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High-density 3-D mapping of Internal Strain by Tracking Microstructural Features

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Abstract

The three-dimensional strain map is useful to elucidate the relationships between microstructures and locally caused deformation and fracture. However, a robust tracking method, which enables error-free tracking in synchrotron radiation computed tomography (SR-CT) images with more than ten-thousand microstructural features, is not currently available. In this study, a model sample was subjected to a tensile test and scanned by the SR-CT technique in order to develop a new tracking method. The developed tracking methods indicated a high tracking ratio and tracking success ratio of nearly 100% in a wide strain range, which included the assumed strain in a practical experiment. It was confirmed that tracking errors produce an incorrect strain distribution in three-dimensional strain mapping. This study verified the validity of the developed tracking method. The application of this method to high-resolution SR-CT images will make measurement and visualization of the strain distribution possible in three dimensions in bulk materials.

1. Introduction

The microscopic inhomogeneous strain distribution that develops during deformation in metals is important for understanding local events such as fracture, crack initiation, crack propagation, shear band formation, dynamic recrystallization, and so on. A specimen's shape and loading condition influence the macroscopic strain distribution. However, the spatial arrangement of microstructural features such as various defects, precipitates, dispersion particles, grain boundaries, and so on, affects the microscopic strain distribution. The concentration of microscopic strain is an important influence on the mechanical properties of materials, because a strain concentration point can become the origin of yielding and cracks. Therefore, we need to clarify the relationship with the local strain distribution and microstructures.

The most fundamental procedure to measure the local strain distribution is the lattice grid method, which measures displacement of a minute grid drawn on a surface by various techniques such as scratching and etching [1,2]. The geometric moiré and moiré interferometry method, which are optical techniques, can measure local deformation with high precision [3-5]. The laser speckle method, which utilizes the speckle pattern produced by an irradiating laser, is a feasible technique for detecting strain on a surface directly without preparing a grid on the surface [6-8]. Recently, the digital image correlation method, based on digital image processing, has also been utilized because a digital camera can capture and transfer images easily to a computer [9-12]. These techniques enable the measurement of strain distribution with sufficient precision. However, they can obtain only two-dimensional strain maps on a surface. An application

of the stereo-correlation technique for accurately measuring the three-dimensional shape of stamped sheet metal has also been reported [13]. The strain obtained by this method is just surface strain on a three-dimensionally formed material. Deformation on a surface satisfies the plane strain condition without the effect of stress in the direction of the sheet thickness. On the other hand, internal deformation in a material generally shows triaxial strain. Therefore, information of the surface strain condition cannot provide true knowledge of the interaction of the deformation and microstructure. Three-dimensional strain distribution has been investigated by inserting marker materials in a sample for plastic deformation studies on rolling [14], severe deformation [15], and so on. However, it is difficult to improve the resolution of strain measurement with this method because of the limitation on the size of the inserted marker. The three-dimensional strain distribution obtained is too irregular to compare with the microstructural features. Furthermore, the strain distribution would be different in the true strain distribution that we want to know because the inserted markers, which usually have different mechanical properties than the sample matrix, would change the natural deformation behavior to an unnatural one.

X-ray computed tomography (CT) is a non-destructive inspection technique that can convey three-dimensional structure information of a sample as digital image stacks. Although the X-ray CT is a well known and widely used technique in the medical field, it has lately attracted attention in the material science field because of the improvement of image resolution of the X-ray source with high flux and energy, high-sensitivity detector system and fast computer system for short processing time. Recently, the synchrotron radiation (SR) CT,

which is available as a third-generation SR facility, has achieved sub-micron voxel size and has been utilized for three-dimensional visualization of the internal structure of various materials. A few hundred-thousand micro-pores and precipitates can be observed in 1 mm³ of bulk materials by them. Recently, SR-CT achieved nano order resolution has been developed [16].

High-resolution X-ray CT provides worthwhile information of not only the internal structure but also the mechanics of materials. An analysis of CT images by finding and tracking the same point, which is similar to two-dimensional strain measurement, before and after deformation has produced three-dimensional distributions of local displacement and strain. Toda et al. carried out an SR-CT experiment to apply the sub-micron voxel size of (0.7 μm)³ by extending a small fatigue crack step by step in aluminum alloy [17]. They obtained the internal local crack driving force separating modes I, II and III by measuring the internal displacement of micro-pores densely distributed around a crack tip. Ohgaki et al. also applied a micro-pore tracking method to investigate grain boundary widening due to gallium penetration into a grain boundary in 2024 aluminum alloy [18]. Quantitative analysis using microstructural feature tracking in CT images enables the clarification of mechanical behavior in materials in three dimensions. However, to find and track the same point is not easy in three-dimensional space. It is necessary to identify a tracked point one by one manually in order to obtain reliable data. To manually track microstructural features, the number would be limited to a maximum of a few thousand features.

In contrast, automatic measurement of strain in X-ray CT images has been proposed and reported. Bay et al. developed digital volume

correlation for lab-scale CT on the order of several micrometers of resolution [19]. Digital volume correlation is a three-dimensional extension of the two-dimensional digital image correlation for measuring surface strain. Smith et al. modified the digital volume correlation by extending the rotation degrees of freedom into a minimization problem and improved the performance of strain measurement [20]. Nielsen et al. proposed a useful procedure using tracking markers for the measurement of local plastic deformation [21,22]. Using powder metallurgy, they made an Al-W alloy sample by compacting aluminum powder with 1 vol.% tungsten powder. The sample was investigated by SR-CT with voxels of size $(2.8 \mu\text{m})^3$ during a compression test with several loading steps. Of ~ 5000 particles, 2544 W-particles were tracked automatically by selecting those particles that moved less than the average distance between neighboring W-particles. Then, displacement gradient components were determined. Ohgaki et al. investigated by SR-CT the strain distribution at a cell wall in aluminum foam during a compression test [23]. Various sizes of micro-pores observed in the cell wall were tracked automatically with consideration of not only position but also of size. Although three-dimensional strain distribution was represented quantitatively in the abovementioned studies, these studies did not disclose whether the automatic tracking methods were reliable.

Many studies of tracking markers in two-dimensional images have been performed in the field of information engineering. Few tracking methods were found to be utilizable for a lot of markers in three-dimensional space. Particle tracking velocimetry (PTV) is one measuring technique based on marker tracking that visualizes the velocity distribution of fluid flow in the field of fluid mechanics

[24-26]. Some PTV methods proposed in PTV studies enable the extension of three-dimensions. However, measurement of the velocity distribution in fluids is not compatible with that of strain distribution due to marker objects in solid materials having different properties. That is, PTV markers generally have a sphere shape of the same size, and the number does not change in a flow. In contrast, markers for measuring strain in materials may deform (micro-pores), break (particles) and generate (voids) uniquely. These features make tracking more difficult. There is no standard method that is possible to track correctly a very large number of microstructural features at present. The tracking performance of the PTV methods has been evaluated to examine the tracking success ratio using basic flow data obtained by simulations. The evaluations enable clarification of the validity and limitations of these methods. In the case of microstructural features tracking in actual materials, it is preferable to examine the performance of a tracking method and clarify the validity and limitations, because there is a possibility that a tracking error would produce incorrect strain information. Tracking performance and accuracy should be assessed before investigating the relationship between microstructural features and deformation mechanisms.

The goal of this study is the development of a tracking method with verified accuracy for microstructural features in order to obtain high-density three-dimensional strain maps from high-resolution SR-CT images. Although the goal is to achieve perfect tracking for a few hundred-thousand microstructural features, the accuracy of the tracking method must be demonstrated first for a limited number of markers. In this study, a new tracking method was developed and

evaluated by using a model sample containing 188 artificial micro-pores. Furthermore, a three-dimensional strain map that was estimated from the displacements of the tracked marker is presented and compared with a CT cross section after fracture. If all of the micro-pores and precipitates are tracked completely in high-resolution SR-CT image, a high-density strain map of the inside of materials can be generated in three dimensions. So, the map is expected to reveal local deformation and fracture mechanics depending on the microstructural features found in the SR-CT.

2. Experimental and analysis methods

2.1. Preparation of model sample

Complicated microstructural feature of a practical material, such as the agglomeration of particles, make the verification of tracking difficult. We investigate the performance of developed tracking algorithm by using a model sample that has a limited number of tracking features. The model sample was made of rolled sheets of dispersion-strengthened copper alloy with alumina particles. The sample contained 188 artificial micro-pores formed by the following production process. Four sheets of 15 μm thickness were provided with laser-drilled holes that were 15 μm in diameter at random locations. The sheets were sandwiched between hole-free sheets, which were 30 μm and 50 μm in thickness for the inside and outside, respectively, then diffusion-joined together. Tensile test specimens with a cross section of $250 \times 300 \mu\text{m}^2$ were cut from the joined plate. The artificial micro-pores are utilized as a microstructural feature.

2.2. SR-CT experiment

High-resolution tomographic experiments were performed using a monochromatic X-ray beam with a photon energy of 35 keV by a Si (111) double crystal monochromator at BL20XU, whose light source is an undulator in the Japanese third-generation synchrotron radiation facility of SPring-8. The CT setup consists of a high-precision rotation stage, $\text{Lu}_2\text{SiO}_5\text{:Ce}$ scintillator, $\times 10$ optics lens and CCD camera. The CCD camera with a 4000×2624 element was used in 2×2 binning mode. A lightweight test rig driven by compressed air (maximum load of 2 kN) was installed on the rotation stage. The rig was available for control from outside an experimental hatch and the displacement was kept at $\pm 0.1 \text{ }\mu\text{m}$ accuracy during the CT scans. The sample was scanned at the unloaded state and loading states of three levels in plastic deformation. The distance from the sample to the detector was established at 55 mm so as to enhance detectorability of microstructural features by the phase contrast technique [27]. Nine-hundred radiographs were captured for 30 minutes by rotating the sample. The set of radiographs were reconstructed by means of the convolution back-projection algorithm [28]. An isotropic voxel with a cutting edge of $0.474 \text{ }\mu\text{m}$ was achieved by the present setup.

2.3. Quantitative analysis of microstructural features

The reconstructed CT image, which consists of stacks of cross-sectional images, was provided with quantitative analysis of the microstructural features by means of three-dimensional image processing. Each slice of the CT image stores a linear absorption coefficient (LAC) value described in 16-bit grayscale in pixels. A 16-bit grayscale (LAC) value in the range of $0 - 80 \text{ cm}^{-1}$ was linearly mapped to a range between 0 and 255 in an 8-bit grayscale to reduce

the data size and computing time. The gray-scale range was inverted and unnecessary blank space surrounding a sample, e.g., air, was removed beforehand. The air, which has a similar gray value to pores, was selected and its gray value was replaced with the gray value of the background. Then, the image was converted into a binary image with either gray values of 0 (background) or 1 (object) as the object. A threshold value of 100 in 8-bit ($LAC=31.4 \text{ cm}^{-1}$) was chosen, which is a median between the gray value peaks of air and sample matrix. A labeling algorithm was applied in order to track each feature at a later stage. Geometrical properties of each microstructural feature, e.g., surface area, volume and gravity center position, were quantified utilizing the marching cube algorithm that gives a pentagonal faceted isointensity surface [29]. The microstructural features having a volume more than $106.5 \text{ } \mu\text{m}^3$ ($=1000$ voxels) were utilized for the tracking study because the small features were artifacts or image noise.

