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Effect of powder shape and size on mechanical properties of Al thin plate formed by compression shearing method at room temperature

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Abstract

The goal of the present study is development of high strength pure aluminum by Compression shearing method at room temperature. The powder shape and mean particle size of ultrafine-grained pure aluminum thin plate were changed using the compression shearing method at room temperature. The grain sizes of the ultrafine-grained pure aluminum thin plates were 0.5–1.2 µm. The mechanical properties of the plates were measured, and the Vickers hardness and tensile strength were determined to be 56–90 HV and 175–320 MPa, respectively. Ultrafine-grained pure aluminum thin plates were developed that can have practically any breaking elongation and strength by discretionally changing the shape and mean particle size of the powder.

Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University

Keywords: Aluminum; Powder metallurgy; Severe plastic deformation; Mechanical property; Microstructure

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1. Introduction

Aluminium and its alloys are used extensively in industrial fields. Therefore, it is desired to improve their mechanical properties and characteristics because the environments in which they are used are harsh in terms of load, temperature, and other factors. Therefore, Al and its alloys are enhanced by heat treatment and alloying. However, it is difficult to recycle. In recent years, the focus has been on enhanced materials by way of severe plastic deformation. Severe plastic deformation can be used for crystal refinement of the materials, and the mechanical properties are enhanced by the Hall–Petch relationship (Hall, 1951; Petch, 1953). In a past study, bulk material is used for the working material, and it is required to be heated. Therefore, the recrystallization of the bulk material is taken into consideration during working. Our research group developed the Compression Shearing Method at Room Temperature process (Takeishi et al., 2005), in which metal powder is loaded by shearing force and compressive stress simultaneously in air at room temperature. Since the metal powder is fabricated at room temperature, it is considered that grain coarsening does not occur in the metal thin plate, and good mechanical properties are obtained.

This study attempts to develop a high-strength pure Al thin plate formed by Compression shearing method at room temperature process, and it is revealed that the powder shape and mean particle size directly affect the mechanical properties.

Nomenclature

σ_N	Compressive stress
L	Shearing distance
t	Sample thickness
γ	Shearing strain
Al_T	Aluminum powder of teardrop shape
Al_S	Aluminum powder of sphere shape

2. Experimental setup

2.1. Compression shearing method at room temperature

Compression Shearing Method at Room Temperature (COSME-RT) is a method of forming a thin plate by simultaneously applying a shearing strain and a compressive stress to a metal powder. A schematic diagram of the COSME-RT process is shown in Fig. 1. First, metal (Al) powder is filled between a stationary plate and a moving plate. Second, compressive stress is applied to the moving plate and is maintained throughout the forming process. Third, a shearing load is applied to the moving plate, which is displaced in the shearing direction. A metal (Al) thin plate is fabricated using these steps.

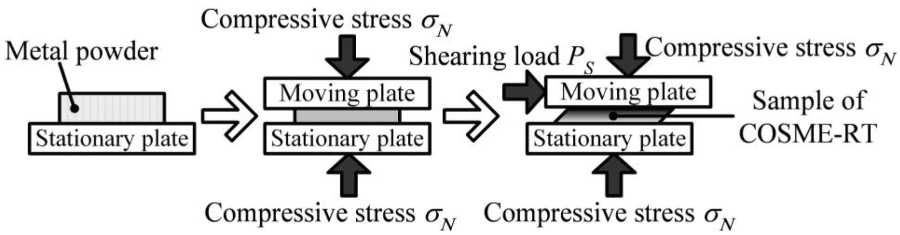

Fig. 1. Schematic illustration of COSME-RT process.

2.2. Materials

The powders used for solidification in this study include six types of pure Al powders, which are shown in Table 1. Both teardrop and sphere shapes were used, and three mean grain sizes were used for each shape. The teardrop-shape powders were produced using the gas-atomized process, and the sphere-shape powders were produced using the centrifugal spray process. The mean grain sizes of the teardrop-shape powders were 9.836 μm (Al_T-9), 31.02 μm (Al_T-31), and 84.57 μm (Al_T-84). Therefore, the mean particle sizes of the sphere powders were under 38 μm (Al_S-38), 90–106 μm (Al_S-90), and 125–150 μm (Al_S-125). The mean crystal sizes of the Al thin plate after forming by COSME-RT are also shown in Table 1 (N. Nakayama et al., 2013).

