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Processing Aluminum and Aluminum Alloys by Continuous High-Pressure Torsion

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A continuous high-pressure torsion (CHPT) developed recently was applied to high purity aluminum (99.99%) and an Al–3%Mg–0.2%Sc alloy. It is shown that CHPT can be used for straining under high pressures and producing ultrafine grained microstructure as the conventional high-pressure torsion using disc and ring samples. Furthermore, CHPT provides an opportunity to use sheets of the materials in a continuous way which is promising for industrial applications. Tensile tests show that the Al–3%Mg–0.2%Sc alloy after processing with CHPT is superplastic at 573 K.

Keywords: *high-pressure torsion; ultrafine grained; severe plastic deformation; aluminum, superplastisity.*

1. Introduction

Processing bulk metallic materials through the application of high-pressure torsion (HPT) leads to attainment of ultrafine-grained structures with a high strength and reasonable ductility. In the HPT method, a thin disc or ring is placed between two massive anvils under a high pressure and intense shear strain is introduced by rotating the two anvils with respect to each other [1, 2]. As a main merit of HPT, since the process is conducted under high hydrostatic pressures, the fracture is significantly suppressed and thus it is applicable to hard and less ductile metals such as magnesium [3] and tungsten [4] even including intermetallics and ceramics such as Ni_3Al [5] and Al_2O_3 [6]. The HPT process has been used in a form of disc or ring but it is strongly desired to be performed in a form of wire or sheet although the sample size is currently extended to 35 mm in diameter for discs [7] and 100 mm in diameter for rings [8].

In this study, thus, a newly developed severe plastic deformation method, which we call continuous high-pressure torsion (CHPT) [9], is applied for processing of metallic sheets with HPT in a continuous way. It is shown that the CHPT can be used for sheets or even wires with the principle of HPT and be a potential process for industrial application.

2. Principle and Facility

The facility for the CHPT is schematically illustrated in Fig. 1 [9]. It consists of two anvils: the lower anvil, which is rotated during process, has a flat surface with a roughened ring-shaped area; and the upper anvil, which is fixed during process, has a half ring-shaped groove on the surfaces with 0.5 mm depth, 3 mm width and outer diameter (*OD*) of 20 or 30 mm. A U-shaped specimen with 1mm thickness, as shown in Fig. 1, is used as an initial sample. Each sample is placed on the lower anvil and the pressure is applied on the sample by raising the lower anvil up to a rigid contact with the upper anvil. The lower anvil is then rotated with respect to the upper anvil and shear strain is introduced in the sample under a high pressure. Accordingly the material starts to flow in the rotation direction. Fig. 2 shows the appearance of an Al sample with *OD*= 20 mm before and after CHPT for 1/4 and 2 revolutions. The equivalent strain produced by CHPT, ε, is given as

$$\varepsilon = (1-s)\frac{\pi}{\sqrt{3}}\frac{R}{t} \qquad (1)$$

where s is the fraction of sample slippage as described in an earlier report [10], R is the mean radius of U-shaped sample, as shown in Fig. 2, and t is the thickness of sample. For this study, R is either 8.5 or 13.5 mm, t is 0.6 mm and s is in the range of $0 < s < 1/2$ as estimated earlier [9].