2.4. Registration of sample position

The microstructural features analyzed quantitatively by three-dimensional image processing are utilized as a gauge marker for strain calculation. Before the beginning of marker tracking, two successive data is necessary to adapt registration, because the tensile test developed parallel and rotation translations of the specimen on measuring coordinates. The registration is executed as follows: first, eight sets of tracking marker pairs, which can be readily distinguished from surrounding markers, are selected manually from each tomographic volume. Custom software that can output marker locations is used for this task. Second, a transformation matrix is

calculated so that the sum of differences in the distance between corresponding pairs is minimized. It is applied to all the markers to superpose a chronologically late volume onto a chronologically advanced volume.

2.5. Microstructural feature tracking

As is easily supposed, it is not easy to find a set of the same markers from images before and after deformation. The markers will change not only position but also volume and surface area after deformation. Artifacts, which are noise caused by the beam hardening effect and a CCD pixel defect, may appear to be a marker. It is also expected that some tracking markers are impossible to supply due to formation of a crack and damage. In this study, a matching probability parameter (MPP), M_p , is introduced to extract tracking errors as well as correctly matched pairs. The MPP between a marker with index numbers of i and j , which are assigned in a labeling process, is given by

$$M_p(i, j) = \alpha \times M_L(i, j) + \beta \times M_V(i, j) + \gamma \times M_S(i, j), \quad (1)$$

where $M_L(i, j)$, $M_V(i, j)$ and $M_S(i, j)$ are the distance, volume and surface area parameters, respectively. Coefficients α , β and γ are weights for each parameter, such that $\alpha + \beta + \gamma = 1$ is satisfied.

In general, a marker set having the highest value of MPP would be selected as matched markers. However, in this study, the two requirements for a matched marker are given as follows to prevent tracking errors and obtain as many tracked markers as possible.

- 1) The maximum MPP is larger than the first threshold value, M_p^{th1} .
- 2) The difference between the first and second highest MPP (given as ΔM_p), is larger than the second threshold value, M_p^{th2} .

If 1) and 2) are satisfied, the sets of markers are accepted as matched. We call them tracked markers after this. When the condition of 1) is satisfied and 2) is not satisfied, we cannot distinguish the matched markers exactly, because there are some markers having high MPP values close to each other. We call them pended markers. If the condition of 1) is not satisfied (i.e., no matched marker is found), the marker is not used. We call them rejected markers. In summary, markers are classified into tracked marker, pended marker and rejected marker by applying threshold values, M_p^{th1} and M_p^{th2} , as shown in Fig. 1.

As shown in Eq. (1) above, the MPP value is a function of parameters, M_L , M_V and M_S , related to distance, volume, and surface area. These parameters are given as follows:

Distance parameter

Distance parameter, $M_L(i, j)$ is given by distance

$$M_L(i, j) = \begin{cases} (r_s - d_{ij}) / r_s & , d_{ij} \leq r_s \\ 0 & , d_{ij} > r_s \end{cases}, \quad (2)$$

where d_{ij} is the distance between markers with index i and j , r_s is the radius of the search space in which the corresponding marker is searched. Therefore, d_{ij} increases when a marker suspected to be identical is located close to the relevant marker. The maximum value of $M_L(i, j)$ is 1 when $d_{ij} = 0$, and $M_L(i, j)$ becomes 0 outside the search space.

Volume parameter

Volume parameter $M_V(i, j)$ is given by

$$M_V(i, j) = \begin{cases} v_i / v_j & v_i \leq v_j \\ v_j / v_i & v_i > v_j \end{cases}, \quad (3)$$

where v_i and v_j are the volumes of the marker with index i and j . $M_V(i,$

j) takes the maximum value of 1 when $v_i = v_j$.

Surface area parameter

Surface area parameter, $M_s(i, j)$ is given by

$$M_s(i, j) = \begin{cases} s_i / s_j & s_i \leq s_j \\ s_j / s_i & s_i > s_j \end{cases}, \quad (4)$$

where s_i and s_j are the surface areas of the marker with index i and j .

$M_s(i, j)$ takes the maximum value of 1 when $s_i = s_j$.

2.6. Macroscopic trajectory prediction

Two kinds of additional tracking procedures are used together with the abovementioned procedure. One is a macroscopic trajectory prediction (MTP) on the basis of the known macroscopic deformation pattern. The method adopted here is quite simple. Provided that applied strain distributes homogeneously throughout a material, the center of gravity coordinate of each marker in the image dataset of a deformed sample is linearly interpolated before applying the two-frame tracking algorithm described above. In this study, the model sample was monotonously tensioned, so the image dataset was extended only in the longitudinal, i.e. tensile, direction and contracted in the vertical directions assuming Poisson's ratio of 0.5.

2.7. Identifying marker pairs among pended markers

The increase of pended markers, for which the MPP value cannot provide a reliable matched marker, reduces the number of tracked markers. It is necessary to enlarge the number of tracked markers to achieve strain mapping as dense as possible. In the present study, tracking for pended markers is attempted by the modified spring model algorithm (SMA) method. The SMA method is one of the PTV

methods utilized in the field of fluid mechanics [25], and it can be extended easily in three dimensions. The SMA is expected to work effectively for the tracking of pended markers because it identifies marker pairs by searching for the smallest total spring force among marker clusters, in which particles are connected by imaginary springs to each other (see Fig. 2). The basic function for the SMA method to calculate the total elastic energy for imaginary springs, E_{sp} is given as

$$E_{sp} = \frac{1}{N_{sp}} \sum_{i=1}^{N_{sp}} \frac{|\mathbf{b}'_i - \mathbf{b}_i|}{|\mathbf{b}_i|} \quad (5)$$

where N_{sp} is the number of imaginary springs connecting with the markers, and $\mathbf{b}_i$ and $\mathbf{b}'_i$ are relative vectors produced by the marker position before and after deformation, respectively. Although the SMA method is sometimes used in the entire tracking region in the PTV, it is applied only to the agglomerated pended markers in this study. Furthermore not only pended markers but also several tracked markers, which are close to pended markers, are taken for the calculation of E_{sp} .

2.8 Model to verify efficacy of markers volume and surface area

Artificial pores were used as the microstructural features for developing the tracking method in this study. A pore filled with a gas tends to change its volume and surface area in a highly deformed sample. Therefore, the model sample prepared in this study is inappropriate to investigate the efficacy of volume and surface area parameters in the tracking results. However, to perform the tracking using the volume and surface area parameters may be effective when the invariable features, such as a precipitate, intermetallic, and so on, are tracked. Therefore, we examine the parameters' effect by providing arbitrary values of volume and surface area for actual data. Volume, v' ,

and surface area, s' , which are the volume and surface area after deformation, are given by randomly converting the values of volume, v , and surface area, s , before the deformation by using the following equation:

$$v' = v(1 + c_{dv} \times N_{\text{rand}}(0,1)) \quad (6)$$

where c_{dv} is a constant that gives the volume deviation, $N_{\text{rand}}(0,1)$ is a random number with a normal distribution. For surface area, a similar equation is used:

$$s' = s(1 + c_{dv} \times N_{\text{rand}}(0,1)) \quad (7)$$

If c_{dv} is equal to 0, the volume and surface area in the markers are unchanged. A larger c_{dv} value makes tracking difficult because it reduces similarity in corresponding markers.

2.9 Evaluation of tracking results

The tracking result solved automatically by the developed tracking method is compared to the result obtained beforehand by manual tracking and considered to be correct. The ratio of tracking successes, η , is defined as the percentage of correct tracked markers. The ratio of tracked marker, ρ , is also evaluated, which would be crucial factor to realize high-density strain mapping.

2.10. Calculation of strain

When many markers are given in three-dimensional space, the Delaunay tessellation algorithm [30], which produces a set of planes connecting each marker to its natural neighbors, generates many tetrahedrons. The strain inside a material is calculated from each tetrahedron. Assuming a linear displacement field inside the tetrahedron and displacements $u_i, v_i, w_i, u_j, v_j, w_j, u_k, v_k, w_k, u_l, v_l,$

w_l at tetrahedron vertices i, j, k, l in a rectangular coordinate system, then normal strains, $\varepsilon_x, \varepsilon_y, \varepsilon_z$, and shear strains, $\gamma_{xy}, \gamma_{yz}, \gamma_{zx}$, can be calculated in the following equation.

$$\{\varepsilon_x \varepsilon_y \varepsilon_z \gamma_{xy} \gamma_{yz} \gamma_{zx}\}^t = [\mathbf{B}_i \mathbf{B}_j \mathbf{B}_k \mathbf{B}_l] \{u_i v_i w_i u_j v_j w_j u_k v_k w_k u_l v_l w_l\}^t, \quad (8)$$

where $[\mathbf{B}_i]$ is given as

$$[\mathbf{B}_i] = \frac{1}{6V} \begin{bmatrix} o_i & 0 & 0 \\ 0 & p_i & 0 \\ 0 & 0 & q_i \\ p_i & o_i & 0 \\ 0 & q_i & p_i \\ q_i & 0 & o_i \end{bmatrix}, \quad (9)$$

$$o_i = y_k z_j + y_l z_k + y_j z_l - y_k z_l - y_j z_k - y_l z_j, \quad (10)$$

$$p_i = x_l z_j + x_j z_k + x_k z_l - x_j z_l - x_l z_k - x_k z_j, \quad (11)$$

$$q_i = x_l y_k + x_j y_l + x_k y_j - x_j y_k - x_k y_j - x_l y_k, \quad (12)$$

where $x_j, y_j, z_j, x_k, y_k, z_k, x_l, y_l, z_l$ indicate the vertex positions of j, k, l in a tetrahedron. Shifting indices such as $i \rightarrow j, j \rightarrow k, k \rightarrow l$ and $l \rightarrow i$ brings $[\mathbf{B}_j], [\mathbf{B}_k]$ and $[\mathbf{B}_l]$. Variable V is the tetrahedron volume. Not only strain but also the vertices and gravity center positions of the tetrahedron are recorded for three-dimensional strain mapping. The internal strain distribution is demonstrated by assigning colors corresponding to the strain level of each tetrahedron. The three-dimensional strain map shows overlapping in the volume rendered image in the sample. A strain contour map in some sections is also obtained and indicated by linear interpolation of the distributed strain data into a discrete grid.

3. Results

3.1. CT images and quantitative analysis of microstructural features

Figure 3 shows the load-displacement curve applied to the sample

in this study. CT scans were performed in the non-loaded state and three loading states during plastic deformation. The numbered arrows indicate the CT scan points. At each CT scan point, a little decline in load is found. This is due to stress relaxation. Although there is a possibility that stress relaxation makes the CT images blurry, the actual image quality has no influence. The transition region of the LAC value between the matrix and micro-pore was found to be approximately 2-3 μm .