Table 1. Pure aluminum powders used for COSME-RT

	Shape	Mean particle size (μm)	Mean crystal size (μm)	Purity (%)
Al_T-9	teardrop	9.84	4.88	99.81
Al_T-31	teardrop	31.02	4.53	99.82
Al_T-84	teardrop	84.57	7.58	99.81
Al_S-38	sphere	-38	7.91	99.83
Al_S-90	sphere	90-106	2.88	99.70
Al_S-125	sphere	125-150	5.35	99.70

2.3. Forming conditions

The specimens were formed using a compression shearing apparatus (Dip Ltd., DRD-NNK-001). The shearing strain γ is defined as$\gamma = L / t$. The forming compressive stress was set at 1250 MPa, and the target size was fixed at 10 × 40 × 0.25 mm; the shearing velocity was set at 5 mm/min. The Al thin plates were formed under a shearing strain g of 20 (sliding distance = 5 mm) for each of the Al powders. Surface roughness of formed sample has 0.2 μm. In the forming process of COSME-RT, it is not desired for lubrication and moving plate and stationary plate was used for die steels.

3. Experimental procedures

3.1. Vickers hardness test

To investigate the effect of the powder shape and mean particle size of the Al powders on the mechanical properties of the formed samples, a Vickers hardness test was performed using a Micro Vickers Hardness Testing Machine (SHIMADZU, HMV-1). The test conditions were as follows: test load P = 4.903 N, and holding time = 10 s. Fig. 2 shows the relationship between the Vickers hardness and the mean particle size of the Al powder, and Fig. 3 shows the relationship between the Vickers hardness and the crystal size of the samples. The crystal size of the Al thin plate was observed using a back-scattered electron microscope (Hitachi High Technologies, SU-8000). In Figs. 2 and 3, the solid circle marks indicate the Al thin plate made with sphere powder, and the solid triangle marks indicate the Al thin plate made with teardrop powder. The break lines show the Vickers hardness of rolled aluminum.

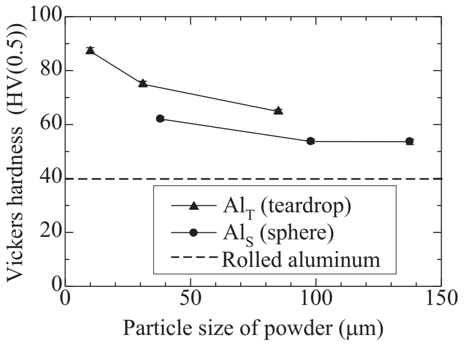

Fig. 2. Relationship between Vickers hardness and particle size of powder.

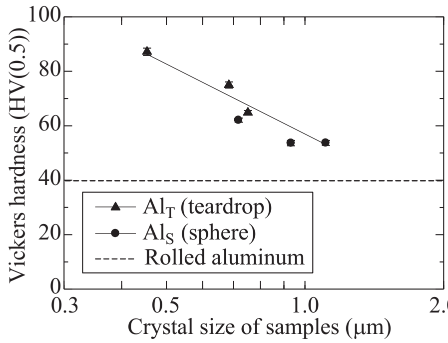

Fig. 3. Relationship between Vickers hardness and crystal size of samples.

It can be seen that the Vickers hardness of the samples can be improved with a fine particle size and refinement of the crystal size. The Vickers hardness of the teardrop Al thin plate was increased by using a sphere powder Al thin plate. Therefore, the Vickers hardness of Al_T-9 was found to increase by 2.2 times compared to the Vickers hardness of the rolled Al material (40 HV(0.5)). In turn, the Vickers hardness of Al_S-38 was found to increase by 1.35 times compared to the Vickers hardness of the rolled Al material based on Fig. 2. From the above, COSME-RT is considered useful for enhanced materials.

The relationship between the crystal grain size and the Vickers hardness is shown to be linear from Fig. 3. In summary, the crystal size decreased with an increase in the Vickers hardness. The same crystal grain size (Al_T-84 and Al_S-38) of the formed samples is shown as nearly Vickers hardness. It is thought that the crystal grain size and the tensile strength, proof stress, and Vickers hardness have a linear relationship according to Hall and Petch. Therefore, the crystal grain size of the formed samples decreased with an increase in the Vickers hardness in this study.

3.2. Tensile test

To investigate the mechanical properties, a tensile test of the Al thin plate was conducted using a small tabletop universal testing machine (SHIMADZU, EZ-L-5kN). The test condition is as follows: tensile velocity V = 0.5 mm/min. The tensile specimen shape is shown in Fig. 4.

The load-displacement curves of the Al thin plate and the rolled Al material are shown in Fig. 5. It can be seen that the tensile load increased with a decrease in the mean particle size. Therefore, the tensile loads of all of the Al thin plates formed by COSME-RT were higher than that of the rolled Al material. The tensile strength and breaking elongation were calculated from the sample thickness and the test data in Fig. 5.

