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Differential speed rolling of an AZ31 magnesium alloy and the resulting mechanical properties

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Formability in the secondary processing strongly depends on the orientation of basal plane in magnesium alloys, because the critical resolved shear stresses for the non-basal slips are much higher than that for basal slip near the room temperature [1]. Primary processing such as hot rolling and hot extrusion generally gives rise to a strong basal texture [2, 3], and this leads to a very limited ductility near the room temperature. Therefore, texture control during primary processing is important in order to enhance the formability in the secondary processing. For example, Mukai *et al.* [4] succeeded in greatly enhancing the room temperature ductility in an AZ31 magnesium alloy by adopting equal-channel angular extrusion method, which could introduce shear strain inclined to ∼45° against the extrusion. On the other hand, it is assumed that an asymmetric rolling, such as single roller drive rolling (SRDR) [5] and differential speed rolling (DSR) [6, 7], can also introduce shear strain. The SRDR has already been applied for the AZ31 magnesium alloy [8]. It has been shown that the SRDR effectively weakens the orientation of basal plane in the rolling plane and enhances the press formability compared with normal (symmetric) rolling. The DSR is a more controllable and reproducible process compared with SRDR. Therefore, in the present study, asymmetric rolling of AZ31 magnesium alloy was performed by the DSR method. Especially, the effect of rolling direction during DSR on the resulting microstructure, texture and mechanical properties was examined.

The material used in the present study was a commercial Mg—Al—Zn alloy, AZ31. A hot extruded plate with a thickness of 6.35 mm was received from Osaka Fuji Corp., Japan. The as-received material had both coarse and fine grains with the size of 100 and 20 μm, respectively. The hot rolling was carried out at a specimen pre-heating temperature of 573 K and at a roll surface temperature of 383 K. The roll surface was lubricated by oil to prevent the adhesion of magnesium to the roll surface. The specimens were first pre-heated for 5 min.

