Experimental investigation of pure aluminum sheets processed by constrained groove pressing

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Recently, a new severe plastic deformation method named constrained groove pressing (CGP) has been invented for producing ultra-fine grained sheet metals. Here, a multi-pass CGP is carried out on 1060 commercially pure aluminum sheets. Through a series of experimental research, the evolutions of microstructure, tensile properties, forming load and surface residual stress during the process are investigated. The grain size is greatly refined from 29 µm of annealed samples to about 18 µm after pass four. Polygonized and dislocation-free substructures of submicron level with well-defined boundaries is obtained. The ultimate tensile strength and yield strength increase continuously until pass three and then decrease by further deformation. Residual tensile stress is observed on the surface of all pressed samples due to the unique stress-strain state, and it increases dramatically during the first pass. The results show that lubrication reduces the average residual tensile stress and its distribution homogeneity along the longitudinal direction.

Keywords: Constrained groove pressing, Microstructure, Strength, Forming load, Residual stress

Nowadays, bulk ultra-fine grained (UFG) materials of excellent physical and mechanical properties have been produced by severe plastic deformation (SPD)\cite{1-6}. Amongst the most common SPD methods, such as equal channel angular pressing (ECAP), high pressure torsion (HPT), and accumulative roll bonding (ARB), only ARB is available for processing plate or sheet materials. However, its practical application is limited by strict technological requirements. Instead, constrained groove pressing (CGP) is a newly developed technique for producing UFG sheet metals overcoming the disadvantages of ARB\cite{7}. Without substantial changes in dimensions, CGP imposes sufficient plastic strain to materials via alternate pressings by asymmetrically grooved dies and flat dies. Coarse grains can be refined to levels of sub-micrometer or even nanometer. Till now, this technique has been successfully applied to grain refinement and property improvement of various sheet metals, such as aluminum and aluminum alloys, copper and Cu-Zn alloys, low-carbon steel and nickel\cite{8-17}.

Numerous verifications on the availability of CGP to different materials have already been performed in laboratories, but successful application of the processed materials in various industrial fields is our ultimate purpose. For sheet metals, residual stress plays an important role in their formability. Generally, the surface of sheets suffers more intense working stress than the interior during actual processing. Thus, stress corrosion cracking and a short fatigue life tend to happen to material with residual tensile stress on the surface\cite{18,19}. Nevertheless, few reports have been concerned on the surface residual stress of SPD sheets. In this work, X-ray diffraction is adopted to measure the surface residual stress of CGP sheets. Furthermore, the forming load of dies is an important parameter during processing because it reflects the deformation characteristics and provides guidance for technical optimization in practical manufacturing. Here, the load-stroke curves for all CGP passes are investigated experimentally.

Experimental Procedure

Cold-rolled 1060 commercially pure aluminum sheets with dimensions of 100x100x2 mm\textsuperscript{3} were used. Table 1 presents the chemical composition. Before deformation, the sheets were annealed at

| Table 1 – Chemical composition of 1060 commercially pure aluminum (wt %) |
|------------------|-------|-------|-------|-------|-------|-------|-------|
| Si | Fe | Cu | Mn | Mg | Zn | V | Ti | Al |
| ≤0.25 | ≤0.35 | ≤0.05 | ≤0.03 | ≤0.03 | ≤0.05 | ≤0.05 | ≤0.03 | ≥99.60 |