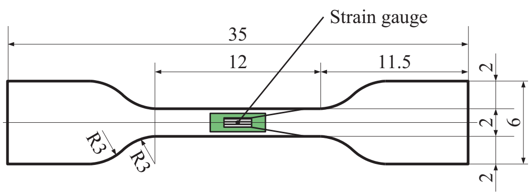

Fig. 4. Shape and dimensions of tensile test specimen.

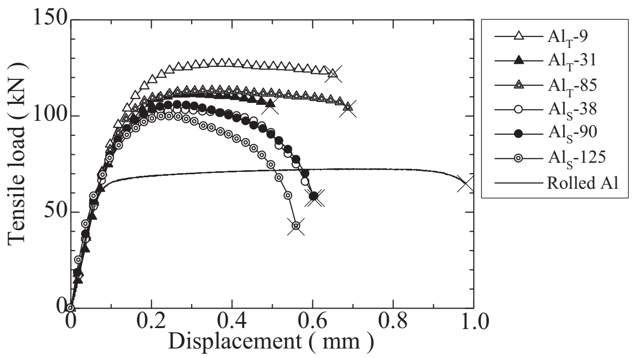

Fig. 5. Tensile load-displacement curve of Al thin plate formed by COSME-RT; here, the solid line represents the rolled Al material.

The relationship between the tensile strength and the particle size of the powder is shown in Fig. 6. The tensile strength of the teardrop powder Al thin plate is higher than those of the sphere powder Al thin plate and the rolled Al. This phenomenon is related to the Hall–Petch relationship, just as in the Vickers hardness test. Therefore, the tensile strength of Al_T-9 (320 MPa) was found to increase by 2.53 times compared to the tensile strength of the rolled Al material (126 MPa). In turn, the tensile strength of Al_S-38 (200 MPa) was found to increase by 1.6 times compared to the tensile strength of the rolled Al material from Fig. 6.

The relationship between the breaking elongation and the particle size of the powder is shown in Fig. 7. The breaking elongation of the Al thin plate increased with an increase in the particle size of the powder. Then, the breaking elongation was changed to 5–8%. In general, the tensile strength is a high value, and the breaking elongation is a low value. Therefore, the tensile strength and breaking elongation were related in inverse proportion. However, the sphere powder Al thin plates did not see a change in the breaking elongation. It is thought that the crystal grain size of the sphere powder Al thin plate has a wide range. This is because the sphere particles were made at a variety of compressive and shear stresses in the forming process. On the surface of the powder, the compressive and shearing stresses act by point contact. However, the inner powder cannot contact the rest of the powder. Therefore, the crystal grains of the inner powder cannot change size. As a result, the sphere powder Al thin plate has a wide range of crystal grain sizes.

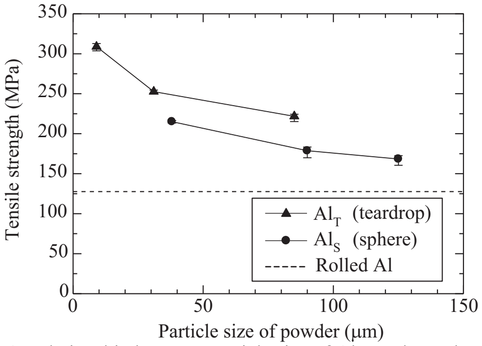

Fig. 6. Relationship between particle size of Al powder and tensile strength.

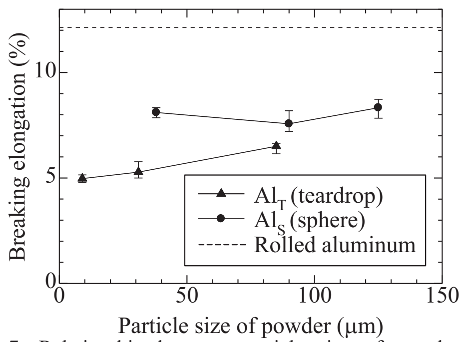

Fig. 7. Relationship between particle size of powder and breaking elongation.

Fig. 8 shows that the relationship between the tensile strength and the breaking elongation of the Al thin plates made by COSME-RT and the rolled Al. It can be seen that the relationship between the tensile strength and the breaking elongation has a curvilinear relationship. Therefore, the discretional mechanical properties of the Al thin plate could change based on the powder shape and mean particle size used in COSME-RT forming. Put simply, COSME-RT is considered useful and easily allows for the design of the material's mechanical properties.