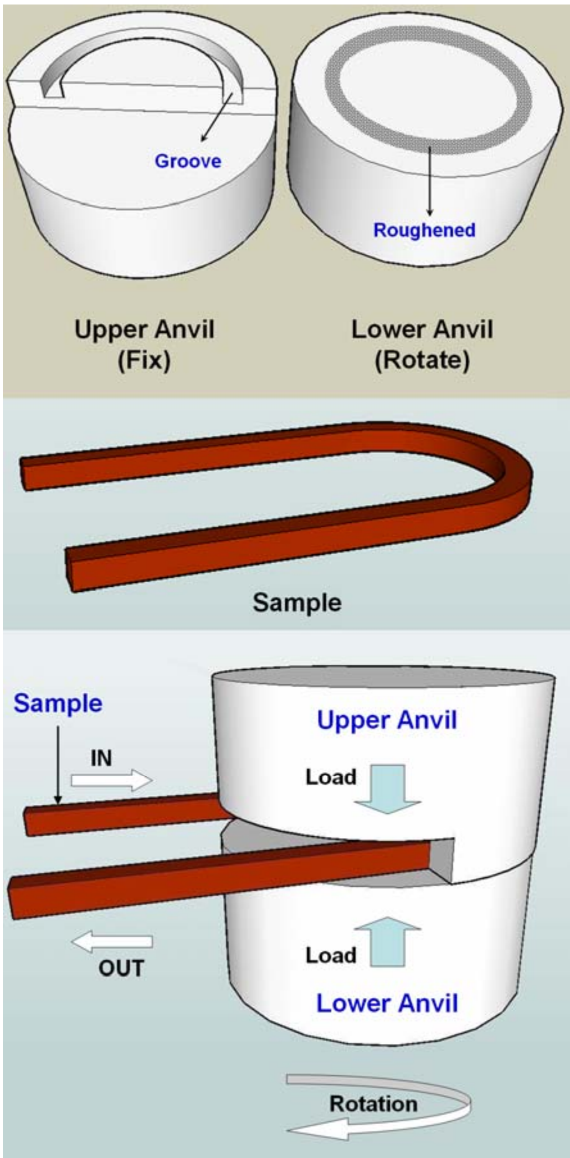

Fig. 1. Schematic illustration of CHPT.

3. Experimental

The experiments were conducted using high-purity Al (99.99%) and an Al–3%Mg–0.2%Sc alloy sheets where the composition is given in wt.%. These materials were selected because Al (99.99%) matches the material used in earlier reports with conventional HPT [2, 8, 11] and the Al–3%Mg–0.2%Sc alloy exhibits a superplasticity after processing with HPT [12, 13]. The sheets were cut to U-shaped specimens, as shown in Fig. 3, having 1mm thickness, 3mm width and 40 to 80mm length including a half circle with outer diameter of *OD*= 20 or 30 mm for Al and *OD*= 20 mm for Al–3%Mg–0.2%Sc. The Al specimens were annealed for 1 hour at 773 K and the Al–3%Mg–0.2%Sc alloy was solution treated in air for 1 hour at 873 K. Each sample was placed on the lower anvil, and the upper and lower anvils were rotated with respect to each other at room temperature with a rotation speed of 1 rpm under a pressure of 1 GPa for Al and 1.25 GPa for Al–3%Mg–0.2%Sc. The rotation was continuously undertaken until termination after 2 revolutions.

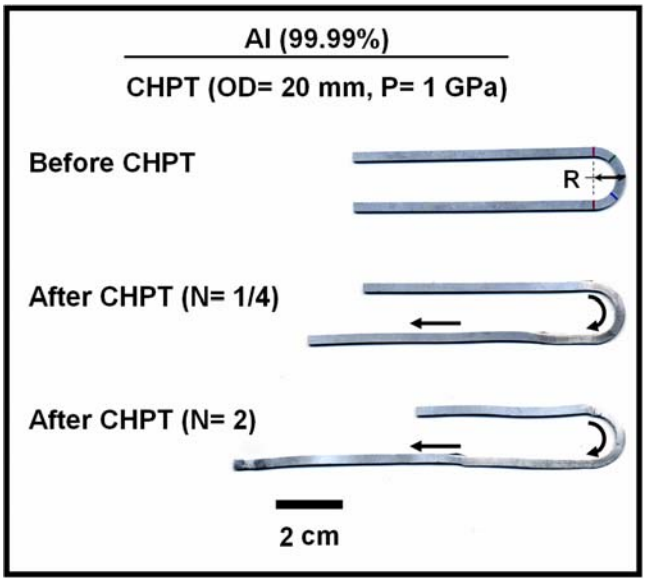

Fig. 2. Appearance of U-shaped Al samples with *OD*= 20 mm before and after CHPT for 1/4 and 2 revolutions.