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500°C for 4 h in an SX2-4-10 resistance-heated furnace utilizing high-pure nitrogen as the protective atmosphere to ensure the annealing process. Room temperature pressings were conducted on a 5000 kN computer-controlled electro-hydraulic servo compression testing machine. A constant speed of 5 mm/min was used when pressing. Molybdenum disulfide (MoS$_2$) was chosen as the lubricant. The schematic of CGP technique is shown in Fig. 1. A set of asymmetrically grooved dies and a set of flat dies are prepared, and both are tightly constrained in square containers. Firstly, groove pressing is conducted, and the gap between upper die and lower die should be kept the same with the sample thickness (Fig. 1a). Thus, the inclined region of the sample is subjected to pure shear deformation under plane strain condition while the flat region undergoes no deformation (Fig. 1b). Then, the grooved sample is flattened, and the inclined region deformed previously is subjected to reverse shear deformation while the flat region remains undeformed (Fig. 1c). After that, a rotation of the sample by 180° about the Z-axis perpendicular to the sheet plane is performed. This ensures the undeformed region to be deformed during the second groove pressing due to the asymmetry of the grooved dies (Fig. 1d, e). Finally, the successive pressings with grooved dies and flat dies result in a homogenous strain distribution throughout the sample (Fig. 1f). Generally, one CGP pass is made up of two groove pressings and two flattenings. The strain accumulated in one pass can be figured out theoretically if the groove angle is given.$^{20}$ In this experiment, the groove angle and width were designed as 45° and 2 mm, respectively. Therefore, a total effective strain of 1.16 would be obtained within the whole sample after one pass.

Optical microscope (OM) and transmission electron microscope (TEM) were employed to examine the microstructure evolution of aluminum sheets. Specimens for both were cut from the central part of the sheet plane. For OM observation, specimens were grounded orderly on abrasive papers and polished mechanically and electrolytically. The microstructure was observed via polarized light after the anodic film coated on the surface of specimens with an XJP-6A inverted metallographic microscope. The grain size was statistically measured by quantitative metallographic method. TEM specimens were conventionally prepared by mechanical polishing and ion thinning. The observation was performed on a JEM 2100 TEM operated at 200 kV.

According to ASTM E8M standard, the tensile specimens were machined with the gage dimensions of 25×6×2 mm$^3$. The gage length was aligned perpendicular to the groove direction. Room temperature tests were carried out on an INSTRON 5569 universal material testing machine. A constant cross head speed of 3 mm/min was used.

XSTRESS 3000 system was utilized to measure surface residual stress. The configuration and detailed procedure are reported elsewhere.$^{18}$ Cr K$_\alpha$ radiation ($\lambda$=2.2909 Å) was employed as X-ray source. The operation voltage and current were 30 kV and 6.7 mA, respectively. The collimator size was 4 mm, and the exposure time was 15 s. The 311-diffraction of aluminum was analyzed, and $\psi$ of 0°, 24°, 33° and

![Fig. 1 – Schematic of constrained groove pressing (CGP) technique](image-url)
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Fig. 2 – Schematic diagram of surface residual stress measurements

Fig. 3 – Optical micrograph for (a) annealed sample, and TEM micrographs with their SAED patterns for (b) annealed sample, (c) three-pass sample and (d) four-pass sample

38° were selected to plot $d \cdot \sin^2 \psi$ curves. To ensure the precision, a standard ferrite specimen was used for calibration before the measurements. In this study, surface residual stress at the sheet plane of annealed and deformed samples with and without lubrication was measured. Figure 2 shows the schematic diagram of stress measurements. Seven points were taken along the longitudinal direction with a constant gap of 15 mm.

Results and Discussion

In this work, a four-pass CGP with a total strain of 4.64 was successfully conducted on pure aluminum sheets. The microstructure evolution is shown in Fig. 3. The grain size was measured based on OM observation and given in Table 2. The as-received material mainly consists of uniform and equiaxed grains with an average size of 29 µm (Fig. 3a). Also, dislocation cells sized about 1 µm or more are evident in Fig. 3b. Submicron and dislocation-free subgrains with well-defined boundaries begin to form at pass three (Fig. 3c). In Fig. 3d, the subgrain size undergoes slight increase, and new tiny “grains” begin to appear along the boundaries, which is in accordance with the observation in ref.21. More diffused SAED pattern indicates higher misorientation angles between adjacent subgrains. Finally, the grain size estimated from OM observation is refined to 18 µm after pass four and just 62% as that of the annealed material, as given in Table 2.
Table 2 also shows the variations of tensile properties of aluminum samples with pass number. The ultimate tensile strength and yield strength increase rapidly to 101.1 MPa and 93.8 MPa after pass one, respectively. However, in the following passes, the increase slows down. After that, the ultimate tensile strength and yield strength reach their maximum values, followed by reductions at pass four. This can be explained by the dynamic recovery of dislocations and subgrain coarsening shown in Fig. 3d. Micro-cracks appeared on the sample surface during the later stages also contribute to the strength loss. The elongation decreases greatly from 53.6% to 7.4% after pass one. Then, it experiences a continuous and moderate reduction. No recovery of the elongation occurs due to flow softening, indicating that the effect of micro-cracks on tensile properties of material processed by CGP is more significant than flow softening.