Figure 4 shows a series of reconstructed CT volumes during tensile deformation rendered by means of volume rendering software. The pictures are a combination of an internal micro-pore image with a sample appearance image. The man-made micro-pores have the same size in the non-loaded state (Fig. 4 (a)). The size and shape of the micro-pores change gradually during deformation. Necking occurs at the specimen center with the increasing tensile load. Micro-pores with an ellipsoid shape are observed in the necking region in Fig. 4 (c), while the shape of the micro-pores at both ends of the specimen remains spherical. Delamination that occurs from the joined interface and the coalescence of micro-pores is confirmed in the necking region in Fig. 4 (d). Some artifacts are observed in all results. The artifact having a semicircular shape is caused by a pixel fault of the CCD. The artifact is another factor that makes tracking microstructural features difficult. The results of the quantitative analysis for the micro-pores used as tracking markers are presented in Table 1. The measured location, volume and surface area are listed. The number of markers slightly increased during the tensile test. This is probably caused by the presence of artifacts and formation of delamination. The average volume and average surface area increased during the test, as expected.

The average distance to the nearest neighbor marker, which is measured as the difference of the gravity center position, remained almost the same. The distance between markers at both ends along the tensile direction of the z-axis is also listed in Table 1. The distance, which is regarded as a gauge, was used to estimate macroscopic strain. The macroscopic strain is listed in Table 2. Various combinations of loading steps were measured to apply the proposed tracking method across a wide range of strain levels in this study. Generally, the tracking experiments were performed at as low a strain as possible. The tracking method was examined in strain from $\Delta=3.5\%$ to $\Delta=22.1\%$ in order to evaluate the tracking performance. The number of traceable markers, which was obtained manually by visual checking, is also listed in Table 2. Not all markers were utilizable for tracking because some markers moved out of the field of view during the tensile test and damage sometimes connected the markers together. From 180 to 186 micro-pores were matched and utilized for the tracking study, as listed in Table 2. The set of matched markers were recorded and used as the standard for calculating the tracking success ratio.

3.2. Tracking results

Figure 5 shows the effects of the MPP first threshold value, M_p^{th1} , in the macroscopic strain, $\Delta=3.5\%$. Only the distance parameter, M_L , was applied to the MPP. The ratio of the weight coefficient was given as $\alpha: \beta: \gamma = 1.0: 0.0: 0.0$. The radius of the search space, r_s , was selected as $75.8 \mu m$ ($=160 \text{ voxels} \times 0.474 \mu m$). The second threshold value, M_p^{th2} , required for the MPP method was set to zero. Having a large first threshold value, M_p^{th1} , means the matching becomes severe. By

decreasing M_p^{th1} from 1.00 to 0.60, the ratio of tracked markers increases gradually and the ratio of rejected markers decreases gradually (Fig. 5(a)). When M_p^{th1} is less than 0.82, the ratio of rejected markers becomes 0% and the ratio of tracked markers is 100%. It does not necessarily mean that all of the markers have been tracked successfully. Figure 5(b) indicates the ratio of tracking successes and the number of tracking failures. When M_p^{th1} is larger than 0.87, 100% tracking success is achieved. A few tracking failures are found when the threshold value is less than 0.87.

The effect of the second threshold value, M_p^{th2} , in the case of $\Delta=3.5\%$ is shown in Fig. 6. The first threshold value, M_p^{th1} , was given as 0.80. A large value of M_p^{th2} makes the tracking results reliable. In Fig. 6(a), the ratio of tracked markers decreases gradually with the increasing threshold value, M_p^{th2} . The reduction rate is accelerated when M_p^{th2} is larger than 0.16. The ratio of pended markers increases in response to the reduction of tracked markers. The ratio of pended markers increases slightly, and then it rises sharply when M_p^{th2} is larger than 0.16. The ratio of tracking successes is 100%, providing that M_p^{th2} is larger than 0.10, as shown in Fig. 6 (b). Although a few tracking failures are found when the threshold value of M_p^{th2} is less than 0.10, no tracking failures are found above 0.10.

Figure 7 shows changes in the ratios of the tracked, pended, and rejected markers and correctly matched markers with increasing r_s , which is the radius of the search space for finding the same marker. The results in $\Delta=3.5\%$ and $\Delta=16.3\%$ are shown in Fig. 7 (a) and (b), respectively. The threshold values of M_p^{th1} and M_p^{th2} were given as 0.80 and 0.10. The ratios of the tracked, pended and rejected markers indicate similar tendencies of dependence on r_s . Especially, the ratio

of the rejected markers decreases with the increase of r_s . The ratio of the tracked markers reaches a peak. The peak values in (a) $\Delta=3.5\%$ and (b) $\Delta=16.3\%$ are obtained at $71.1 \mu\text{m}$ ($=150 \text{ voxels} \times 0.474 \mu\text{m}$) and $106.7 \mu\text{m}$ ($=225 \text{ voxels} \times 0.474 \mu\text{m}$), respectively, for the radius of the search space. The number of markers contained in the search space varies from 7 to 35 for $r_s = 71.1 \mu\text{m}$ and $\Delta = 3.5\%$ depending on the marker location. The ratio of the pended markers increases with increasing r_s . The ratio of the tracked markers in Fig. 7 (b) for $\Delta=16.3\%$, which means slightly heavy deformation, is lower than that in Fig. 7 (a), where $\Delta=3.5\%$. The ratio of tracking successes always shows 100% in the light deformation condition of Fig. 7 (a), $\Delta=3.5\%$. Namely, no error is achieved without dependence on r_s . In contrast, the ratio of tracking successes in Fig. 7 (b) for $\Delta=16.3\%$ is approximately 25% with a slight dependence on r_s . There were error markers in the tracked markers in this case.

The ratio of tracked markers, ρ , and tracking successes, η , depending on the radius of the search space, r_s , are shown in Fig. 8. The same tracking condition as in Fig. 7 was applied. Figure 8 (a) and (c) represent the results of the MPP method. Figure 8 (b) and (d) represent the results of the MTP method. There is a peak in the ratio of tracked markers vs. r_s in the MPP (Fig. 8 (a)). The peak tends to shift to the larger side of r_s with increasing macroscopic strain. The peak values are not proportional to the macroscopic strain level. Although 100% tracking successes are obtained in $\Delta=3.5\%$, as shown in Fig. 8 (c), the ratio of tracking successes decrease approximately, depending on the increase of macroscopic strain. On the other hand, a high ratio of tracked markers is obtained in the result of the MTP method (Fig. 8 (b)). In $\Delta=3.5\%$, $\Delta=5.0\%$, $\Delta=12.4\%$ and $\Delta=16.3\%$, the ratio

approaches almost 100% without dependence on the radius of the search space, r_s . A ratio of tracking successes close to 100% is obtained in all macroscopic strain conditions, as shown in Fig. 8 (d). The MTP improved the ratios of tracked markers and tracking successes.

The ratio of tracked markers, ρ , and tracking successes, η , are summarized in Fig. 9. The results of MPP, MTP+MPP and MTP+MPP+SMA for $r_s=118.5 \mu\text{m}$ are plotted for macroscopic strain, Δ . When macroscopic strain is small, the MPP method indicates high ratios of tracked markers and tracking successes. However, the ratios decrease gradually with increasing macroscopic strain. Applying MTP before MPP improves not only the ratio of tracked markers but also that of tracking successes. For the cases of $\Delta=3.5\%$, $\Delta=12.4\%$ and $\Delta=16.3\%$, 100% is achieved as the ratio of tracking successes. The SMA develops a higher ratio of tracked markers and tracking successes for $\Delta=5.0\%$ and $\Delta=8.6\%$, which show a slightly low ratio of tracking successes in the MTP+MPP method. However, the ratio of tracking successes decreases in the macroscopic strain of $\Delta=22.1\%$, while the ratio of tracked markers increases.

Figure 10 shows the effectiveness of the volume parameter, M_v , and surface area parameter, M_s , in the MPP method. The effect was investigated by parameter weights of α : β : γ set as 0.6: 0.2: 0.2. The models having a variety of volumes and surface areas after deformation were prepared by using Eqs. (6) and (7) on the basis of volumes and surface areas in actual markers before deformation. The constant, c_{dv} , which gives the deviation of the volume and surface area, was selected as 0.00, 0.05 and 0.10. The original volume and surface area are kept when $c_{dv} = 0.00$. The volume and surface area of the

markers after deformation varied in the range of $\pm 5\%$ and $\pm 10\%$ for $c_{dv}=0.05$ and 0.10 , respectively. Original marker positions are unchanged. The radius of the search space, r_s , of $118.5 \mu\text{m}$, threshold values, M_p^{th1} and M_p^{th2} , of 0.80 and 0.10 were used, as is similar to the condition of Fig. 9. The highest ratio of tracked markers is observed when the volume and surface area are unaltered ($c_{dv} = 0.00$). The ratio of tracking successes of more than 98% is obtained independently of the difference of the marker volume and surface area.

3.3. Three-dimensional strain mapping

Three-dimensional strain mappings calculated from the displacements of tracked markers are shown in Fig. 11. The figure indicates ε_z strain corresponding to the tensile direction superimposed on the 3-D rendered CT image. Tracking was performed on the condition of $\alpha: \beta: \gamma = 1.0: 0.0: 0.0$, $M_p^{\text{th1}}=0.80$, $M_p^{\text{th2}}=0.10$ and $r_s=118.5 \mu\text{m}$ by means of the MTP + MPP method. Figure 11 (a), (b) and (c) represent the results of $\Delta=12.4\%$, $\Delta=16.3\%$ and $\Delta=22.1\%$, respectively. The ratio of the tracked markers was 97.9%, 97.7% and 63.3%. The ratio of tracking successes was 100% in (a) and (b), and the ratio of tracking successes was 98.3% in (c). Two tracking failures were observed in (c) while no failure was found in (a) and (b). It was found that ε_z rises gradually with increasing macroscopic deformation. High strain is observed at the necking region in Fig. 11 (c). The three-dimensional strain distribution inside material was measured successfully.

Figure 12 shows strain distributions in the section of Fig. 11 at $x = 100 \mu\text{m}$. In (a), $\Delta= 2.4\%$, the contour lines are sparse, meaning the tensile specimen deformed almost homogeneously. In contrast, dense

contour lines are found in the center of the specimen in (b), $\Delta=16.3\%$. Local deformation progressed at the necking region. A high strain region was formed depending on the arrangement of the micro-pores. Further development of local strain is recognized at the necking region in (c), $\Delta = 22.1\%$, while little strain is observed away from the necking region.

4. Discussion

4.1. Effect of parameters for microstructural feature tracking

4.1.1. Threshold values of matching parameters, M_p^{th1} and M_p^{th2}

The threshold values, M_p^{th1} and M_p^{th2} , for the MPP method are very important for finding the correspondence markers. The threshold values should be given appropriately to achieve successful tracking. To make a one-to-one marker combination, it is necessary to have at least one marker with a larger value of MPP than M_p^{th1} . If the threshold value of M_p^{th1} is close to 1.00, which is the maximum MPP value, most markers are stored as rejected markers, as shown in Fig. 5(a), because markers satisfying the condition are limited. With decreasing M_p^{th1} , the ratio of tracked markers increases and the ratio of rejected markers decreases. The ratio of rejected markers becomes 0% in M_p^{th1} less than 0.82. In this case, all markers are tracked. However, it is not clear whether the tracking result is correct or not. In the present study, verification was possible because the correct answer was obtained beforehand. The ratio of tracking successes was shown in Fig. 5(b). The variation in the ratios of tracking successes has a tendency to correspond with the variation in the ratios of tracked markers. Tracking failure is found when M_p^{th1} is less than 0.87. Tracking failure is a serious problem because it will produce an

incorrect and unrealistic strain in strain mapping. The second tracking condition in relation to the second threshold value, M_p^{th2} , was utilized to eliminate an unreliable tracked marker set from the tracking results. Giving M_p^{th2} a large value reduces the tracking error, as shown in Fig. 6. However, the largest value of M_p^{th2} increases the number of pended markers and decreases the number of tracked markers. The decreasing number of tracked markers is not desirable because it makes strain maps irregular. Therefore, we need to provide a somewhat smaller value than the value at which the number of tracked markers decreases sharply with M_p^{th2} .