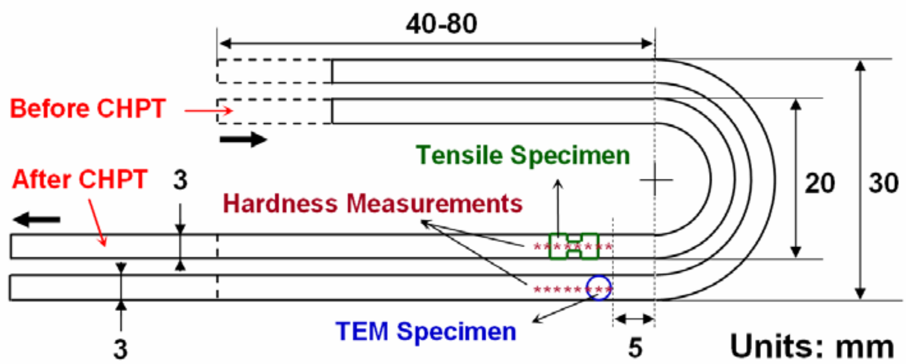

Fig. 3. Dimensions of U-shaped samples including positions for microhardness measurements and locations for tensile specimen and TEM disc.

The samples subjected to CHPT were evaluated in terms of Vickers microhardness, tensile properties and microstructures. First, the sample were polished to a mirror-like surface and the Vickers microhardness was measured on the upper and lower surfaces of the sample as well as on the surface ground successively to ~~at~~ the mid-point of the thickness. Hardness was measured on the center part every 1 mm starting at 5 mm away from the exit of the upper anvil, as drawn by dotted lines in Fig. 3. For each hardness measurement, a load of 50 g for Al and a load of 200 g for Al–3%Mg–0.2%Sc were applied for 15 seconds and the average of hardness values at 24 positions was calculated. Thereafter, as illustrated in Fig. 3, miniature tensile specimens having 1 mm gauge length and 1 mm width were cut from the Al–3%Mg–0.2%Sc samples using a wire-cutting electric discharge machine. Each tensile specimen was mounted horizontally on grips and pulled to failure using a tensile testing machine with an initial strain rate of 3.3×10^{-3} s^{-1} at 573 K and the stress-strain curve was delineated for each specimen. Third, discs with 3 mm in diameter were punched from the Al sample at 5 mm away from the exit of the upper anvil as also illustrated in Fig. 3. The 3mm discs were ground mechanically to a thickness of 0.4 mm and further polished with an electro-chemical polisher using a solution of 10% $HClO_4$, 20% $C_3H_8O_3$ and 70% C_2H_5OH. Transmission electron microscopy (TEM) was performed at a voltage of 200 kV for microstructural observation and for recording selected-area electron diffraction (SAED) patterns.

4. Results and Discussions

The average of hardness values among the upper, middle and lower surfaces was taken for each sample and plotted in Fig. 4 together with earlier data obtained by conventional HPT of Al (99.99%) using disc and ring specimens [8]. Here, the equivalent strain was estimated with s= 1/4±1/4 in eq.(1). It is apparent that the hardness values for CHPT-processed samples lie well on the steady state (saturated) level obtained for disc samples and ring samples after processing with HPT.

A TEM bright-field micrograph including an SAED pattern is shown in Fig. 5 for Al after CHPT. Inspection of Figs. 5 reveals that few dislocations are visible in the grains and that grain boundaries are straight and well defined with an average grain size of ~2.1 μm. These microstructural features are consistent with the earlier observation using conventional HPT, where an average grain size of ~1.9 μm was reported [11].