For clarity, load-stroke curves of forming dies for pass one and two are displayed in Fig. 4a and b, respectively. From the figures, forming loads for all pressings can be divided into three distinct stages: rapid increase, moderate increase and second rapid increase. At the beginning of groove pressing, groove edges firstly contact and bend the sheet. After a short elastic deformation, the material begins to yield and comes to initial shearing around the groove edges, leading to the rapid increase of forming load. Then, as the upper die moves downwards, plastic deformation extends to other areas and results in the gradual increase of flow stress. Obviously, this stage covers more than one half of the total pressing time and is the main stage of the three. A relatively steady load can be observed in this stage. At last, the grooves contact the entire surface of the sheet. The sheet is forced to be the same shape as the grooved dies. Thus, another noticeable increase of forming load appears after the dies are fully closed. The load for flattening exhibits a similar variation tendency. Interestingly, a short plateau at the initial part of the second stage is observed from each flattening curve, as presented in the red circles of Fig. 4. This is substantially attributed to the constraint from the container of flat dies. Before the extension of the plastic deformation to other areas, the sheet extends along the longitudinal direction firstly and is fully constrained by the side walls of the container.

In addition, as shown in Fig. 4a, the stage division of load-stroke curves for the first groove pressing and flattening is not as clear as that for the other pressings because no strengthening was induced to the annealed aluminum sheets. It is concluded from the curves for all passes, not shown here, that the steady forming load in the second stage increases with CGP pass, and a higher increasing rate is observed during the former passes. Within one pass, the steady loads for the two groove pressings are lower than those for the two flattenings which are almost equal to those for the groove pressings of the next pass. There are several contributing factors: (i) the strengthening of material increases with pass number and saturates at a high strain magnitude, (ii) the inclined regions to be deformed in flattening have already been strengthened by shear deformation from the last groove pressing and (iii) the constraint by the side walls plays a more significant role in flattening than in groove pressing.

<table>
<thead>
<tr>
<th>Pass number</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain size (µm)</td>
<td>29.0</td>
<td>23.0</td>
<td>20.2</td>
<td>19.3</td>
<td>18.3</td>
</tr>
<tr>
<td>Yield strength (MPa)</td>
<td>23.8</td>
<td>93.8</td>
<td>98.2</td>
<td>103.6</td>
<td>93.5</td>
</tr>
<tr>
<td>Ultimate tensile strength (MPa)</td>
<td>66.9</td>
<td>101.1</td>
<td>109.1</td>
<td>111.5</td>
<td>96.4</td>
</tr>
<tr>
<td>Elongation to failure (%)</td>
<td>53.6</td>
<td>7.4</td>
<td>7.5</td>
<td>7.3</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Table 2 – Variations of grain size and tensile properties with pass number

Fig. 4 – Load-stroke curves for (a) pass one and (b) pass two
Usually, according to its deformation mode, the grooved CGP sample is simply divided into shear region, undeformed flat region and interface region\(^{22}\). In this work, based on its stress-strain state, another subdivision is proposed and shown in Fig. 5. Approximately treating the deformation of interface region as a bending process of wide sheet, each half of one groove cycle (one cycle includes four contiguous groove widths) is segmented into Regions I, II and III. The cubic stress and plane strain (\(\varepsilon_2=0\)) states of the regions are described in Fig. 5.