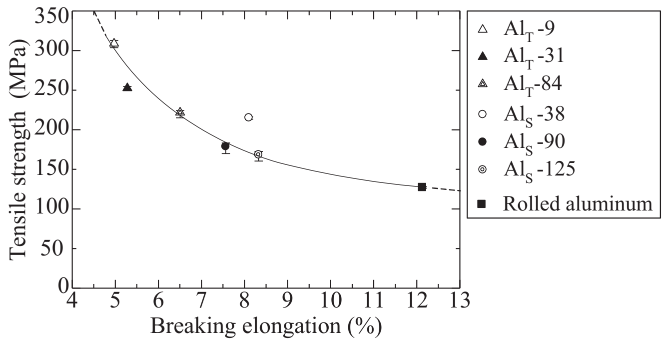

Fig. 8. Relationship between tensile strength and breaking elongation of Al thin plate formed by COSME-RT and rolled Al.

3.3. Discussions

The tensile strength and particle size of the Al thin plate made by COSME-RT has a linear relationship based on the Hall–Petch relationship. Therefore, the Hall–Petch relationship of the Al thin plate formed by COSME-RT was considered. Fig. 9 shows the relationship between the mean grain size and the 0.2% offset proof stress. It can be seen that the gradient of the Hall–Petch equation of the COSME-RT specimens was much higher than that for pure Al (N. Ono et al., 2002), and it is close to that of the oxide particle dispersed Al made by Spark Plasma Sintering (SPS) (G.M. Lee et al., 2013). It is thought that the grain refinement and oxide particles affect the gradient of the Hall-Petch equation. Therefore, the oxide content ratio and oxide shape of the Al thin plate were measured.

Fig. 10 shows the oxide content ratio of the Al thin plate made by COSME-RT. It can be seen that the teardrop powder Al thin plate is 2.3 mass% oxygen. Also, the sphere powder plate is 1.0 mass% oxygen. Fig. 11 shows a typical TEM image of the Al thin plate. It can be seen that Alumina is observed along the initial grain boundary, and it has an approximately 200 nm grain size. Therefore, grain refinement occurs and oxide particles are dispersed in Al thin plate formed by COSME-RT, which enhance the mechanical properties based on the Hall–Petch equation.

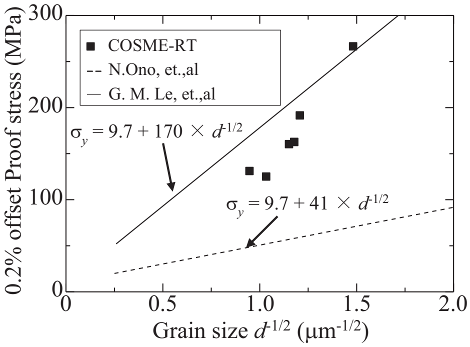

Fig. 9. Relationship between grain size $^{-1/2}$ and 0.2% offset proof stress of Al thin plate; here, the solid line is the Hall–Petch equation of Al dispersed oxide particles by SPS (G.M. Lee et al.), and the break line is the Hall–Petch equation for pure Al (N. Ono et al.).

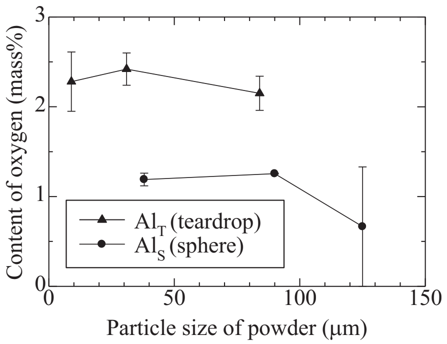

Fig. 10. Oxide content ratio of Al thin plate formed by COSME-RT.

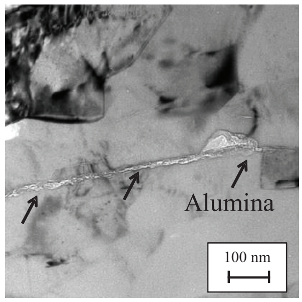

Fig. 11. Typical TEM image of Al_T-9.

Summary

The purpose of this study was to develop high-strength pure Al thin plate formed by COSME-RT, and it revealed that the powder shape and mean particle size directly affect the mechanical properties.

(1) The Vickers hardness of Al thin plate formed by COSME-RT is 56 to 90 HV(0.5). Therefore, it was found to increase by 1.35 to 2.2 times compared to the Vickers hardness of the rolled Al material (40HV(0.5)).

(2) The tensile strength of Al thin plate formed by COSME-RT is 175 to 320 MPa. Therefore, it was found to increase by 1.6 to 2.53 times compared to the tensile strength of the rolled Al material (126 MPa)

(3) The tensile strength of Al thin plate increased with a decrease in the mean particle size.

(4) Al thin plate formed by COSME-RT is 1–2.3 mass% oxygen. Also, Alumina lies in the initial grain boundary.

Finally, COSME-RT can be used to discretionally change the mechanical properties of Al thin plate by changing the powder shape and mean particle size. Therefore, COSME-RT is useful and easily allows for the design of the material's mechanical properties.

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