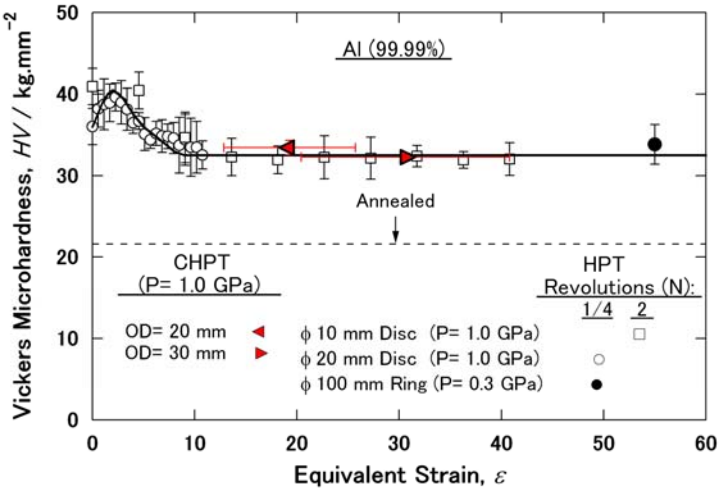

Fig. 4. Hardness value for CHPT plotted against equivalent strain in graph reported earlier using conventional HPT for disc and ring specimens of Al [8].

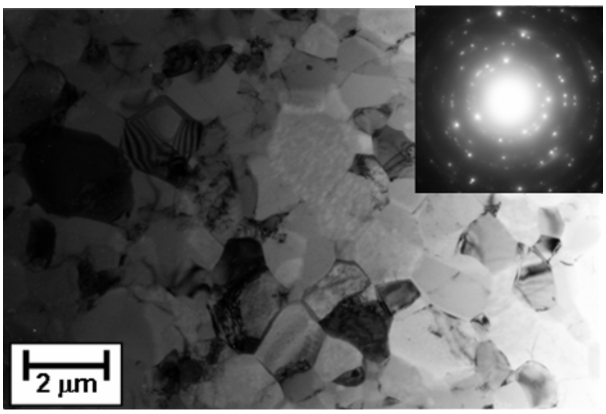

Fig. 5. Bright-field TEM micrograph and SAED pattern of Al after processing with CHPT.

The average of hardness values for Al–3%Mg–0.2%Sc after processing with CHPT is plotted in Fig. 6 together with earlier data obtained by conventional HPT using disc and ring specimens [13]. Here, the equivalent strain was calculated with s= 1/4±1/4 in eq.(1). The present results of CHPT are reasonably consistent with those of HPT-processed disc and ring samples. It is found that the hardness value for CHPT is still in the level before reaching the saturation.

The stress-strain curves are shown in Fig. 7 from tensile testing conducted at 573 K at an initial strain rate of 3.3×10^{-3} s^{-1} for Al-3%Mg-0.2%Sc before and after processing with CHPT. Following the CHPT, the tensile strength decreases from 96 MPa to 45 MPa but the total elongation to failure increases from ~40% to ~500%. It is confirmed that a superplastic elongation of ~500% is obtained by processing with CHPT. However, this elongation is insufficient when compared with 1510% reported earlier for processing with conventional HPT. The difference can be attributed to the fact that less strain is introduced as shown in Fig.6 and thus full development of ultrafine-grained microstructure is not attained. The appearance of the tensile specimens before and after testing is shown in Fig. 8. It is demonstrated that processing by CHPT enhances significant ductility, leading to the advent of superplasticity at 573 K. Another obvious difference is the presence of a serrated region on stress-strain curves of the sample before processing with CHPT, whereas such a region cannot be observed after CHPT. This could be attributed to the effect of solute atoms on dynamic strain hardening behaviour and Portevin–LeChatelier instability as often observed in alloys with solid solution hardening [14].

In summary, it is emphasized that the method of CHPT can provide a continuous process for the conventional HPT while achieving grain refinement and subsequent strengthening in metallic materials. The method of CHPT can be used for producing ultrafine-grained metallic sheets and wires and be promised as a potential process for industrial application.

