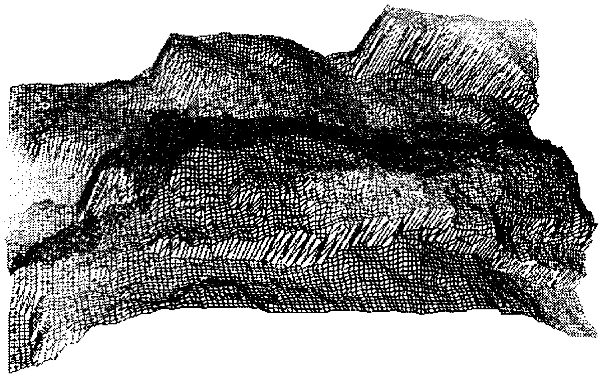


Fig. 5. Reconstructed fracture surface profile on specimen A by proposed method. Here Template size is varied between 51×51 and 7×7 pixels.

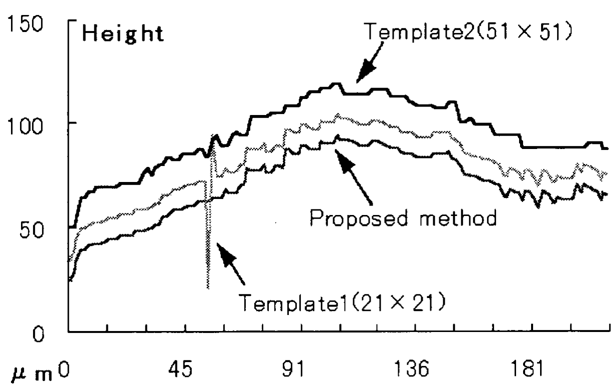


Fig. 6. Measured profile height of one line in Fig. 2.

So it is difficult to keep both accuracy and correct matching by the conventional method. In contrast, the proposed method can attain no mismatching point and high accuracy. Moreover, in the case of template 21×21 in the conventional method, as compared with that of the combination of template 51×51 & 7×7 in the proposed method, profile forms are alike and accuracy is considered almost equivalent. But the result of conventional method (21x21) will produce clear mismatching points from Fig. 6. By using the proposed method, if the template size 51x51 & 7x7 is set to 51x51 & 21x21, there doesn't exist a big difference in analyzing accuracy of the results, but the calculation time of the latter increases for a while. Therefore, template 51×51 & 7×7 which needs less calculation time is adopted here.

Figure 7 shows a creep-fatigue fracture surface of 2¼Cr-1Mo steel on the specimen B failed in vacuum. Figure 8 shows the reconstructed 3-dimensional bird's-eye view whose area corresponds to the zone enclosed with white line in Fig. 7. Most of the fracture surface in SEM image is shown to be smooth and flat intragranular surface. The grain boundary in the fracture surface can also be easily found. It can be concluded that this is a fracture surface of transgranular fracture.

VRML (Virtual Reality Modeling Language) is a language used to create interactive, 3-dimensional virtual worlds on the Web. In order to understand 3-dimensional surface forms better, the results can be expressed in Fig. 9 and Fig. 10 for analyzed result of Fig. 5 and Fig. 8, using VRML after carrying out texture mapping. The validity to understand the unevenness of fracture surface was checked.

6. CONCLUSIONS

In this paper, a new stereo matching algorithm is developed to analyze 3-dimensional information of fracture surface. Conclusions are summarized as follows:

(1) Template size is set to be variable and the efficient stereo matching algorithm was newly developed to reconstruct 3-dimensional fracture surface.

(2) The resulting proposed method has few mismatching points and can guarantee accuracy. It takes about 7 minutes to process all the heights of 130×90 analyzing

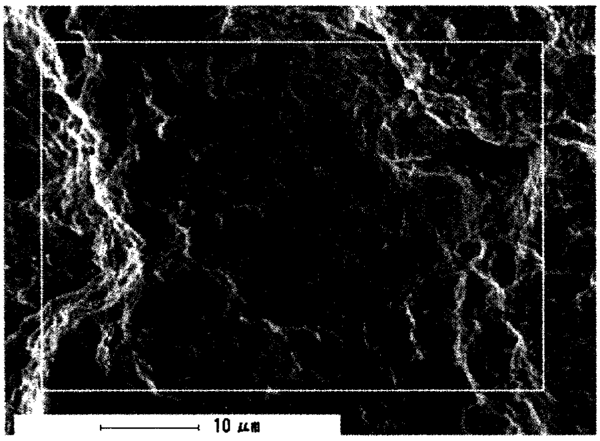


Fig. 7. SEM image of creep-fatigue fracture surface on 2¼Cr-1Mo specimen failed in vacuum.

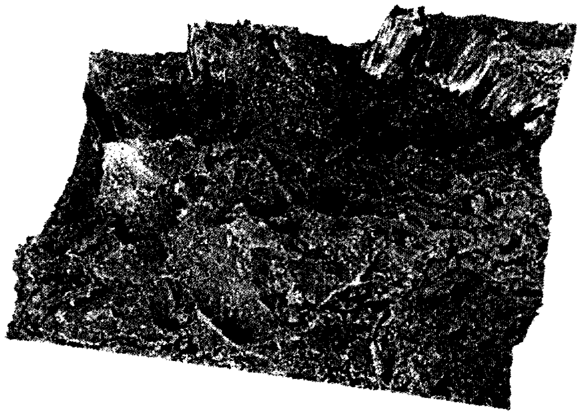


Fig. 9. Bird's-eye view of Fig. 5 displayed in VRML file.

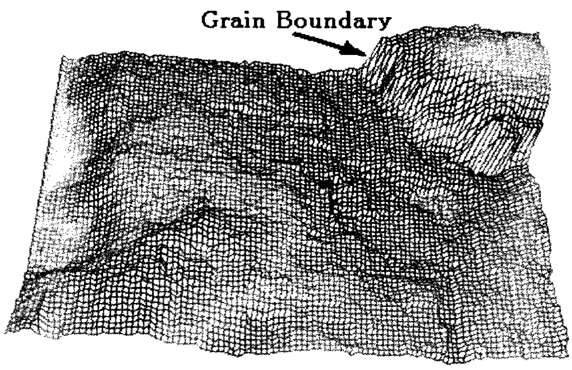


Fig. 8. Reconstructed surface profile of specimen B by the proposed method.

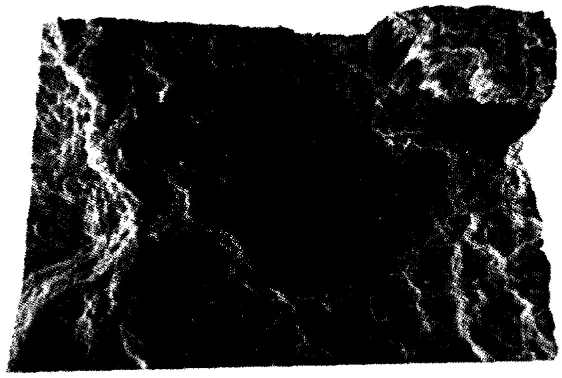


Fig. 10. Bird's-eye view of Fig. 8 displayed in VRML file.

points in a personal computer with a 233-MHz CPU and 64-MB of memory. Compared with the conventional template matching method, the proposed method also requires little processing time and 3-dimensional fracture surface analysis in a personal computer level can be carried out on a practical level.

(3) The proposed method was applied on two typical metal fracture surfaces, and the validity was verified.

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