When groove pressing, the outer fibers (Region I) of the sheet are placed in tension while the inner ones (Region II) are placed in compression. Region I exhibits a tensile tangential stress, \(\sigma_1\) as the maximum principle stress and a tensile tangential strain, \(\varepsilon_1\) as the maximum principle strain; in contrast, Region II shows a compressive \(\sigma_1\) and a compressive \(\varepsilon_1\). Obviously, Region I covers a larger area and has a greater effect on CGP results than Region II. A transition region from Region I to II exists around Region III. Under plane strain condition, Region III is subjected to pure shear deformation. When flattening, Regions I and II change to each other, and Region III experiences reverse shear deformation. A small groove width of 2 mm in this study limits the area of Region III.

In metal forming process, an inhomogeneous deformation often causes residual stress. The stress-strain characteristics discussed above will definitely bring residual stress to the processed sheets after unloading and springback. Thus, it is required to examine the residual stress, especially on the surface. To investigate the surface residual stress distribution along the longitudinal direction, a biaxial plane stress state is assumed. The stress component, \(S_{33}\) in z-axis is zero, as shown in Fig. 2. The components in x-axis and y-axis are marked as \(S_{11}\) and \(S_{22}\), respectively. An initial stress value of nearly zero is achieved for \(S_{11}\) and \(S_{22}\) of the annealed sheets. The influences of pass number and lubrication on the distributions of both are presented in Fig. 6. Obviously, all the processed samples exhibit surface residual tensile stress. The stress value mainly fluctuates between 60 MPa and 120 MPa. Higher values and more uniform distribution of stress are observed without lubrication. No significant difference between \(S_{11}\) and \(S_{22}\) can be observed from the figures.

Table 3 presents the effects of pass number and lubrication on average \(S_{11}\). With the repetition of CGP and accumulation of plastic strain, the tensile stress increases continuously with CGP pass and shows a higher increasing rate at pass one. The improvement of deformation homogeneity and
stress-strain state slows down its increase. For the same pass, lubrication reduces the residual tensile stress effectively. At pass one, the stress decreases by nearly 20% from 86.7 MPa to 69.7 MPa with the lubrication of MoS$_2$. However, the effect of lubrication becomes weaker during the subsequent stages. For example, at the last pass, the average surface residual stresses with and without lubrication are 90.5 MPa and 94.3 MPa, respectively. The difference decreases remarkably from 17.0 MPa of pass one to 3.8 MPa.

It is the unique stress-strain state of the CGP sample that results in residual tensile stress on the surface. Friction between the sheet and dies affects the residual stress mainly by adjusting the stress-strain state. It enhances the further extension of bending influenced area (Regions I and II) to Region III. Thus, a more homogeneous distribution of residual stress is observed without lubrication. However, friction leads to micro-cracks on the surface of sheets, contributing much to a relatively high residual tensile stress, especially during further passes. Furthermore, the mean S22 given in Table 3 does not show this variation tendency like S11, indicating that the deformation at XZ plane more exactly reflects the technical features of CGP than that at XY plane.

Residual tensile stress is unfavorable in subsequent manufacturing of the processed sheets. Thus, proper technological modifications or post-processing techniques to eliminate the existing residual tensile stress must be explored. A study about the influence of post-annealing on microstructure and properties of CGP aluminum sheets is undertaken by the authors.

**Conclusions**

In this work, a four-pass CGP was carried out on commercially pure aluminum sheets. The influence of CGP on the microstructure, tensile properties, forming load and residual stress has been investigated. The main conclusions are as follows.

(i) The grain size is refined from 29 µm of the annealed sample to 18 µm after four passes.

Dislocation-free subgrains of submicron level
with well-defined boundaries are obtained. The ultimate tensile strength and yield strength have been improved significantly.

(ii) All the load-stroke curves can be divided into three stages: rapid increase, moderate increase and second rapid increase. During flattening, a short plateau appears at the beginning of the second stage.

(iii) The unique stress-strain state induces surface residual tensile stress to all the processed samples. Lubrication lowers the stress more effectively, especially during the former passes, but decreases its distribution homogeneity along the longitudinal direction.

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