4.1.2. Radius of search space

The ratio of tracked markers has a peak value depending on the radius of the search space, r_s , as shown in Fig. 7. The peak shifts to a larger side with increasing macroscopic strain. When r_s is smaller than the marker displacement rising from the deformation, a corresponding marker cannot be found in the search space. In contrast, if r_s is larger, the number of pended markers increases because many similar markers, which are impossible to distinguish by MPP, may be found. Therefore, a somewhat larger value than the marker displacement predicted in deformation should be given to r_s . Investigating the numbers of rejected and pended markers would give us the proper value of r_s . However, when the proper r_s is used, a high ratio of tracking successes is not always obtained, as seen in Fig. 8(b). The reason is that all marker positions before deformation are not adjusted for after deformation by registration in an inhomogeneous deformed sample. The registration makes markers before and after deformation close to each other in the specimen center, but also makes them far

from each other at both ends of the specimen.

Application of MTP before MPP reduces the dependence of r_s on the ratio of successful tracking because MTP adjusts the marker position in the whole specimen. Almost a 100% tracking success ratio was obtained in all macroscopic strain conditions for the MTP + MPP method, as shown in Fig. 8(d). However, the ratio of tracked markers depends on r_s , although it is less affected in the MPP method. The ratio of tracked markers is relatively low in $\Delta=8.6\%$ and $\Delta=22.1\%$. The reason for this is the large local deformation that cannot be predicted by MTP assumes a homogeneous strain distribution. If a macroscopic trajectory prediction more similar to the actual deformation pattern is performed, a higher ratio of tracked markers is expected.

4.1.3. Utilization of marker volume and surface area

Utilization of the marker volume and surface area is effective for achieving tracking success in the MPP method. For example, the surface area of a marker is quite different from that of a ring artifact, even if the volumes are the same. The utilization of surface area in MPP eliminates artifacts with a semicircular shape. The parameters of volume and surface area are usable when the marker shape remains unchanged during deformation. Actually, precipitates and dispersed intermetallics are adaptable as markers. Application of the volume and surface area to MPP improves the ratio of tracked markers, as shown in Fig. 10 (a). The highest ratio of tracked markers is obtained when the markers have the same volume and surface area before and after deformation. However, the entirely same volume and surface area are not generally measured before and after deformation in tomographic

experiments. The utilization of volume and surface area in the MPP method decreases tracking failures and increases the ratio of tracking successes, as shown in Fig. 10 (b). Markers with little change of volume and surface also improved the ratio of tracked markers in the MTP+MPP and MTP+MPP+SMA methods. When the shape of the microstructural features remains almost unchanged, the tracking method developed in this study will probably bring correct tracking results.

4.2 Validity of tracking method

Three kinds of tracking methods were examined in this study. These are the MPP, MTP+MPP and MTP+MPP+SMA methods. The ratio of tracking successes in each method was summarized in Fig. 9. The MPP method showed a fairly high ratio of tracking successes. However, some tracking failures were found in both ends of the specimen when large strain is applied, because the displacement is not corrected completely at the ends of the specimen, while the registration decreases the marker displacement in the center of the specimen. The MTP decreases the marker displacement in the whole specimen. The correction of marker displacement by MTP, in which homogeneous strain distribution is assumed, brought a high ratio of tracking successes. The ratio was nearly 100%. According to the ratio of tracked markers, more than 97% of the markers were utilizable for strain calculation in the macroscopic strain range from 3.5% to 16.3%. However, the ratios of tracked markers in $\Delta=5.0\%$, $\Delta=8.6\%$ and $\Delta=22.1\%$ was relatively low, although they were higher than those in the MPP method. This is related to the necking development shown in Fig. 4 (d). The MTP was not effective enough to cause a difference

between the actual strain distribution and the predicted one. In these cases, the number of pended markers increased because the MPP value cannot detect some of the corresponding marker sets. Although the ratio of tracked markers was lower, a ratio of tracking successes of more than 97% was obtained with necking. The developed tracking methods were examined for up to 22.1% macroscopic strain in this study. Macroscopic strain greater than 20% is more than enough to measure the local strain distribution in metallic materials. In general, tracking of microstructural features by using CT could be performed to apply a few percent of macroscopic strain to a sample step by step. By applying the appropriate level of macroscopic strain, the MTP + MPP method is able to track microstructural features without error in the difficult case that the CT image contains artifacts and the sample has damage, coalescence of pores and local deformation such as necking.

High-density strain mapping requires tracking as many markers as possible. However, the ratio of tracked markers declined in the situation in which necking and damage occurred. The main reason for this is a mismatch between the actual deformation pattern and the predicted one. Therefore, utilization of MTP, taking into account the necking development, is expected to improve the ratio of tracked markers. However, we cannot always predict the deformation pattern. It is difficult to predict an actual deformation pattern: for example, a wavy crack, a complex microstructure such as dual phase and composite materials, and so on. Although the MTP method is very effective, tracking success would depend on prediction of the deformation pattern. If tracking by the MTP+MPP method is unsatisfactory, application of SMA to the pended markers will

increase the ratio of tracked markers. The SMA-improved ratio of tracked markers is more than 95% in all macroscopic strains. However, the ratio of tracking successes in $\Delta=22.1\%$ dropped to 86%, while the ratio rose in other macroscopic strains. This means the SMA caused a tracking failure. The error markers obtained in $\Delta=22.1\%$ are distributed in local. This is the reason that one tracking failure influenced the result of the other markers because the SMA matches all markers in an objective cluster. Providing a lot of pended markers with SMA tracking is not recommended to obtain correct results. However, in $\Delta=5\%$ and $\Delta=8.6\%$, the ratio of tracking successes was close to 100% by the application of SMA. The SMA can track pended markers if the macroscopic strain level is limited and the number of pended markers in a cluster is also limited.

4.3. Effect of tracking error on 3-D strain measurement

Figure 13 shows the strain measurement result in which many tracking errors are included. Fig. 13 (a) is a 3-D strain distribution that is comparable with the result in Fig. 11 (a). The 3-D strain distribution of Fig. 13 (a) is obtained by the MPP method while that of Fig. 11 (a) is obtained by the MTP+MPP method. There is no difference in tracking conditions between Fig. 11 (a) and Fig. 13 (a) except the MTP application. The ratio of tracked markers was 59.4% in Fig. 13. The ratio of tracking successes was 60.9% because there were 43 tracking errors. The 3-D strain distribution indicated in Fig. 13 (a) completely differs from that in Fig. 11 (a), which has a ratio of tracking successes of 100%. Large tensile strain is observed in the center of the specimen in Fig. 13 (a). This is similar to Fig. 11 (a). However, incorrect compression strain is clearly found clearly in the

upper and lower part of the tensile strain observed in the center. Figure 13 (b) shows the tracking results plotted on y-z coordinates. Successfully tracked markers are found in the specimen center. Tracking errors are observed on the edges of the specimen. The region in which compression strain occurred corresponds with the location of the tracking errors. That is, the tracking errors caused incorrect compression strain in the tensile deformation. Although the result in Fig. 13 is an extreme example, it is clear that tracking errors provide an incorrect strain distribution.

Figure 14 shows the ε_z strain distribution produced by completely successful tracking on the y-z section at $x=100\ \mu\text{m}$, and also in the CT sectional view at the same position after fracture. Comparison of the strain distribution in Fig. 12 (c) with that in Fig. 14 (a) indicates that the ratio of tracked markers affects the accuracy of strain measurement. When many markers are tracked, as shown in Fig. 14 (a), the gradient of tensile strain is found far from the center toward both ends of the specimen. However, almost zero strain is distributed through the specimen, except at the center, as shown in Fig. 12 (c). This is caused by the few number of tracked markers. The expanse of gauge space due to the limited number of tracked markers reduces the sensitivity of the strain measurement. The comparison also reveals that there are some unnatural strain concentrations, represented by the high-density contour lines around the necking region in Fig. 12 (c). When investigating the tracking result in Fig. 12 (c) in detail, it was proved that there were two causes for the tracking failures: delamination and coalescence of the pores. The failures produced an incorrect strain concentration in the strain mapping. This seems to occur in the presence of artifacts, coalescence of micro-pores,

cracking of particles, and so on. However, applying the volume and surface area of markers to MPP probably decreases such errors because these markers will be observed as changing their shape drastically in a series of CT images.

4.4. Accuracy of strain measurement

In comparison of the strain distribution map (Fig. 14 (a)) with the sectional image after fracture (Fig. 14 (b)), it is found that the fracture occurred through the highest strain point. Tensile loading made the micro-pore's shape ellipsoid, with the major axis parallel to the tensile axis in the necking region, as shown in Fig. 4 (a)-(c). Damage on the interface of the diffusion joining and the coalescence of micro-pores were observed in the 4th loading step (Fig. 4 (d)). The arrangement of micro-pores affected the strain distribution and fracture path significantly, as shown in Fig. 14. It was also found that contour lines in the strain mapping are drawn as connecting with the neighboring micro-pores. The path on the fracture surface corresponds with the strain distribution obtained just before fracture by tracking the microstructural features.

In tracking that utilizes microstructural features for a gauge of the strain in CT images, accuracy of the strain measurement depends on the voxel size, which is a unit of displacement measurement, and the marker distance. In this study, the edge length of the voxel in the CT was 0.474 μm . In contrast, the average distance between the nearest neighbor markers was 35.3 μm before applying the tensile deformation. Marker displacement that is less than the length of one voxel is not detectable precisely due to the partial volume effect, which means the linear absorption coefficient changes little at the

boundary of two different materials in the CT image. A measurement error of about one voxel size should be included when measuring the gravity center position of a marker. Here, assuming simply that there is a measurement error of $0.474\text{ }\mu\text{m}$ for a gauge length of $35.3\text{ }\mu\text{m}$, a strain error of 0.013 is estimated. Although the estimation is not simple because there is some measurement error in tomographic experiments and the calculation of three-dimensional strain is different from the estimation, strain measurement by means of tracking microstructural features in CT images has enough accuracy to investigate the strain distribution in materials non-destructively and three-dimensionally.

5. Conclusion

An accurate tracking method for high-resolution SR-CT images has been developed in order to measure the three-dimensional local strain distribution inside the material. Tracking performance and accuracy have been assessed using a model sample.

Providing two threshold values of M_p^{th1} and M_p^{th2} for the MPP lowers the number of tracking failures. The MPP method led to high ratios of tracked markers and tracking successes. Successful tracking of nearly 100% was achieved by applying the MTP before the MPP method. It was proved that the proposed tracking method is available to use for tensile deformation with $\sim 16\%$ macroscopic strain, which covers the practical strain assumed in the CT experiment enough. The SMA method, which finds corresponding marker pairs from clustered pended markers, improved the ratio of tracked markers.