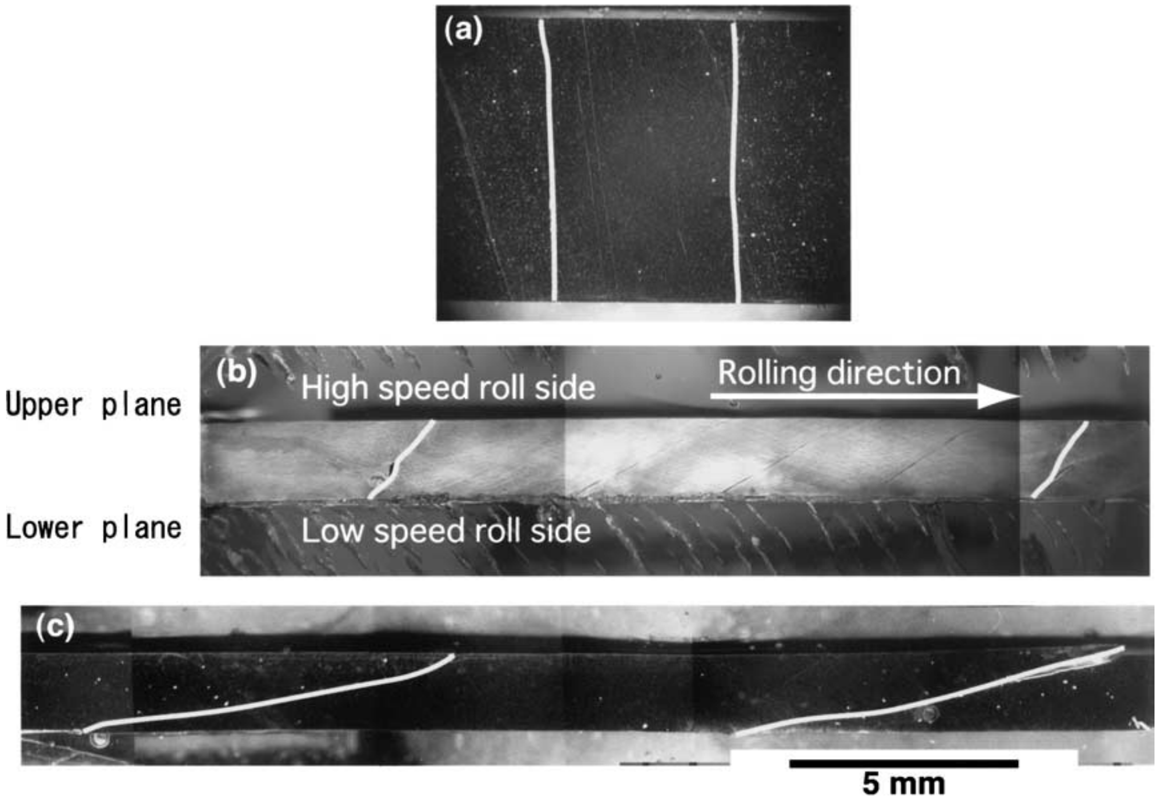

Figure 1 Macroscopic change of the inserted pin for (a) material before hot rolling, (b) asymmetrically rolled material by reverse rolling and (c) asymmetrically rolled material by unidirectional rolling. White lines show the boundary between the matrix sheet and the inserted pin.

Between each pass, the specimens were pre-heated for 3 min. The rolling was performed with a reduction of approximately 20% per pass to the final thickness of 1.7 mm. The total reduction was 73%. For DSR, rolling speed of upper and lower rolls were 2.5 and 2.0 m/min, respectively. Two routes with different rolling direction of "unidirectional rolling" and "reverse rolling" were examined. In reverse rolling, after the *i*-th rolling, the specimen was rotated "back and forth" so that the shear strain is introduced alternatively between each pass. In unidirectional rolling, after the *i*-th rolling, the specimen was rotated "back and forth" and "upside down" so that the shear strain is introduced unidirectionally throughout the rolling.

Macroscopic flow introduced during rolling was observed by the distortion of an inserted AZ31 pin with its diameter of 4 mm. The pin was inserted normal to the rolling plane before rolling as shown in Fig. 1a.

Optical microstructures were observed by a color laser 3D profile microscope using a light screen mode. X-ray texture analysis was performed by the Schulz refection method at α-angles ranging from 15 to 90 °. The (0002) pole figures were measured at the mid-layer of the rolling plane for all specimens.

Tensile specimens had tensile axes parallel to the rolling direction. The specimens had a parallel length of 30 mm, width of 5 mm and thickness of 1.7 mm. Before the tensile tests, the specimens were annealed at 423 K for 30 min under a weight pressure of 4×10^{-3} MPa to straighten the rolled sheets. Tensile tests were carried out at room temperature and at an initial strain rate of 5×10^{-4} s^{-1}.

Deformation of an inserted pin during DSR is shown in Fig. 1b and c. The pins were inclined towards the final rolling direction for both reverse rolling and unidirectional rolling. Almost uniform shear deformation was introduced throughout the thickness of the rolled sheets in spite of the lubrication of roll surface. The shear strain calculated from the inclination of the pin [9] in the material processed by unidirectional rolling was estimated to be approximately 1.6.

The optical microstructures of rolled materials are shown in Fig. 2. After the hot rolling, the grains were refined and uniform compared with that of as-received material. Hot rolled materials had equiaxed grains, indicating that recrystallization took place during rolling. Twins were observed for both materials. Grain sizes were calculated to be 10.7 and 11.8 μm for materials processed by reverse rolling and unidirectional rolling, respectively.

The (0002) pole figures of (a) as-received material, (b) hot rolled material by reverse rolling and (c) hot

