Localization of shear strain and shear band formation induced by deformation in semi-solid Al-Cu alloys

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Abstract. In situ observation of deformation in globular Al-Cu samples at a solid fraction of ~50% and a global shear strain rate of 10^{-1} s^{-1} was performed using time-resolved X-ray imaging. The solid particle motion during shear was quantitatively analysed. The force was transmitted through the contacts between solid particles over a long distance parallel to the shear plane (18 mean grain size, d) after only a 1d increment of the Al_{2}O_{3} push-plate motion. On the other hand, the distance of transmitted force in the perpendicular direction to the shear plane was restricted to approximately 11d even for a high displacement of the Al_{2}O_{3} push-plate. A relatively high shear strain rate became localized at the shear domain after a small amount of deformation (a 1d increment). The solid fraction decreased in the region of localized shear strain rate. The shear band width, where the shear strain was localized and the solid fraction decreased, remained mostly unchanged over a 4d increment of Al_{2}O_{3} push-plate motion.

1. Introduction
Deformation of semi-solid alloys induced by solidification shrinkage and external forces applied by several casting processes often causes casting defects including macrosegregation, porosity, and cracking [1–4]. For example, segregation bands, containing positive segregation and porosity result from the significant stress applied on semi-solid microstructure in high pressure die casting [1–2] and centrifugal casting [3]. The formation mechanism of casting defects is closely related with various mechanical phenomena in the mushy zone. It has been reported that the rheology of semi-solid metallic alloys shows agglomeration/disagglomeration [5–7], deformation of solid particles [6–8], and granular phenomena [1–2]. Moreover, the rheology is dependent on the liquid viscosity, the shear rate, and microstructural features (solid fraction, solid morphology, and grain size) [9–10]. The most direct approach for understanding the complexity of semi-solid deformation is to directly observe the deformation behavior at the grain scale. Recently, techniques for in situ observation of solidification phenomena and casting defect formation using synchrotron X-ray radiography have been developed to...
understand microstructural evolution and to build physical models [9–16]. In situ observation of deformation in semi-solid metallic alloys has been performed using a similar technique [17–26]. In our previous studies, the microstructure, deformed at 10^3 s^{-1} global shear strain rate in semi-solid Al-15wt.%Cu alloys at 48% solid was characterized [19–20]. The shear-induced dilation occurred by rearrangement including rotation and translation of solid particles in response to a force chain network, resulting in the shear band with decreased solid fraction [19–20] Examination of the solid motion showed that localization of the high shear strain rate occurred at the shear domain [20]. This paper demonstrates the in-situ observation of deformation at the faster global shear strain rate of 10^{-1} s^{-1} in semi-solid Al-15wt.%Cu alloys and a solid fraction of 48% using a time-resolved X-ray imaging. The developing processes of the localized shear strain rate and the shear band are studied by quantitative image analysis of solid motion during shear. The influence of the high global shear strain rate on the solid motion during shear is also examined.

2. Experimental Procedures

The ingot with a composition of Al-15Cu-0.5Ti-0.25B (mass %) was produced by arc-melting. Samples were cut to dimensions of 10 × 10 mm with 200 μm thickness. Figure 1 shows a schematic of the sample cell for deformation of semi-solid Al-Cu alloys. The sample was placed in the mold which consists of an Al2O3 plate with a thickness of 200 μm. The mold and Al2O3 window plates were retained by BN plates. The sample cell was placed in the furnace with the graphite heater [16]. The semi-solid specimen with the globular morphology was produced by partially remelting the fine equiaxed microstructure and isothermally holding for ~5 min. Deformation was applied by pushing the Al2O3 push-plate upward. Shear deformation is induced around the corner of the Al2O3 push-plate. The temperature was kept at a given temperature during the experiment. The Al2O3 push-plate displacement rate was 2900 μm/s, corresponding to a global shear strain rate of 10^{-1} s^{-1}.

Experiments were performed at beamline BL20XU of the SPring-8 synchrotron facility, Hyogo, Japan. The X-ray energy was set at 15 keV to obtain sufficient solid-liquid contrast. The observation area was 5.2 × 5.2 mm, and the pixel size was 5.2 × 5.2 μm. An X-ray imaging detector with a CMOS-type high-speed camera, an optical lens, and a phosphor screen of Ce-doped YAG, was used to record high-speed images at 250 fps [26].