Three-dimensional strain distributions were calculated and demonstrated by measuring the displacement of the tracked markers.

Comparison of the obtained strain map and fracture image in a CT section obviously suggested the validity of the measured strain distribution. However, it was confirmed that the presence of even one tracking error produced an incorrect strain in a strain map. A decrease in the number of tracked markers caused a decline of the precision of the strain measurement. To accomplish accurate tracking, using as many markers as possible is very important to obtain a precise and a high-density strain distribution.

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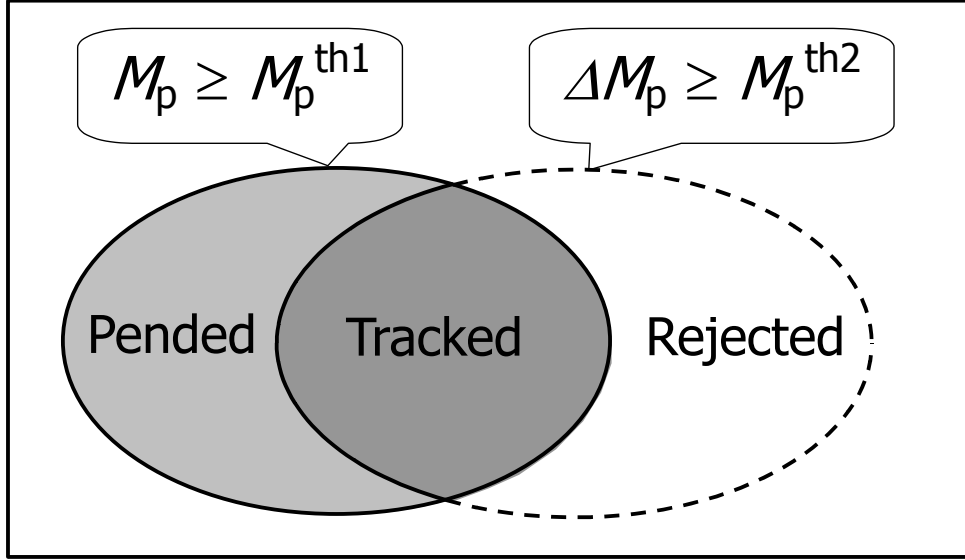


Fig. 1 Illustration of marker classifications. Markers are classified into tracked, pended and rejected ones by the threshold values of the matching parameters, M_p^{th1} and M_p^{th2} . The sets of tracked markers are accepted by following conditions: the maximum MPP is larger than the first threshold value, M_p^{th1} . And the difference between the first and second highest MPP (given as ΔM_p), is larger than the second threshold value, M_p^{th2} .

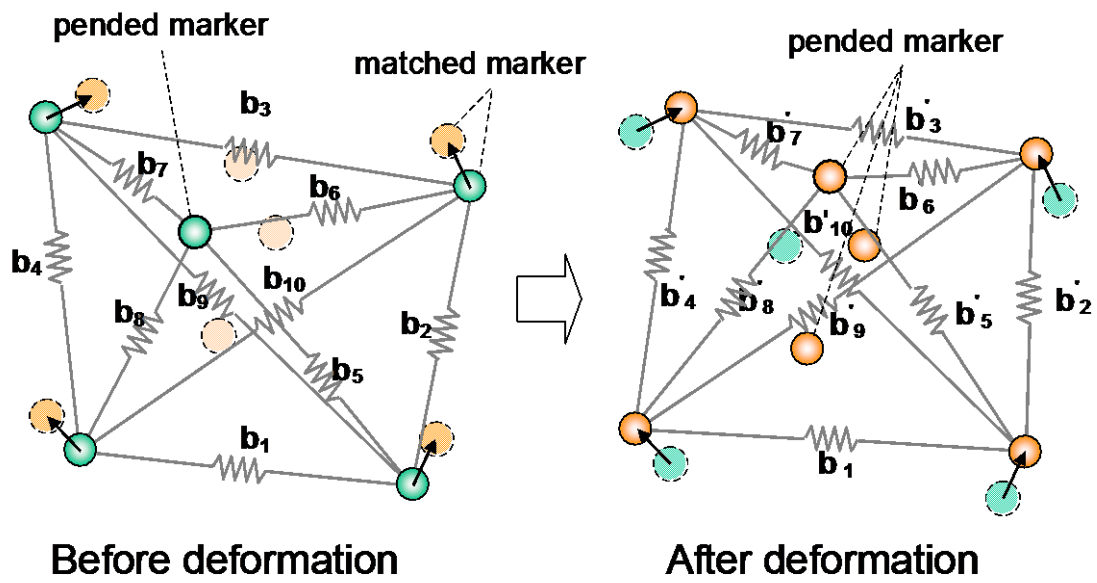


Fig. 2 Schematic illustration of the spring model for matching pended markers.

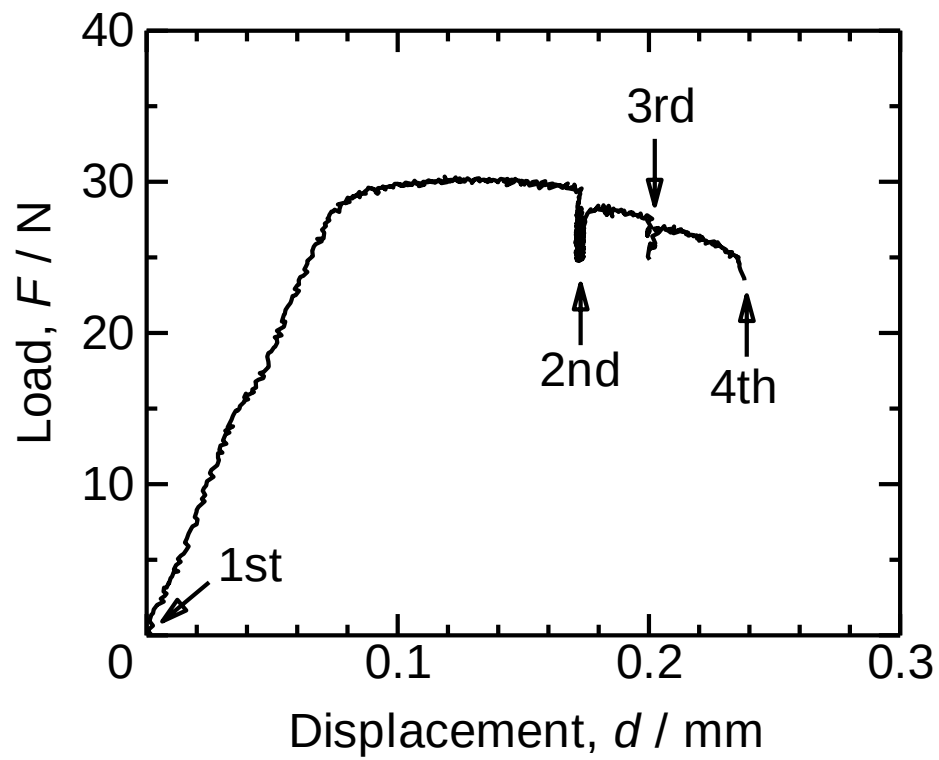


Fig. 3 Load-displacement curve in in-situ tensile test. Tomographic scans were performed at the points indicated by the arrows.

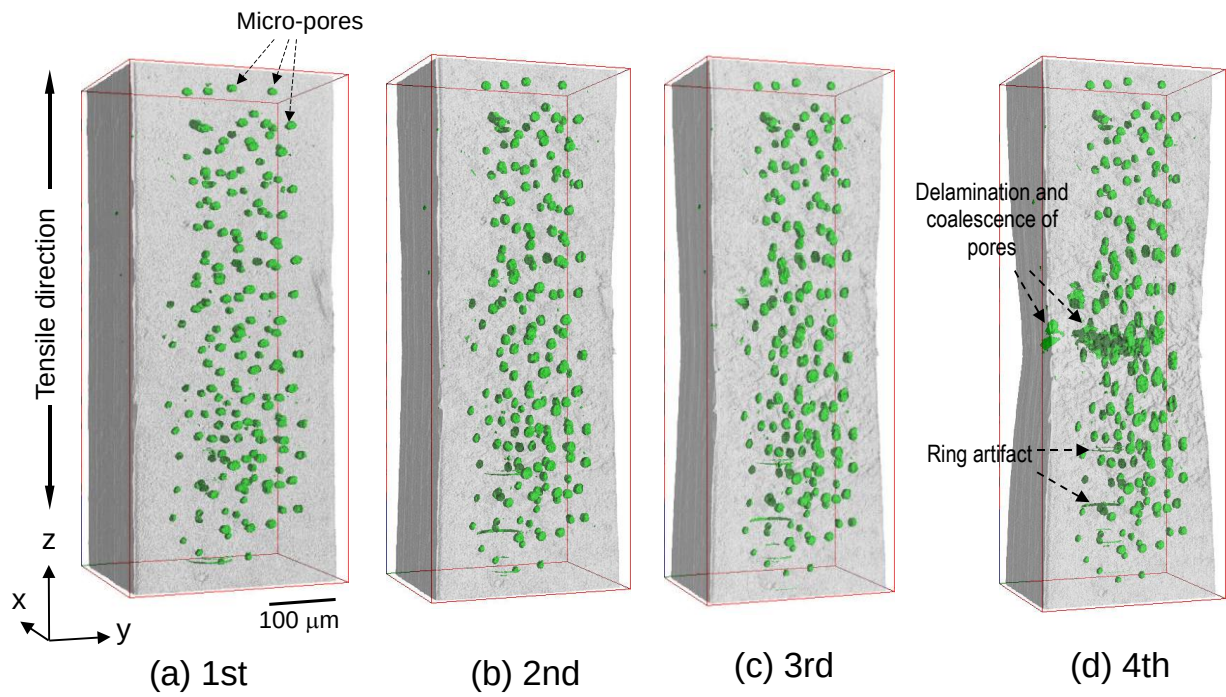


Fig. 4 A series of reconstructed CT volumes during tensile deformation. The pictures are represented by laying a micro-pore image on a sample image.

