Random Walk Analysis of Grain Motion during Superplastic Deformation of TZP

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Abstract. This study focuses on grain motion in TZP (Tetragonal Zirconia Polycrystal) ceramics during superplastic deformation. The specimen was 16 times elongated repeatedly at 1400°C in air. The increment of true plastic strain was set to be 2%, and the specimen was deformed up to 30.3% true plastic strain finally. After each deformation, displacement vectors of specified 748 grains were measured from their position vectors determined by FE-SEM micrographs. As a result, the grains move to the tensile loading direction in zigzag way. And also, the zigzag motion changes with plastic strain: The grains move randomly (random walk motion) by the first 15% true plastic strain, and then grain motion becomes spatially uniform gradually. It is related to changes of constraint of surrounding matrix.

1. Introduction
Since superplasticity of ceramics was discovered by Wakai et al. in 1986 [1], many ceramists have studied to understand its deformation mechanism. Most studies have been discussed by means of a traditional method based on a high-temperature creep theory. However, the present authors focus on grain motion during superplastic deformation [2-4]. In this paper, superplastic deformation of a TZP (Tetragonal Zirconia Polycrystal) specimen was repeatedly conducted at 1400°C in tension. After each deformation, displacement vectors of specified 748 grains were measured from their position vectors determined by FE-SEM micrographs. Then, grain motion was discussed by using random walk theory.

2. Experimental procedure
2.1. Preparation of TZP specimen
Raw material was ZrO₂ powder TZ-3Y (Tosoh, Japan) containing 3 mol% Y₂O₃ as a stabilization agent. This powder was uniaxially pressed at 30 MPa for 2 min, and isostatically cold-pressed at 100 MPa for 2 min. The compact was sintered at 1500°C for 2 hr in air. The sintered body was ground and cut to obtain a tensile specimen. A gage section of the specimen was 10 mm in length and 2 mm square in cross section. Finally, the specimen surface was polished with diamond slurry(2 μm- 4 μm), and thermally etched at 1300°C for 10 min in air.
2.2. Repeated superplastic deformation
After the specified 748 grains were observed by FE-SEM, tensile deformation was conducted at 1400°C. Crosshead speed was 0.2 mm/min (its strain rate was on the order of $1 \times 10^{-4}$ [s$^{-1}$]). The increment of true plastic strain was set to be about 2%. After the deformation, the same grains were observed by FE-SEM again. These observations and deformations had been repeated 16 times, and the specimen was elongated to 30.3% true plastic strain finally.

3. Result and discussion

3.1. True stress/true strain curve
Figure 1 shows a true stress/true strain curve of these deformations. All the plastic deformations seem to start at about 30 MPa. Maximum stresses are about 40 MPa at the first 4 deformations. After the 5th deformation, however, maximum stresses drop to about 35 MPa (except for the 9th deformation). Namely, the specimen was deformed easier after the 5th deformation.

![Figure 1. True stress/true strain curve.](image)

3.2. Displacement vectors

3.2.1. Calculation of displacement vectors of the grains
As shown in figure 2, $x$-axis is set to be a tensile loading direction, and $y$-axis is perpendicular to $x$-axis. Grain position vectors were determined as follows: (i) A longest line parallel to $y$-axis was drawn on a grain, then a midpoint of the line was set to be a representative position of the grain. (ii) An arbitrary grain was set to be a temporary origin of the coordinate. (iii) From the temporary origin, temporary position vectors of the 748 grains were calculated. (iv) A center of gravity of the grains was determined from the temporary position vectors of the grains. (v) The origin was changed to this center of gravity, and position vectors of the grains were recalculated. From equation (1), displacement vectors $u$ were calculated,

$$u = (x_2 - x_1, y_2 - y_1)$$

![Figure 2. Measurement of a displacement vector.](image)
where \((x_1, y_1)\) is a position vector of a grain before deformation, and \((x_2, y_2)\) is that after deformation.

### 3.2.2. Displacement vectors map

Figure 3 shows displacement vector maps at each deformation. At the initial deformation shown in figure 3(a), the grains move to the tensile directions. However, at the second deformation, the grains move convergent to the origin though the specimen was actually elongated with 2.2% of true plastic strain increment during loading (figure 3(b)). Then, the grains move divergent against the origin again (figure 3(c)). Namely, grain movement repeats divergent out and convergent back.

![Figure 3. Displacement vector maps.](image)

Figure 4 shows a trajectory of a grain whose initial position vector is \((x_0, y_0) = (2.7 \mu m, 4.1 \mu m)\). We see the grain moves with zigzag way. We also note that the grain moves with smaller displacement magnitude at latter half of the deformations (i.e. after about 15% true plastic strain). If the zigzag motion is concerned with constraint of surrounding matrix, these results indicate that spatial distribution of constraint becomes uniform as superplastic deformation advances. This motion looks like random walk of Brownian motion or diffusion phenomenon.

![Figure 4. Trajectory of a grain.](image)
3.2.3. Trajectory analysis of grains by random walk theory

In this section, grain motion is analyzed approximately by means of random walk theory containing drift motion. In this analysis, random walk motion is corresponding to constraint of surrounding matrix and drift motion is driven by an external stress. Namely, grain motion can be approximated by,

$$\mathbf{u}(\varepsilon_p) = A\varepsilon_p + \mathbf{Z}(\varepsilon_p) \tag{2}$$

where $\varepsilon_p$ is true plastic strain, $\mathbf{u}(\varepsilon_p)$ is a displacement vector at $\varepsilon_p$, $A$ is a constant vector along linear drift motion and $\mathbf{Z}(\varepsilon_p)$ is a random walk vector. Drift motion of the grains is set to be a linear vector from 0% to 30.3% of $\varepsilon_p$ (figure 5). Figure 6 is histograms of random walk motion at each deformation. The distribution of them becomes narrow gradually. That is, constraint of surrounding matrix becomes small as superplastic deformation advances.

![Figure 5. Drift motion of the grains.](image)

![Figure 6. Histograms of random walk motion of the grains.](image)

4. Conclusion

Superplastic deformation of the TZP specimen was repeatedly conducted. After each deformation, the displacement vectors of the specified 748 grains were measured from their position vectors determined by FE-SEM micrographs. As a result, the grains move to the tensile loading direction in zigzag way. And also the random walk analysis shows that constraint of surrounding matrix becomes small gradually as superplastic deformation advances.

References

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