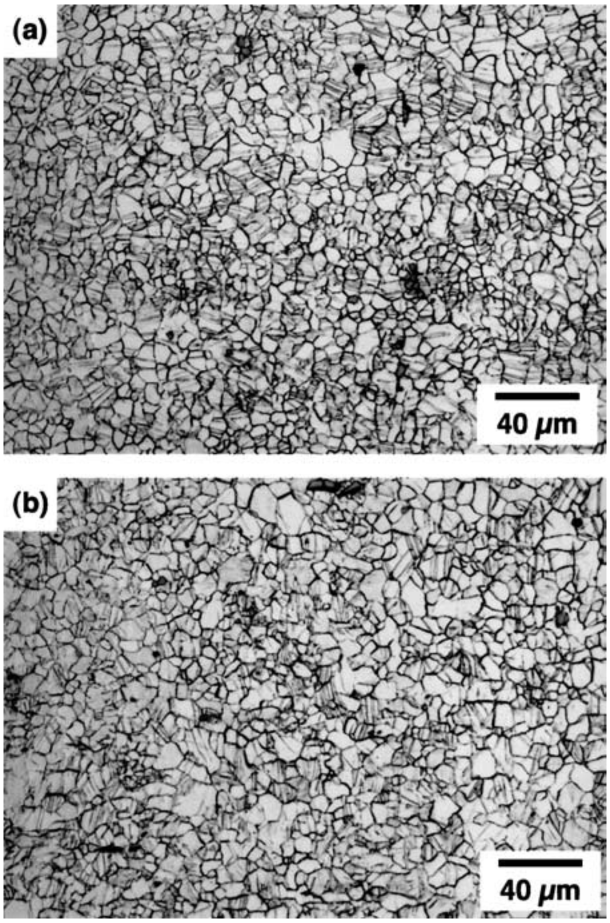

Figure 2 Optical microstructures of (a) asymmetrically rolled material by reverse rolling and (b) asymmetrically rolled material by unidirectional rolling. The rolling direction is horizontal. The vertical direction is short transverse direction.

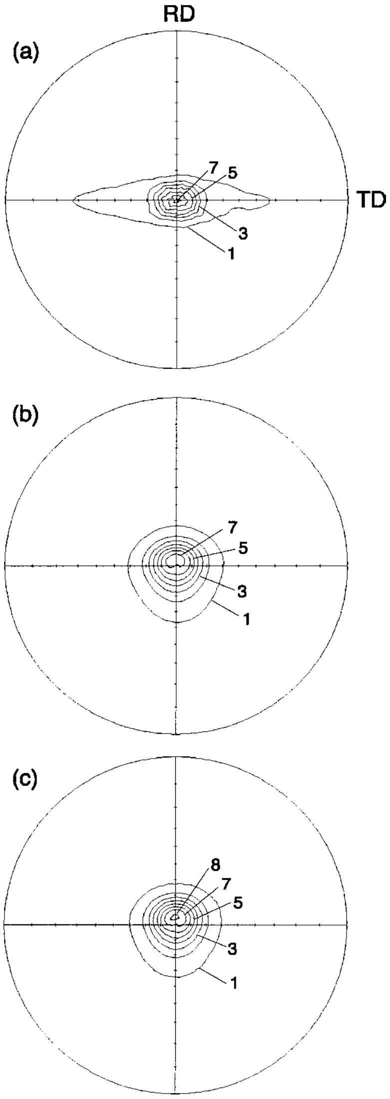

Figure 3 The (0002) pole figures of (a) as-received material, (b) asymmetrically rolled material by reverse rolling and (c) asymmetrically rolled material by unidirectional rolling.

rolled material by unidirectional rolling are shown in Fig. 3. The as-received material had texture typically observed in extruded magnesium [3]: the majority of basal plane oriented parallel to the extruded direction. On the other hand, the materials processed by reverse rolling and unidirectional rolling showed (0002) pole density at the position inclined by ~5° from the normal direction toward the rolling direction, though the substantial change was not observed in the developed texture. Chino *et al.* [8] reported similar texture in AZ31 processed by SRDR, whose (0002) pole density inclined 10 ° from the normal direction toward the rolling direction. The inclination may be related to the different mode of loading: larger shear strain is introduced during DSR compared with normal symmetric rolling even in the mid-layer. Another thing to be noted is that the basal plane texture in material processed by reverse rolling is somewhat weaker than that by unidirectional rolling.

Mechanical properties of the asymmetrically rolled sheets and normally rolled AZ31 sheet (H24 condition: partially annealed) with the grain size of 10–20 μm [10] are listed in Table I. All materials exhibit similar UTS of ~310 MPa. However, the elongation-to-failure, e_{f}, depends on the rolling method: the materials processed by normal rolling and unidirectional rolling exhibit relatively limited ductility below 10%, whereas the material by reverse rolling exhibits moderate ductility of ~15%. The reverse rolling is suggested to be effective to enhance the room temperature ductility in AZ31 magnesium alloy.