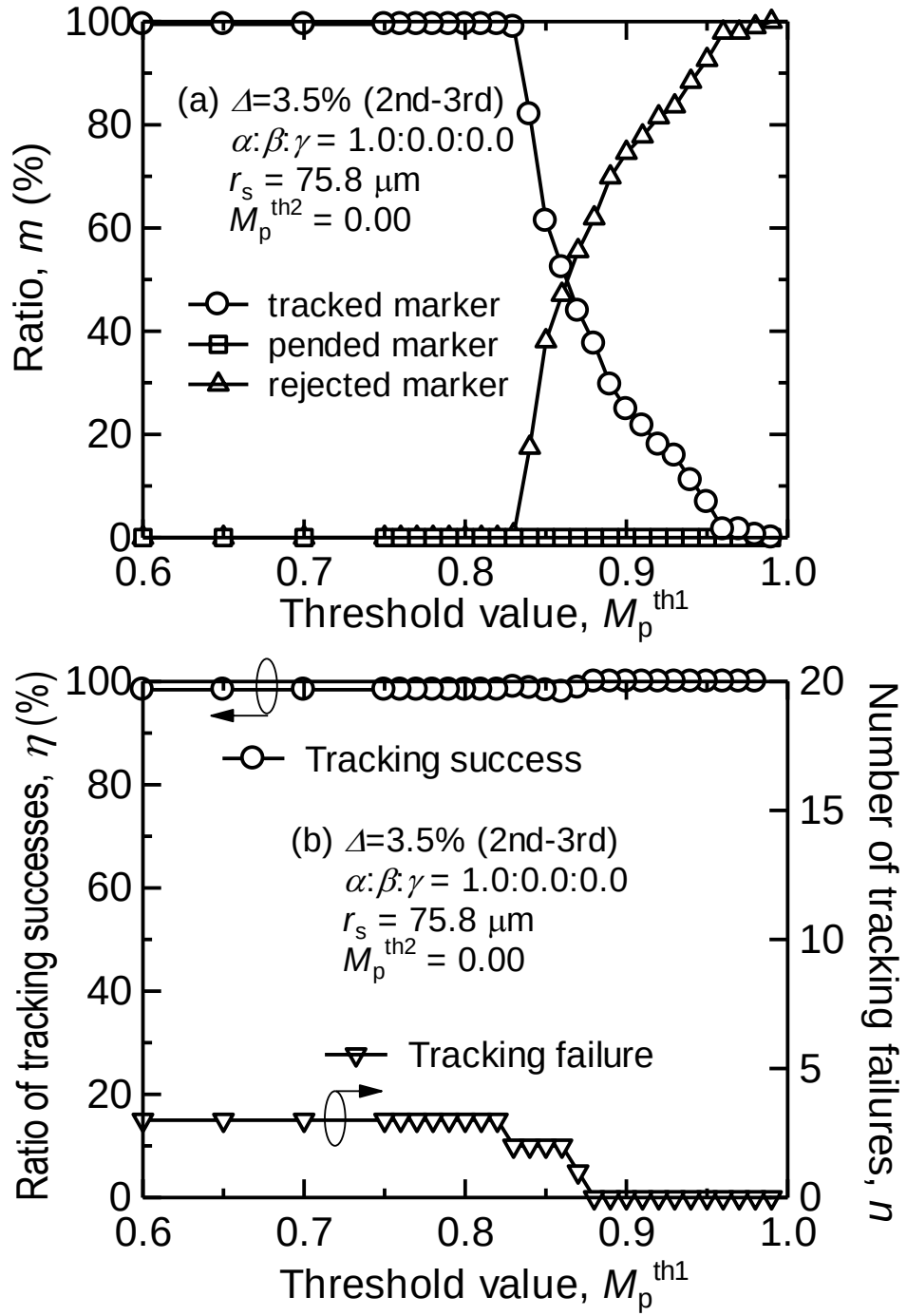


Fig. 5 Effects of the first threshold value, M_p^{th1} , for the MPP method in $\Delta = 3.5\%$. (a) Changes in the ratio of tracking, pended, and rejected markers. (b) Ratio of success tracking, η , and number of tracking failures, n .

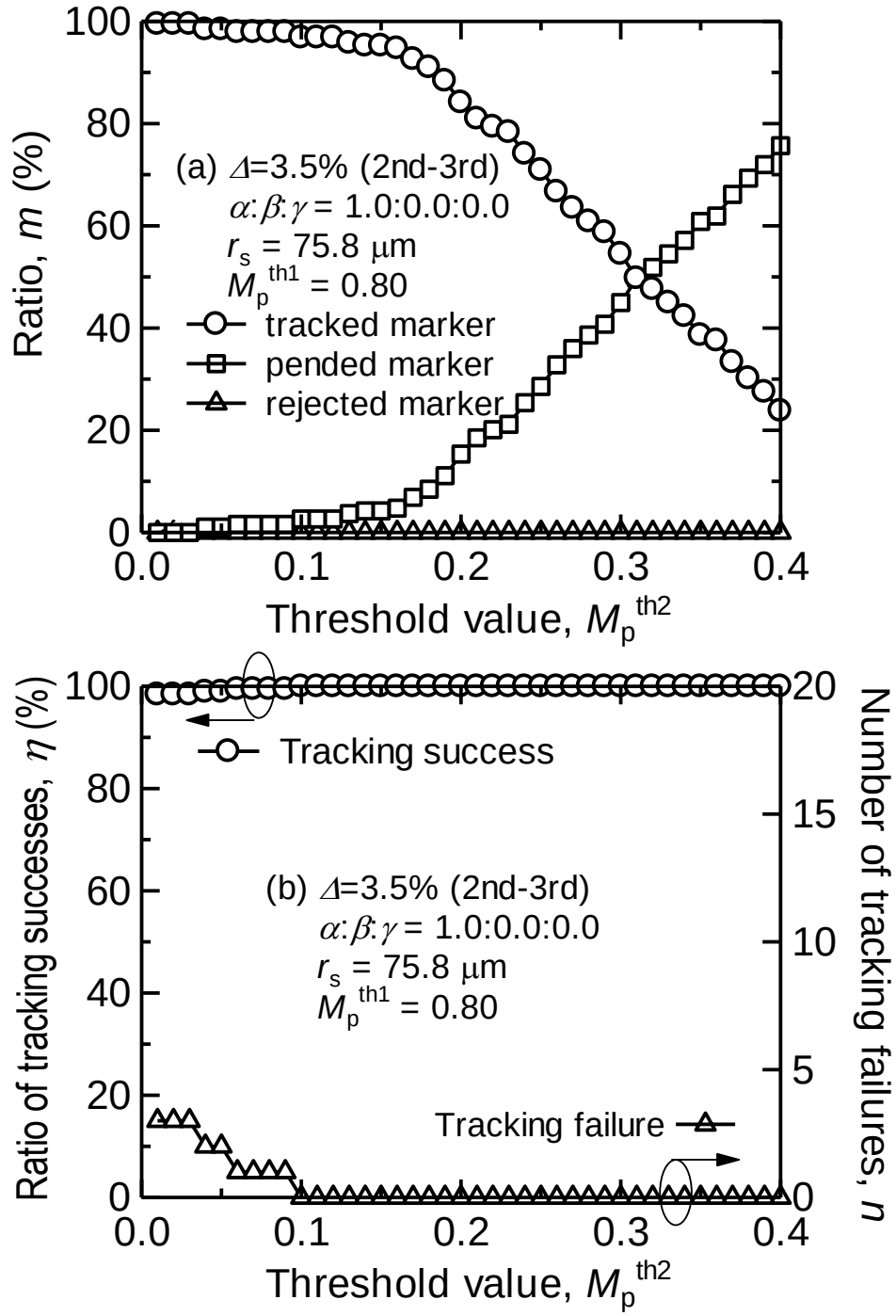


Fig. 6 Effects of the second threshold value, M_p^{th2} , for the MPP method at $M_p^{th1} = 0.8$ in $\Delta = 3.5\%$.

(a) Changes in the ratio of tracked, pended, and rejected markers. (b) Ratio of successful tracking, η , and number of tracking failures, n .

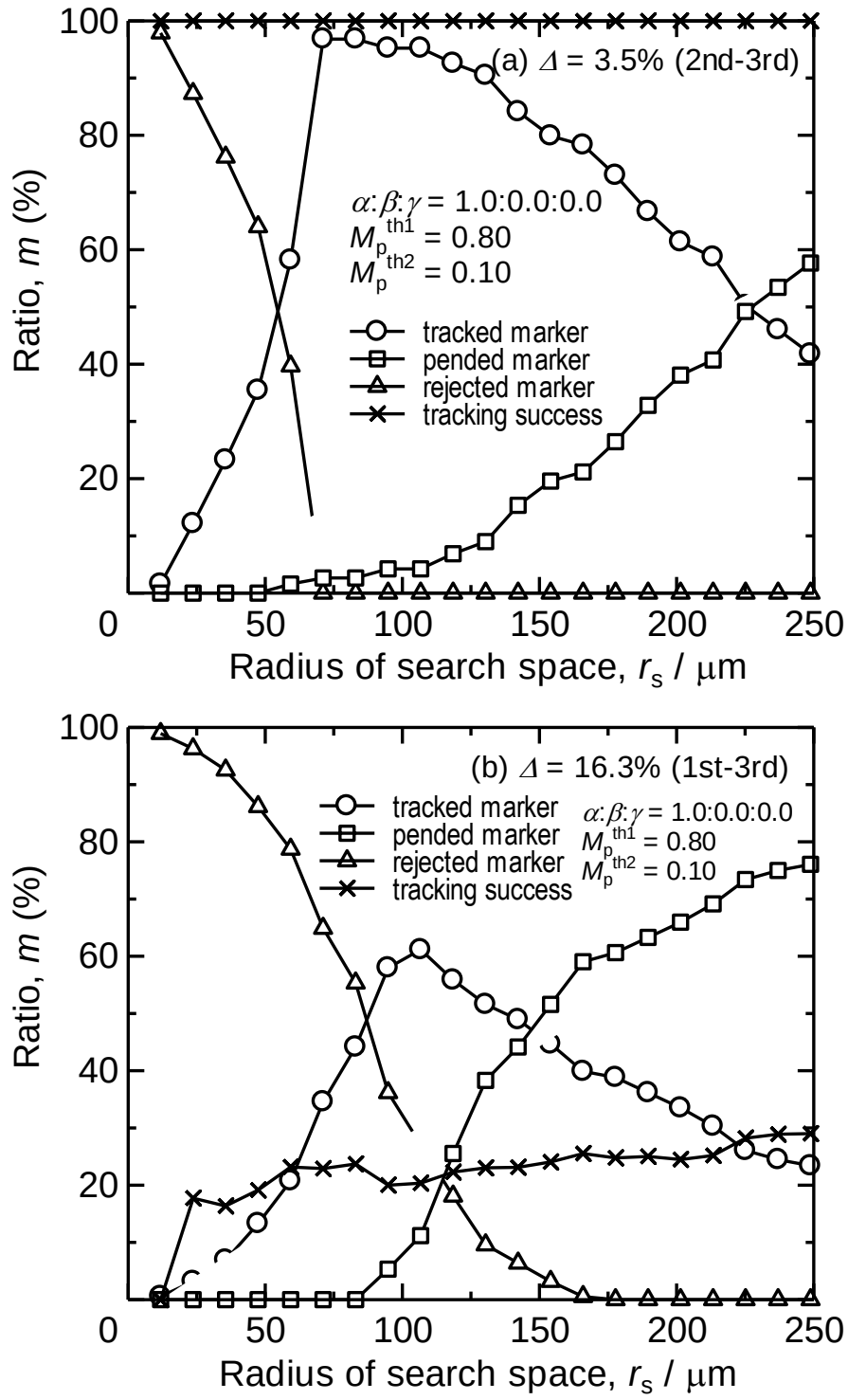


Fig. 7 Changes in ratios of tracked, pended, and rejected markers and successful tracking with the increasing radius of the search space, r_s , in (a) $\Delta = 3.5\%$ and (b) $\Delta = 16.3\%$.

