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Single-roll angular-rolling: A new continuous severe plastic deformation process for metal sheets

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ABSTRACT

In this paper, a new continuous severe plastic deformation (SPD) process for metal sheets called single-roll angular-rolling (SRAR) is introduced. The SRAR process achieves maximized deformation homogeneity of metal sheets by combining circumferential shear deformation with channel-angular shear deformation. The grain refinement and mechanical properties were investigated experimentally in relation to the number of repetitive SRAR passes. The finite element method was used to demonstrate that the SRAR process provides highly uniform SPD by strengthening the less deformed region that inevitably occurs near the lower part of the workpiece during the channel-angular deformation processes.

Severe plastic deformation (SPD) is a state-of-the-art processing method for fabricating ultrafine-grained (UFG) materials by imposing extreme levels of hydrostatic pressure and shear deformation on the material. Because UFG materials are superior to coarse-grained materials in terms of mechanical properties and physical characteristics [1–3], the SPD process is capable of manufacturing bulk UFG materials and thus has great potential for fabrication of various industrial parts [4]. However, the basic SPD processes: equal-channel angular pressing (ECAP) [5], high-pressure torsion (HPT) [6], and accumulative roll bonding (ARB) [7], are limited for practical industrialization because it is hard to apply these discontinuous processes in mass-production.

In order to avoid such obstacles, continuous SPD processes have recently been invented using a variety of concepts by applying continuous drag force on a workpiece [8–10]. Most of these are based on the ECAP process (e.g., con-shearing [11], continuous confined strip shearing (C2S2) [12], and ECAP-Conform [13,14]). Because these continuous processes require a large amount of drag force to drive the workpiece through the channel-angular region where two channels are intersected at a certain angle, the conshearing process uses a large number of rollers to impose high-friction force on the workpiece. On the other hand, the C2S2 process uses a specially designed feeding roller with grooves that cause surface defects on the workpiece. An ECAP-conform process specific to the bar-shaped workpiece, enhances the drag force by transformation of the cross-sectional shape from circular to square.

However, these continuous SPD processes share a common disadvantage in terms of deformation homogeneity: they are accompanied by deformation behavior similar to that of the conventional ECAP process [11,14,15]. In ECAP, the flow velocities between the lower and upper parts of the workpiece inevitably differ, which results in a deformation gradient in the cross-section. This is particularly true of the formation of a less-deformed region near the lower surface of a workpiece [16,17]. Such heterogeneous deformation can degrade the material stability associated with mechanical properties and microstructures, which is particularly lethal for metal sheets with a small thickness to widths ratio.

In this paper, we propose a new continuous SPD process called '*single-roll angular-rolling* (*SRAR*)' to induce highly uniform SPD throughout metal sheets by engaging circumferential shear deformation in the channel-angular deformation process. Because the thickness of the metal sheets is restored to the initial thickness after the SRAR process, the microstructures and mechanical properties of same-thickness specimens were investigated by varying the number of repetitive passes, and the distinctive deformation behavior of the SRAR process was explored using the finite element method (FEM).

Most simply, the SRAR process can be performed by inserting a rotating roll with a relatively rough surface into a specially designed stationary die. In this work, the process was executed using an HPT machine, as shown in Fig. 1a. A cross-sectional view of the stationary die is described in detail in Fig. 1b, and there is a circumferential groove inside the stationary die. Unlike the ECAP-Conform process, in which the thickness of the circumferential groove is constant after transition of the cross-sectional shape from circular to square [14], the thickness

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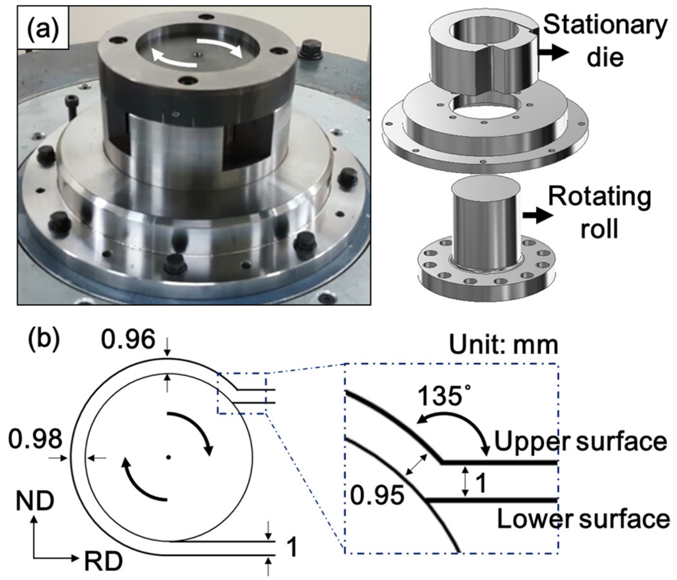

Fig. 1. (a) Equipment for the SRAR process using an HPT machine and (b) schematic cross-sectional view of the SRAR process.

of the circumferential groove in the SRAR process is gradually narrowed (i.e., from 1 to 0.95 mm). The slight reduction in thickness provides enough drag force to help the metal sheets to overcome deformation resistance in the channel-angular region with the channel angle of 135°, and enables the continuous SPD process for metal sheets. Above all, the thickness reduction in the circumferential groove plays an important role in imposing uniform deformation on the metal sheets. Details of the SRAR processing will be discussed later.