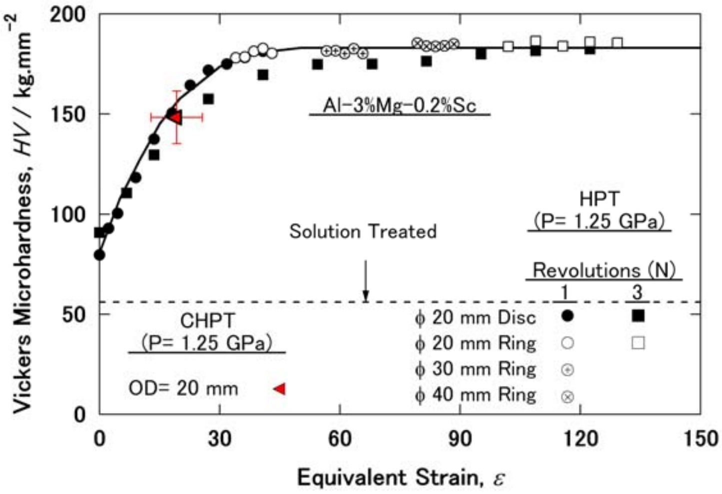

Fig. 6. Hardness value for CHPT plotted against equivalent strain in graph reported earlier using conventional HPT for disc and ring specimens of Al-3%Mg-0.2%Sc [13].

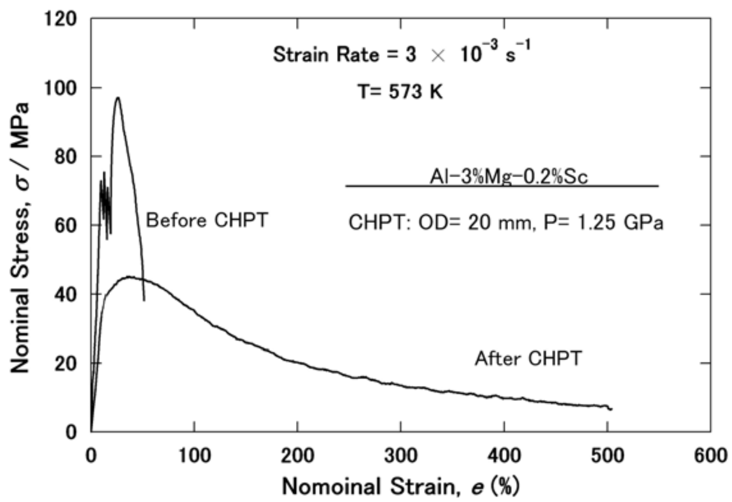

Fig. 7. Nominal stress versus nominal strain curves of Al-3%Mg-0.2%Sc before and after processing by CHPT.

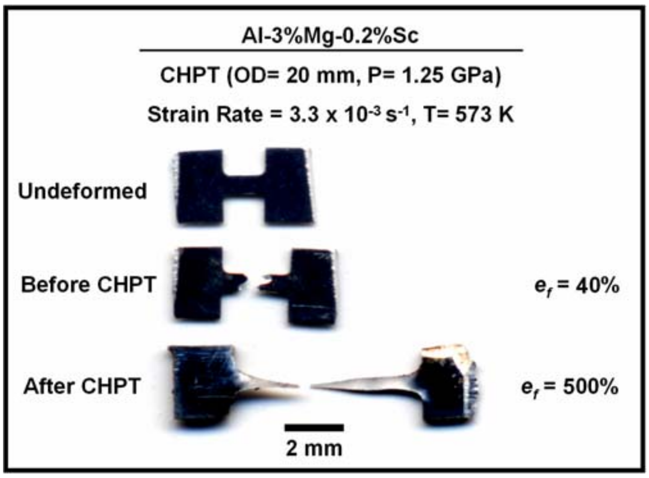

Fig. 8. Appearance of tensile specimens after pulling to failure at 573 K before and after processing by CHPT. Undeformed specimen is also included.

5. Conclusions

A new severe plastic deformation process, called continuous high-pressure torsion (CHPT), was applied to sheets of high purity Al and an Al–3%Mg–0.2%Sc alloy. The results confirmed that processing by CHPT is effective in producing ultrafine grains and subsequent enhancement of hardness in Al and the Al–3%Mg–0.2%Sc alloy. The advent of superplasticity in the Al alloys was also confirmed as in the conventional processing by HPT.

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