Factors Influencing Image Processing to Reconstruct Three-dimensional Fracture Surfaces by the Stereo Matching Method

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(Received on February 16, 2004; accepted in final form on April 16, 2004)

A computer-aided stereo matching method has been recently developed for reconstruction of three-dimensional images,1–4) and has successfully been applied to the quantitative evaluation of fracture surfaces in materials.5–10) Reconstruction procedure is composed of the detection of corresponding points (homologous points) in a stereo pair by the pattern recognition of template and the calculation of height data at all the corresponding points.1–4,10) The authors11,12) proposed a new stereo matching method on the basis of the coarse-to-fine format. However, it is necessary to adopt a suitable procedure of image processing and analysis for acquisition of accurate three-dimensional data in a short processing time.3,4,10) In this study, factors of image processing for three-dimensional image reconstruction such as evaluation function and template size were examined on the stereo matching method based on the coarse-to-fine format. Quantitative analysis on the basis of fractal geometry13,14) was made on the geometrical features of the reconstructed stage I fatigue fracture surface of a Cu–Be alloy (the grain size is about 24 μm). The result of the fractal analysis made on the contours generated from the reconstructed image was also compared with that obtained on the fatigue fracture surface profile of the same alloy in the previous study.12,15)

Figure 1 shows the computed region in the basic image for three-dimensional image reconstruction of the stage I fatigue fracture surface in a Cu–Be alloy (338 x 402 in pixel).12)

Table 1. Evaluation functions for identification of corresponding points.

<table>
<thead>
<tr>
<th>Evaluation function</th>
<th>Equation</th>
<th>Identification condition</th>
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<tbody>
<tr>
<td>Sequential similarity detection algorithm (SSDA)</td>
<td>$R_e = \frac{1}{N} \sum \left( T_x - S_x \right)^2$</td>
<td>Minimum value of $R_e$</td>
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<tr>
<td>Dispersion of the difference</td>
<td>$R_{2D} = \frac{1}{N} \sum \left( T_x - S_x \right)^2 - N \mu^2$</td>
<td>Minimum value of $R_{2D}$</td>
</tr>
<tr>
<td>Dispersion of the quotient</td>
<td>$R_{2Q} = \frac{1}{N} \sum \left( \frac{T_x}{S_x} - 1 \right)^2 - N \mu^2$</td>
<td>Minimum value of $R_{2Q}$</td>
</tr>
<tr>
<td>Correlation factor</td>
<td>$R_c = \frac{1}{N} \sum \left[ \frac{\sum T_x S_y - N \bar{T} \bar{S}}{\sqrt{\left( \sum T_x^2 - N \bar{T} \right) \left( \sum S_y^2 - N \bar{S} \right)}} \right]$</td>
<td>Maximum value of $R_c$</td>
</tr>
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$T_x$: brightness of a pixel within a template in the basic image
$S_x$: brightness of a pixel within a template imposed on the searched area of tilted image
$N$: the total number of pixels in a template

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the median value filter and the mean value filter were also used in the template matching. The median filter can eliminate the noise appeared during the matching process, while the mean value filter can make the reconstructed fracture surface smoother and more realistic. The details of the stereo matching method used in this study are described in the references.\textsuperscript{11,12)

Figure 2 shows the height images generated from the reconstructed three-dimensional images with different evaluation functions on the stage I fatigue fracture surface of a Cu–Be alloy. The template size was fixed at $5 \times 5$ in pixel. The relative height on the fracture surface is shown by the brightness (the color number in 256 grey scale levels) in these images. Therefore, the relative height increases with increasing the brightness (the color number), and the brightest part in the image indicates the highest part on the fracture surface. It is known from comparison of the height images that the correlation factor as an evaluation function seems to give a reasonable result for the three-dimensional image reconstruction (Fig. 2(a)). The dispersion of quotient may give a similar result but a few irregular segments can be seen in the image (Fig. 2(b)). However, the dispersion of difference produces an image with many irregular segments, which may be caused as a result of mismatching (Fig. 2(c)). Kuroda et al.\textsuperscript{9) reported that the sequential similarity detection algorithm (SSDA) is a successful evaluation function for the template matching with a large window size ($120 \times 120$ in pixel) when this evaluation function is applied to the reconstruction of the fracture surface produced by hydrogen embrittlement. However, SSDA is clearly not suitable for the reconstruction of three-dimensional image in this study (Fig. 2(d)). As described above, the fatigue fracture surface of a Cu–Be alloy is considerably complicated with microstructural features such as slip steps, dimples and grain-boundary facets.\textsuperscript{12,15) Inapplicability of SSDA may be attributed to the small template (window) size ($5 \times 5$ in pixel) and also to the complicated microstructures of the stage I fatigue fracture surface in a Cu–Be alloy. Further, it was found that the evaluation functions except the correlation factor were not suitable for the reconstruction of the three-dimensional fatigue fracture surface in the template size range from $3 \times 3$ to $13 \times 13$ in pixel. Thus, the correlation factor is a suitable evaluation function for the template matching in the three-dimensional image reconstruction on complex fracture surfaces.

The effect of the template (window) size on the three-dimensional image reconstruction with the correlation factor was then examined using the template size in the range from $3 \times 3$ to $13 \times 13$ in pixel. The fractal dimensions of thirteen contours generated from the reconstructed three-dimensional images were estimated in the scale length range smaller than about one grain-boundary length (about 14 $\mu$m) on the stage I fatigue fracture surface in a Cu–Be alloy. Figure 3 shows the relationship between the mean value of the fractal dimension of the contours and the template size. The mean value of the fractal dimension is in the range from 1.210 to 1.238, and seems to decrease with increasing the template size. As reported in the previous study,\textsuperscript{12,15) the mean value of the fractal dimension of the actual fracture surface profiles was about 1.210 in the plane in parallel with the crack growth direction (parallel direction) and about 1.190 in the plane perpendicular to the crack growth direction (perpendicular direction) in the stage I fatigue fracture surface of a Cu–Be alloy. Thus, the fractal dimension of the contours obtained in this study is close to the fractal dimension of the real fracture surface profile.

Fine geometrical features of the fracture surface are reproduced in the reconstructed image with small template (Figs. 4(a) and 4(b)), although gray speckles are imposed in the white region (in the upper half of the image) in the image with the smallest template ($3 \times 3$ in pixel) (Fig. 4(a)). These speckles may be noise or mismatching caused by
template matching with too small template (3\times3 in pixel). The speckles are not visible in the images with the larger template size (Figs. 4(b) and 4(c)), whereas unrealistic sharp contrast and patterns that may be a result of mis-matching are observed in the center part of the image reconstructed with the larger template (Fig. 4(c)). The increase in the template size does not always lead to the improvement of the accuracy of template matching. The optimum template (window) size is considered to be 5\times5 in pixel in the stereo matching method based on the coarse-to-fine format. The processing time for the three-dimensional image reconstruction was about 10 seconds for the template size of 5\times5 in pixel when a standard personal computer (Pentium III 600 MHz with 256 MB memories) was used.

Acknowledgements

The authors thank Mitsutoyo Association for Science and Technology (MAST) and The Iron and Steel Institute of Japan for financial support.

REFERENCES