A commercial purity Cu (99.99%) sheet, with 1 mm thickness, 28 mm width, and 300 mm length, was subjected to the SRAR process at room temperature. To homogenize the initial microstructure, the Cu sheet was annealed at 600 °C for 2 h followed by air cooling. Before the SRAR process, the upper surface of the Cu sheet in contact with the stationary die was coated with MoS_2 lubricant to minimize friction. The rotation speed of the roll was approximately 3 rpm. After the thickness reduction in the circumferential groove, the thickness of the Cu sheets was restored to their initial thickness after SRAR processing. Thus, the processes were repeated in up to six passes without rotation of the Cu sheets between each pass. This is similar to the Route A path in the conventional ECAP process.

In order to investigate the evolution of microstructures in relation to the number of passes, electron back-scattered diffraction (EBSD) measurements were performed on the plane perpendicular to the transverse direction (TD) using field-emission scanning electron microscopy (FE-SEM). Tensile tests and Vickers hardness tests were performed to measure the mechanical properties of the SRAR-processed Cu sheets after one to six passes. For each pass, three dog-bone shaped plate specimens, with the gauge dimensions of 1 mm thickness, 2.5 mm width, and 5 mm length along the rolling direction (RD), were used for the tensile tests at a strain rate of $1.0 \times 10^{-3}\ s^{-1}$. From the lower to upper surfaces of the Cu sheets, indicated in Fig. 1b, the Vickers hardness was measured under a load of 100 gf and with a dwell time of 10 s.

The variation of microstructure and mechanical properties according to the number of passes are summarized in Table 1 and Fig. 2. With increasing number of passes, the initial equiaxed grains with average grain size of 51.2 μm, gradually become inclined toward the extrusion direction as shown in Fig. 2(a–c). This increases the fraction of low-angle grain boundaries (LAGBs) and in-grain misorientation to create conditions similar to those produced by the conventional ECAP process [18,19]. Also, the grain subdivision that occurred after four passes was remarkable, and the average grain size after six passes was approximately 5.2 μm. However, the specimen after 6-pass SRAR still had a non-uniform microstructure composed of elongated sub-grains with a large fraction of LAGBs because of the obtuse channel angle (135°). Even if the same amount of deformation is given in the channel-angular deformation, the grain refinement by the obtuse channel angle is weaker than that by the acute channel angle [20]. Therefore, further passes needed to be carried out, in order to create a UFG microstructure with a high fraction of high-angle grain boundaries (HAGBs). However, in this study, the SRAR process was limited to six passes due to the limited capacity of the HPT machine. Indeed, it is necessary to reduce the channel angle for enhancing the grain refinement efficiency and to increase the radius of the rotating roll and stationary die for providing the sufficient drag force.

Table 1
Average grain sizes, fractions of grain boundaries, and tensile properties of the as-annealed and SRAR-processed Cu sheets.

Number of passes	Average grain size (μm)	Fraction of HAGB	Fraction of LAGB	σ_{YS} (MPa)	σ_{UTS} (MPa)	δ (%)
0	51.2	0.851	0.149	91.7	223.5	54.0
1	45.9	0.405	0.595	263.9	287.4	18.0
2	42.6	0.188	0.812	310.0	332.0	16.1
4	15.4	0.180	0.820	337.1	366.2	13.5
6	5.2	0.248	0.752	343.7	388.5	13.9

In the tensile stress-strain curves (Fig. 2d), both the yield strength (σ_{YS}) and ultimate tensile strength (σ_{UTS}) are significantly intensified with increasing number of passes, especially after the first pass. After a low number of passes, strengthening mainly by strain hardening becomes prominent and grain-boundary strengthening by grain refinement is also exhibited with increasing number of passes. The total elongation (δ) showed the opposite trend, representing the strength-ductility trade-off, but there was no significant drop in the ductility from the 4th pass to 6th pass results. Moreover, the hardness values in Fig. 2e become stronger with the number of passes after a drastic increase in the first-pass specimen. Above all, the remarkable point in the hardness results is that the region in the vicinity of the lower surface, where the conventional ECAP process imposes significantly less deformation, becomes hardened to a degree similar to that in the upper surface region. Therefore, the hardness distribution in the SRAR-processed sheet is more homogeneous than in the conventional ECAP-processed bar, which is a distinctive feature of the SRAR process.

In the continuous SPD process for metal sheets, the deformation homogeneity induced by one pass is much more important than for metal bars because the metal sheets cannot be processed via Route B_C, which is well known as a process route favorable for homogenizing mechanical properties and microstructures during the ECAP process. As mentioned above, the channel-angular shear deformation (CASD) in ECAP alone cannot get rid of the less deformed zone near the lower surface of the metal sheets. To overcome this limitation, the circumferential groove used in the SRAR process is designed to progressively diminish the thickness until the metal sheet reaches the channel-angular region, to impose more deformation in the lower surface region prior to the CASD. As shown in Fig. 3a, Region A is a region pre-deformed by the circumferential groove before the channel-angular region, and Region B is where the first pass of SRAR is completed after the Cu sheet passes through the channel-angular region. From the hardness results in each region (Fig. 3b), it is confirmed that the relatively uniform distribution of hardness in Region B is attributable to preferential deformation near the lower surface in Region A. Similarly, kernel average misorientation (KAM) maps in Fig. 3(c–d), evaluated from the EBSD measurements covering all of the thickness of the Cu sheet, also demonstrate that high KAM values are concentrated on the lower surface in Region A and then are evenly distributed over the entire region in Region B.

In order to determine what deformation mode occurs in each region during SRAR, a 2-D elasto-plastic FEM simulation was performed based on an isotropic hardening model in ABAQUS/Standard Ver. 6.9. The