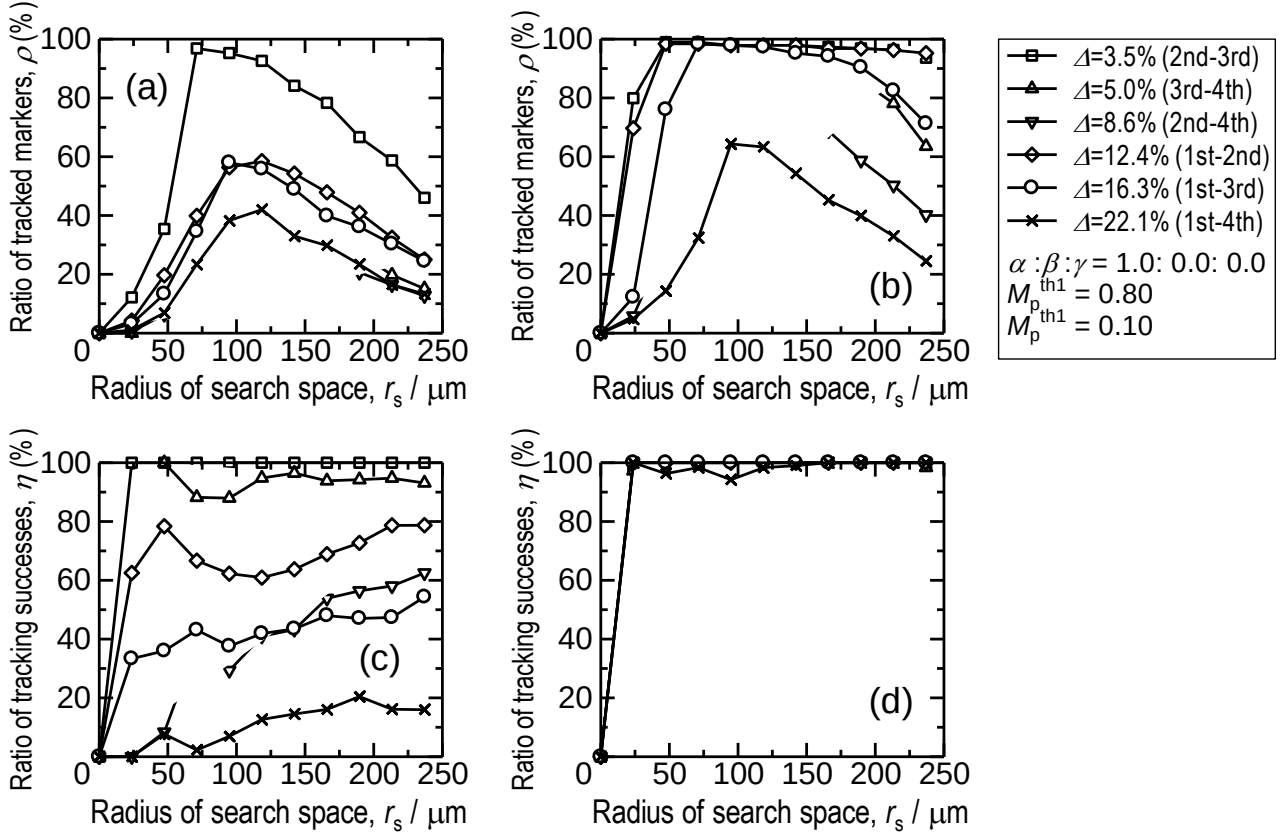


Fig. 8 Tracking results depending on the radius of search space, r_s . (a) and (b) show ratios of the tracked marker, ρ for the MPP and MTP + MPP methods, respectively. (c) and (d) show ratios of successful tracking, η , for the MPP and MTP + MPP methods, respectively.

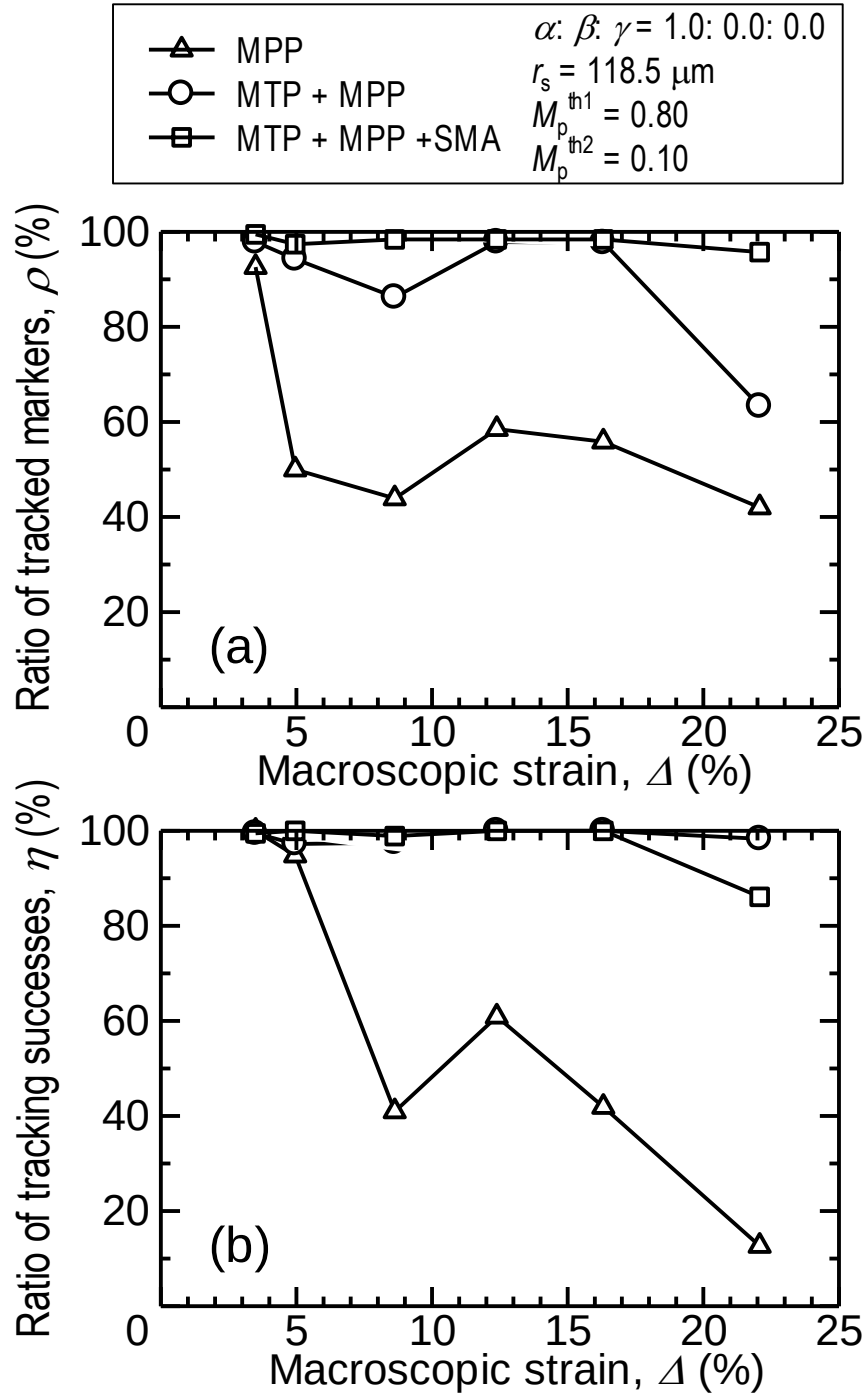


Fig. 9 Comparison of (a) ratio of tracked markers and (b) ratio of successful tracking in MPP, MTP+MPP and MTP+MPP+SMA methods developed in this study.

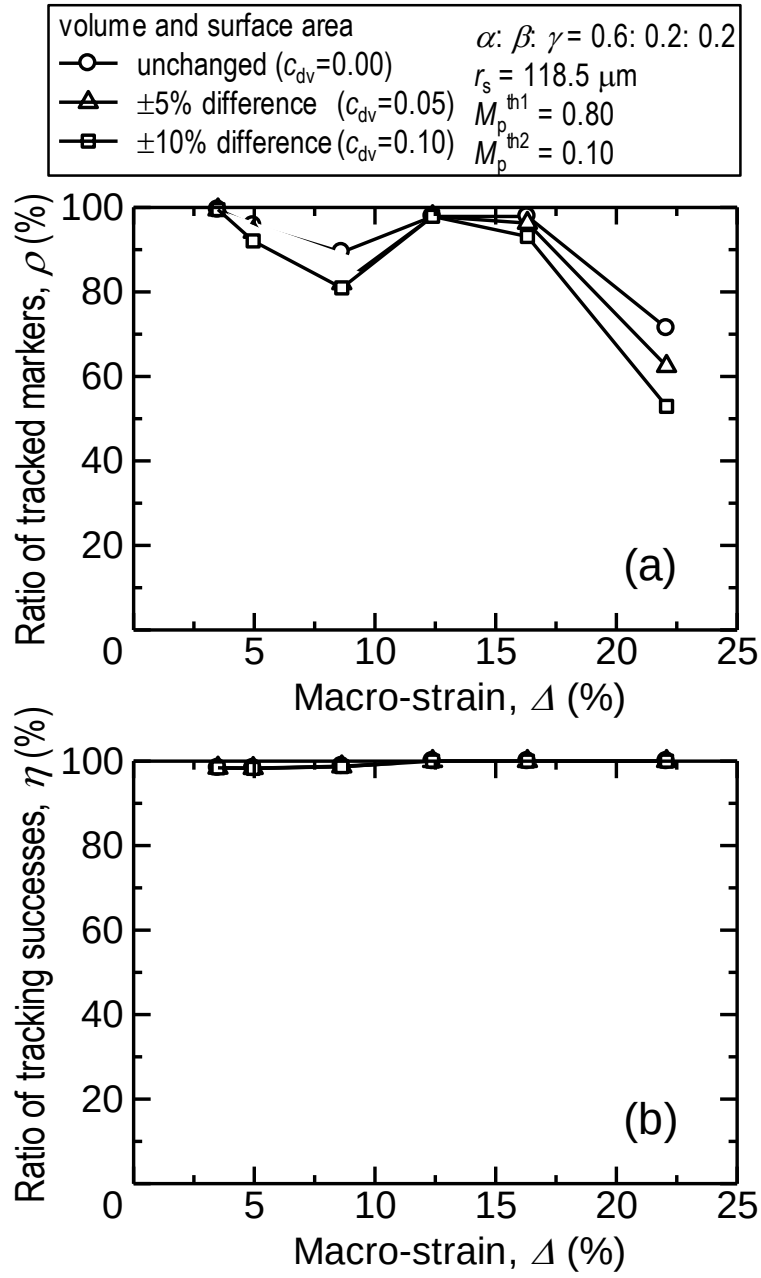


Fig. 10 Effect of volume parameter, M_v and surface area parameter, M_s on (a) the ratio of tracked markers and (b) the ratio of successful tracking in the MPP method. The volume and surface area of the markers after deformation are given by Eqs. (6) and (7) based on those before the deformation using a parameter of volume and surface area deviation, c_{dv} . The results are as follows: unchanged ($c_{dv} = 0.00$), approximately $\pm 5\%$ ($c_{dv} = 0.05$), and $\pm 10\%$ ($c_{dv} = 0.10$). The differences for the volume and surface area are plotted.