![Figure 1. Schematic of sample cell for deformation of semi-solid Al-Cu alloys.](image)

The solid motion during shear was quantitatively examined using a two dimensional image analysis. The transmission image was divided into domains, whose size is approximately two times larger than the mean solid particle size (~2d). The solid velocities in the x1 direction, u_1, and in the x2
direction, \( u_2 \), were estimated using a correlation pattern between the microstructures before and after a 1d increment of the \( \text{Al}_2\text{O}_3 \) push-plate motion. Further details are shown in reference [20]. The strain rate in the x direction, \( \varepsilon_{11} \), the strain rate in the y direction, \( \varepsilon_{22} \), and the shear strain rate, \( \varepsilon_{12} \), where 1 and 2 indicate positive x and y directions, are given by

\[
\varepsilon_{11} = \frac{\partial u_x}{\partial x} \quad (1)
\]

\[
\varepsilon_{22} = \frac{\partial u_y}{\partial y} \quad (2)
\]

\[
\varepsilon_{12} = \frac{1}{2} \left( \frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} \right) \quad (3)
\]

The divergence of solid velocity, \( \text{div}(\vec{u}) \), which corresponds to a change in solid fraction, is expressed by

\[
\text{div}(\vec{u}) = \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} \quad (4)
\]

Mass conservation gives the following relationship.

\[
\frac{\partial f_s}{\partial t} + f_s \text{div}(\vec{u}) = 0 \quad (5)
\]

where, \( f_s \) is the solid fraction.

Here, the initial solid fraction is assumed to be uniform. Since the solid fraction is almost uniform at the initial stage, the assumption is roughly valid. A positive value of the divergence shows a decrease in the solid fraction.

The 3D initial solid fraction, \( g_s \), prior to shear was calculated from the intensity of the transmitted X-ray beam though regions of 100% liquid, \( I_L \), 100% solid, \( I_S \), and semi-solid, \( I_{SL} \). Further details are explained in the reference [19]. In a region, D, the solid fraction is expressed by the following equation.

\[
\left\{ g_s \right\}_D = \frac{\ln I_{SL} - \ln I_L}{\ln I_S - \ln I_L} \quad (6)
\]

The calculated 3D solid fraction of Al-Cu alloys prior to shear was approximately 48%.

3. Results and Discussion

3.1. Solid motion during shear

Figure 2(a) shows radiograph of the semi-solid microstructure prior to shear. The average projected grain size is \( d = 120 \) \( \mu \)m. The solid particles were partially overlapped in the thickness direction. The increment of the \( \text{Al}_2\text{O}_3 \) push-plate was normalized by the mean solid particle size (d). The deformed microstructures after 1.3d, 3.3d, and 6.9d increments of the \( \text{Al}_2\text{O}_3 \) push-plate motion are shown in Figures 2(b-d), respectively. It can be seen that the liquid-filled spaces have dilated between many solid particles in the shear domain due to the impingement between solid particles and the rearrangement of solid particles including translation and rotation. The solid velocity vector fields for the same increment of deformation are shown in Figures 2(e-g). The distribution of the solid velocity vector was similar regardless of the \( \text{Al}_2\text{O}_3 \) push-plate displacement. The solid particles translated upward ahead of the \( \text{Al}_2\text{O}_3 \) push-plate. The magnitude of solid velocity vectors gradually decreased with distance from the \( \text{Al}_2\text{O}_3 \) push-plate front. The solid velocity vectors gradually changed from the upward to the right toward the shear domain. The overall flow pattern was similar to that in the in situ experiments of semi-solid Al-Cu alloys at the low global shear strain rate of \( 10^{-3} \) s\(^{-1}\) [18–20]. The x- and y-positions in solid velocity vectors, which are located farthest from the origin, are plotted against the \( \text{Al}_2\text{O}_3 \) push-plate displacement in Figure 3. Note that the origin is defined as the right top corner of
the Al_2O_3 push-plate prior to shear, as shown in Figure 3. The solid particles with the velocity vector existed at 18d y-position after only a one grain size (1d) increment of the Al_2O_3 push-plate motion. As most of solid particles translated together in the direction of the Al_2O_3 push-plate motion ahead of the Al_2O_3 push-plate, the force was easily transmitted over a long distance parallel to the shear plane owing to the impingement between solid particles. The y-position increased with increasing the Al_2O_3 push-plate displacement and reached 31d, which is the maximum y-position in the sample, at 3.7d Al_2O_3 push-plate displacement. On the other hand, the x-position increased as the Al_2O_3 push-plate displacement rose to approximately 4d, above which it remained almost unchanged. The average value of the x-position was 11.3d for Al_2O_3 push-plate displacement higher than 4d.

![Image](image.png)

**Figure 2.** (a–d) Deformation of semi-solid Al-Cu alloys. (e–g) Solid velocity vector distributions after 1.3d, 3.3d, and 6.9d increments of Al_2O_3 push-plate motion.

![Image](image.png)

**Figure 3.** x- and y- positions in the solid velocity vectors which are located farthest from the origin plotted against Al_2O_3 push-plate displacement (d).