In order to clarify the origin of higher ductility of the material processed by reverse rolling compared with that by unidirectional rolling, optical microstructures of fractured specimens were observed. The optical microstructures near the fracture surface are shown in Fig. 4. By comparing with Fig. 2, it is obvious that many deformation twins are formed

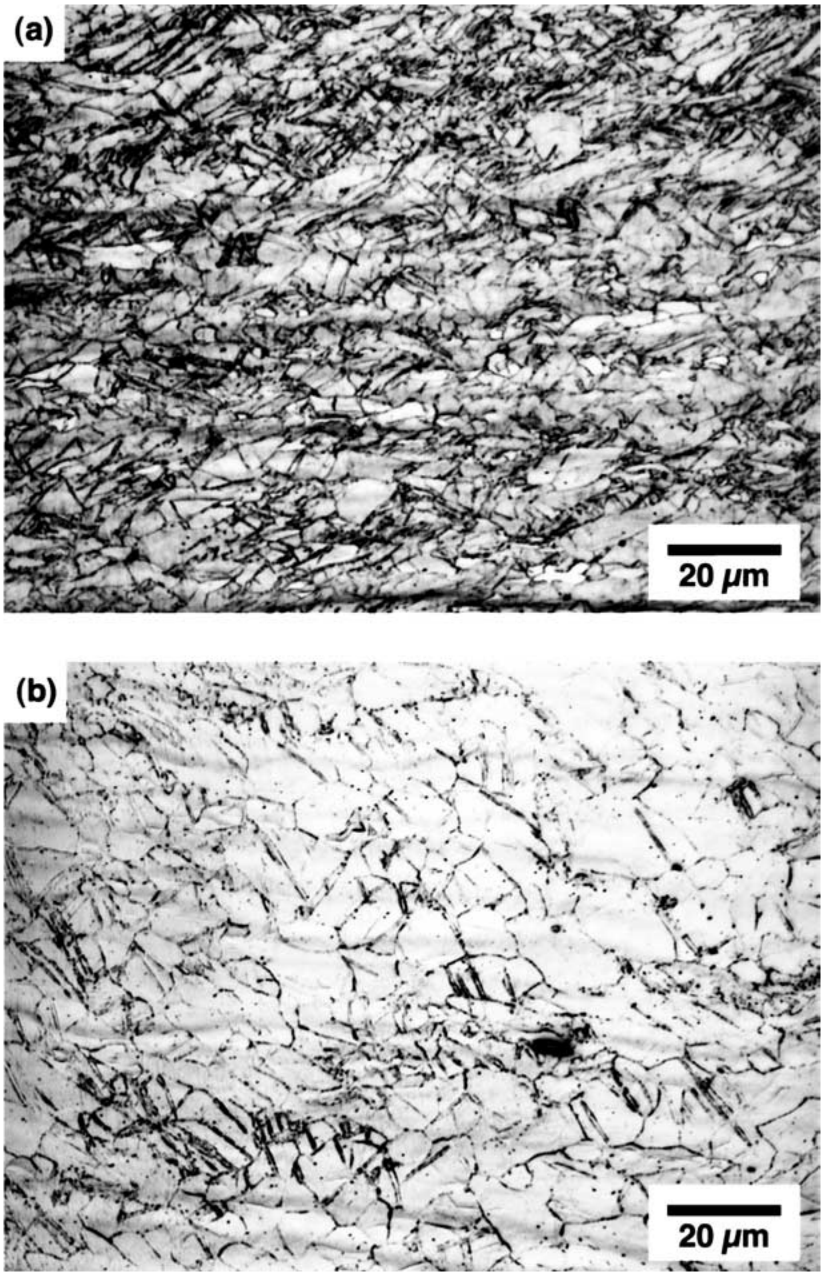

Figure 4 Optical microstructures of the transverse plane after room temperature tensile test for (a) asymmetrically rolled material by reverse rolling and (b) asymmetrically rolled material by unidirectional rolling. Tensile direction is horizontal.

TABLE I Tensile mechanical properties of materials processed by normal rolling and differential speed rolling

Rolling method	YS, MPa	UTS, MPa	e_f, %	Ref.
Normal rolling	–	314	9	[10]
Differential speed rolling				
Reverse	271	311	14.6	This work
Unidirectional	258	300	7.9	This work

during tensile test in the material processed by reverse rolling. On the other hand, fewer twins were observed in the material processed by unidirectional rolling, though the extent of deformation to fracture is different.

Twinning in magnesium occurs either by tensile stress to the *c*-axis direction or compressive stress perpendicular to the prismatic plane [11]. So, the weaker the orientation of basal plane parallel the rolling plane, the easier twinning occurs. It is, therefore, suggested that the higher ductility of the material processed by reverse rolling compared with that by unidirectional rolling is attributed to the weaker orientation of basal plane as has been shown in Fig. 3. In the material processed by reverse rolling, the twinning effectively served as complementary deformation mechanism so as to enhance the room temperature ductility.

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