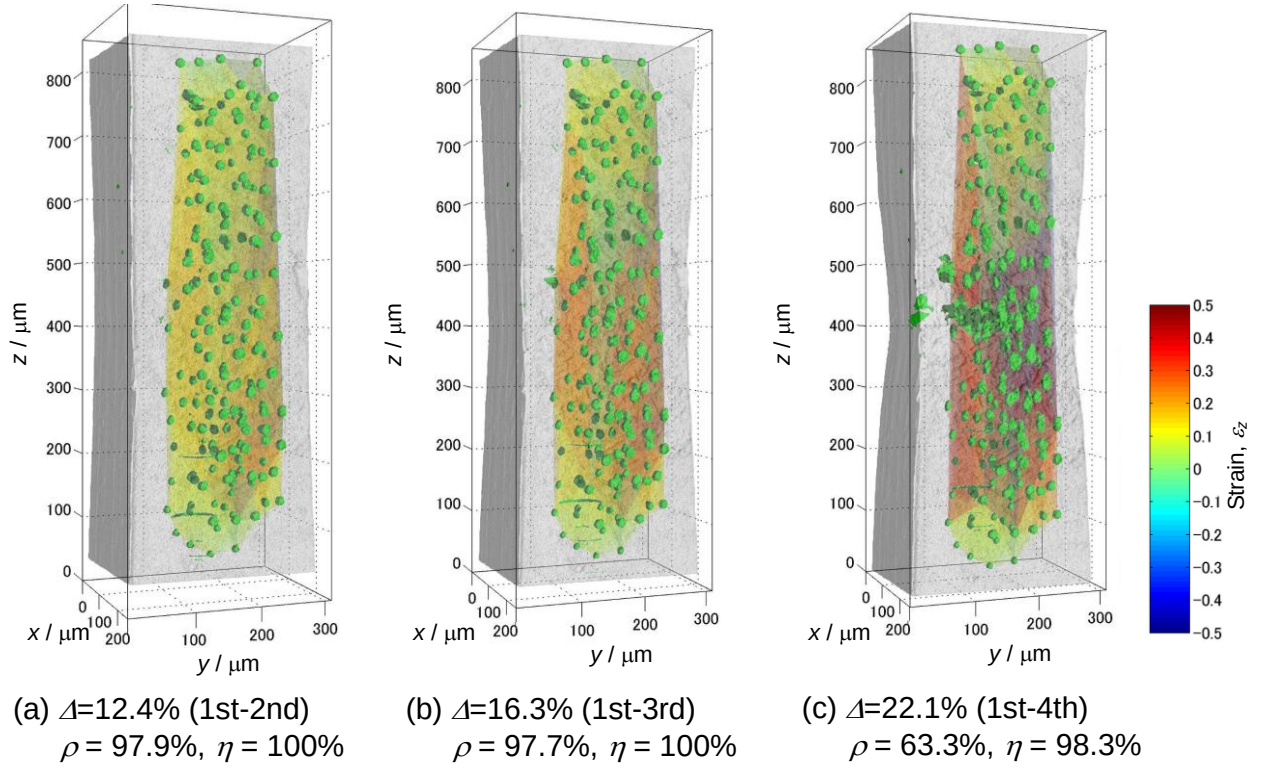


Fig. 11 Representation of 3-D strain distribution obtained by the tracking of microstructural features. The tracking parameters $\alpha: \beta: \gamma = 1.0: 0.0: 0.0$, $M_p^{\text{th1}} = 0.80$, $M_p^{\text{th2}} = 0.10$, $r_s = 118.5 \mu\text{m}$, were used after macro-strain registration.

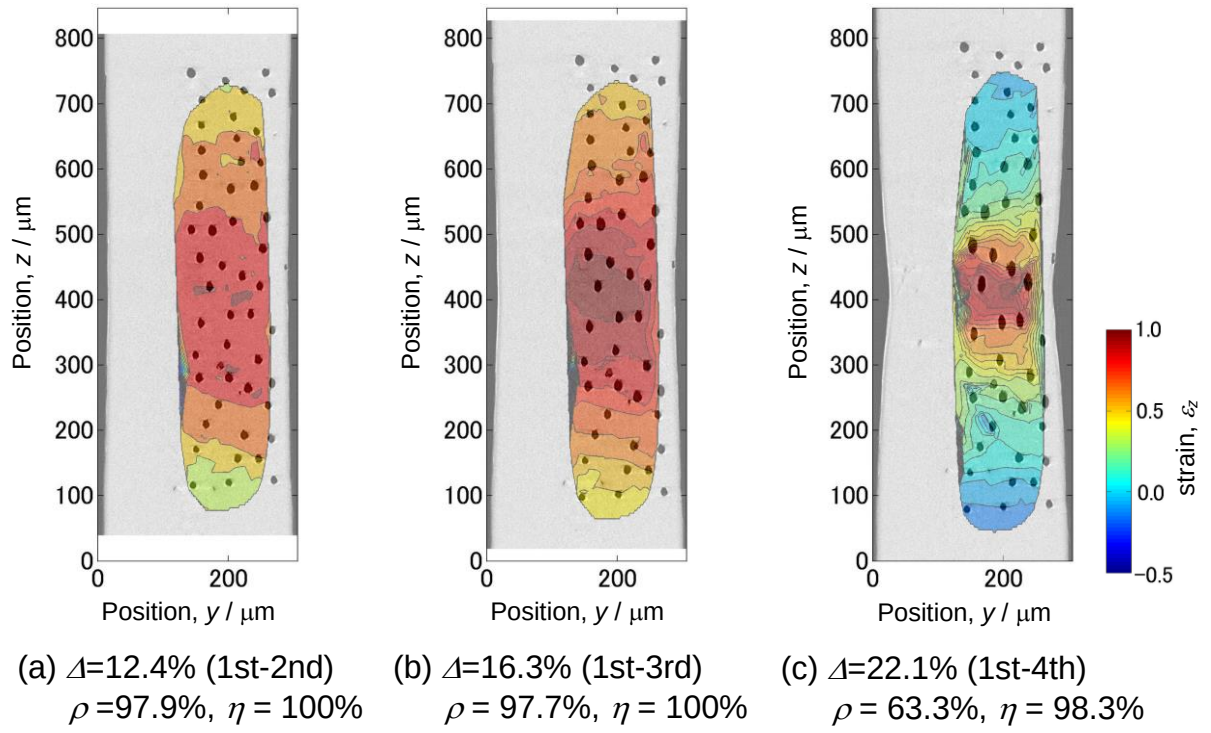


Fig. 12 Representation of ε_z strain distribution on the section at $x = 100 \mu\text{m}$ in Fig. 11.

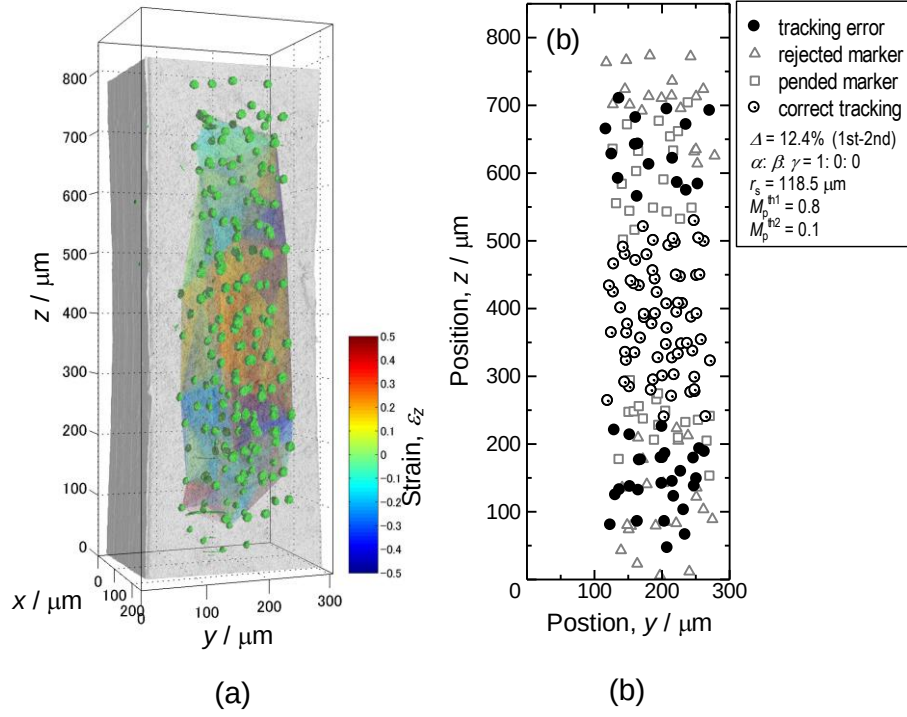


Fig. 13 Demonstration of (a) an incorrect 3-D strain distribution and (b) marker locations with tracking results on the y - z coordinates in the case of many tracking errors included intentionally. The correct result is shown in Fig. 11(a).

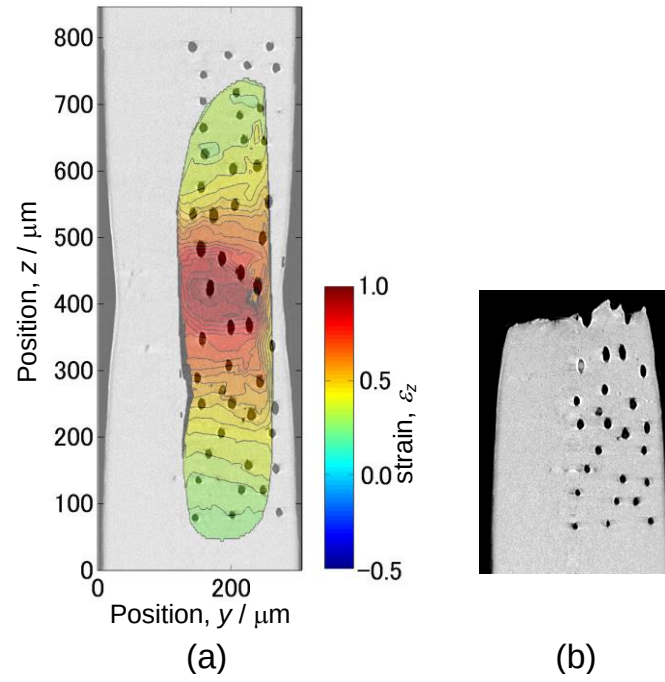


Fig. 14 Demonstration of (a) complete distribution of ε_z strain on the section of $x = 100 \mu\text{m}$ in $\Delta=22.1\%$ (1st-4th). (b) Fracture image in the same section.

Table 1 Marker status obtained by the quantitative analysis for micro-pores.

Loading step	Number of markers	Average volume (μm^3)	Average surface area (μm^2)	Average distance to the nearest neighbor marker (μm)	Distance between markers at both ends (μm)
1st	188	868.921	597.138	35.3	676.7
2nd	189	1196.448	709.219	35.6	760.5
3rd	192	1277.479	743.081	35.9	787.1
4th	193	1551.084	923.706	35.2	826.1

Table 2 Summary of macroscopic strain and number of traceable markers in various pairs of loading steps. Macroscopic strain Δ was detected by the displacement between markers at both ends along the tensile direction.

Macroscopic strain, Δ (%)	Pair of loading steps	Number of traceable markers
3.5	2nd - 3rd	186
5.0	3rd - 4th	180
8.6	2nd - 4th	180
12.4	1st - 2nd	185
16.3	1st - 3rd	185
22.1	1st - 4th	180