The diverging vectors existed especially at the shear domain, which indicates the local dilation, as shown in Figures 2(e–g). An example of local dilation at the shear domain during a 1.2d increment of the Al_2O_3 push-plate motion is shown in Figures 4(a–c). Figures 4(d–f) show the same images after
image processing, where boundaries of solid particles are traced black and liquid region between solid particles are defined as gray. The sequence of images clearly showed that the liquid-filled space is enlarged between solid particles. Five solid particles, labeled A-E, are highlighted that play an important role in dilation. The translation of solid particle A induced by the Al₂O₃ push-plate motion pushed B and E. The rotation and translation of B and E led to push C and D to the right, which opened up the liquid-filled space. These findings indicate that the rearrangement of solid particles including translation and rotation caused the displacement of solid particles in the direction perpendicular to the shear plane, as shown in Figure 3. Past research [24] on the in-situ observation of deformation at higher solid fraction and high global shear strain rate of 10⁻¹ s⁻¹ found that the rearrangement including rotation and translation of solid particles was highly restricted, resulting in strong localization of the shear strain in the narrow region. In this study, no significant influence of shear strain rate on the solid motion was observed because of the lower solid fraction.

![Figure 4. A local dilation event every 0.6d increment of the Al₂O₃ push plate motion.](image)

### 3.2. Localization of shear strain and formation of a shear band

Figures 5(a–c) show the distribution of the shear strain rate, calculated with equation (3), after 1.3d, 3.3d, and 6.9d increments of the Al₂O₃ push-plate motion. Shear deformation occurs in the blue-shaded regions, which corresponds to negative values of shear strain rate. Even in the initial stage of deformation (1.3d Al₂O₃ push-plate displacement), the relatively high shear strain was localized at the upper right region of the Al₂O₃ push-plate, as shown in Figure 5(a). The localized shear strain region gradually developed in the direction parallel to the shear plane as the Al₂O₃ push-plate displacement increased (Figures 5(b–c)). The localization of shear strain occurred throughout of the shear plane at approximately 4d Al₂O₃ push-plate displacement, which is consistent with that where the x- and y-positions reached the maximum value, as shown in Figure 3. The average shear strain rates in the localized regions for 1.3d, 3.3d, and 6.9d increments of the Al₂O₃ push-plate was calculated to be -1.5, -2.0, and -2.2 s⁻¹, respectively. Those values were approximately 10 times as high as the overall global shear rate. The distribution of the divergence of solid velocity, calculated with equation (4), which corresponds to a change in solid fraction, $f_s$, is shown in Figures 5(d–f). The red-shaded region (a positive value of the divergence) shows the decrease in solid fraction. At the Al₂O₃ push-plate front, the solid fraction increased. On the other hand, the red-shaded regions were distributed at the upper
right region of the Al$_2$O$_3$ push-plate. Namely, the solid fraction decreased in the localized shear strain region.

Figure 6 shows the width of shear band plotted against the Al$_2$O$_3$ push-plate displacement. The shear band width was defined as the region of coupled localized shear strain and decreased solid fraction. The shear band width increased as the Al$_2$O$_3$ push plate displacement increased up to approximately 4d and then it remained almost constant. The average shear band width was approximately 12d for Al$_2$O$_3$ push-plate displacements above 4d. Past research [20] on the in-situ observation of deformation showed that the shear band width was approximately 10d at the lower global shear strain rate of $10^{-3}$ s$^{-1}$. It is likely that the global shear strain rate has no significant influence on the shear band width in the globular sample at relatively lower solid fraction.

**Figure 5.** (a–c) Shear strain rate and (d–f) divergence of solid velocity, which correspond to change in solid fraction after 1.3d, 3.3d, and 6.9d increments of the Al$_2$O$_3$ push-plate motion.
4. Summary

Time-resolved X-ray imaging has been used to directly observe the dynamics of deformation in semi-solid Al-Cu alloys at a solid fraction of 48% and a global shear strain rate of $10^{-1} \text{s}^{-1}$. The quantitative analysis of solid motion during shear was performed.

(1) The distribution of the solid velocity vector showed that the force was transmitted a long distance in the direction parallel to the shear plane (18\text{d} y-position) after only a 1\text{d} increment of Al$_2$O$_3$ push-plate motion. On the other hand, the distance in the direction perpendicular to the shear plane is limited to approximately 11\text{d} even after a high increment of the Al$_2$O$_3$ push-plate.

(2) Only a 1\text{d} increment of the Al$_2$O$_3$ push plate motion was sufficient to cause the localization of the shear strain rate at the shear domain. The localized shear strain region fully developed throughout the shear plane at 4\text{d} Al$_2$O$_3$ push-plate displacement. The shear strain rates at the localized area were an order of magnitude higher than the global shear strain rate. The decrease in the solid fraction occurred at the localized shear strain.

(3) At more than 4\text{d} of Al$_2$O$_3$ push plate displacement, the shear band width remained constant (at approximately 11\text{d}), which was similar to that obtained in the lower global shear strain rate of $10^{-3} \text{s}^{-1}$.

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