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ALUMINUM ALLOYS: FABRICATION, CHARACTERIZATION AND APPLICATIONS

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Development and Application

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MECHANICAL PROPERTIES OF AL-ZN-MG-CU ALLOYS PROCESSED WITH HIGH-PRESSURE TORSION

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Keywords: solute element, severe plastic deformation, work hardening, clustering

Abstract

It has been reported that tensile strength of the 7075 alloy, a commercial age-hardenable Al-Zn-Mg-Cu based alloy, is significantly improved by high-pressure torsion (HPT). The present research has been performed to study the effects of alloy compositions and process conditions on mechanical properties in Al-Zn-Mg-Cu alloys processed with HPT. Several Al-Zn-Mg(-Cu) alloys were melted and cast, and disc specimens of 10 mm diameter and 1 mm thick were machined from the homogenized ingots. The disc specimens were solution treated and subjected to HPT with a compression stress of 2 GPa at a rotation speed of 1 rpm. The torque at the steady state increased with increasing amount of alloying elements. The strength after HPT also increased with increasing amount of alloying elements. The tensile strength of Al-10%Zn-2%Mg-2%Cu alloy, in mass %, was increased to about 900 MPa by 10 turns of HPT processing.

Introduction

So far, numbers of attempts have been carried out to improve the mechanical properties of structural metallic materials by solution hardening, work hardening, precipitation hardening or grain refinement, etc. Particularly, strengthening without deteriorating ductility has been a common goal of materials scientists. The authors have been studied the deformation mechanism of a multi-functional titanium alloy, Gum Metal, which is known to have an unusual set of mechanical properties [1]. The actual strength of the alloy is very high, as documented by the results of tension tests on bulk samples of cold-worked alloy [1] and of compression tests on nanopillars [2]. In fact, the resolved shear stress required to deform nanopillars of Gum Metal in compression often approaches the computed ideal shear strength of the material [2]. It is noted that the alloy has good ductility even having very high strength. The reason for this has been attributed to the deformation mechanism without dislocation activity which operates at ideal strength [3].

It has been revealed that similar strengthening can be done in iron-based systems. An Fe-Ni-Co-Ti alloy with similar phase stability to Gum Metal has very high ultimate tensile strength (UTS) of 2.7 GPa with tensile elongation of 9 % [4]. The exact ideal strength of the Fe based alloy has not been calculated yet, but its ideal strength is roughly estimated to be near the actual strength of the alloy, where the ideal strength was calculated from the elastic properties of Fe-Ni binary alloys [4]. One of the common points in Gum Metal and the Fe-Ni-Co-Ti alloy is that very high strength is achieved by applying cold working on the super-saturated solid solution. In the case of Gum Metal, small angle X-ray scattering analysis (SAXS) has revealed that nano-sized clusters are generated during cold working [5]. Theoretical calculations on the stable alloy configurations of Gum Metal approximants have been also carried out, and revealed that inhomogeneous arrangement of solute element stabilizes crystal structure [6]. The present authors consider that the generation of nano-sized cluster during cold working detected by SAXS is responsible to suppress the dislocation activity up to very high strength level near ideal strength in Gum Metal.

Recently, it has been reported that the strength of age-hardenable Al-Zn-Mg-Cu based alloy, commercial 7075 alloy, has been improved significantly by applying high pressure torsion (HPT), one of the typical severe plastic deformation methods [7, 8]. The UTS of 7075 alloy has been raised up to 840 - 1000 MPa by HPT process without further heat treatment. The reported strength of HPT processed 7075 alloy is far higher than the peak-aged 7075 alloy with UTS of 570 MPa. Liddicoat et al. reported that such strengthening is attributed to basically four factors; grain refinement, increase in dislocation density, nano-cluster formation inside the grains and grain boundary segregation during HPT processing. Among these strengthening factors, they conclude that nano-cluster formation is the dominant factor to improve the mechanical properties of their 7075 alloy HPT processed for 10 turns at room temperature. However, the effect of alloying element on the mechanical properties and nano-cluster formation has not been known in the strengthening behavior of Al-Zn-Mg-Cu alloys processed with HPT, because the previous studies [7, 8] are performed only on the 7075 alloy with a specific chemical alloy composition.

The present small paper is intended to examine the effect of alloying elements on the mechanical behavior in HPT processed Al-Zn-Mg-Cu alloys. Here we focus on effects of zinc, magnesium and copper addition on the mechanical properties, because these elements are known to be primary important on the strengthening in the Al-Zn-Mg-Cu alloys using precipitation hardening.

Experimental Procedure

Four ingots of Al-Zn-Mg(-Cu) base alloys were melted and cast in iron mould under Ar gas flow using high purity raw metals. They were homogenized at 400 ºC for 5 hours and furnace cooled to room temperature to eliminate microscopic segregations during solidification process. The chemical compositions are shown in Table 1. It has been known that zinc and magnesium are primary alloying elements which dominate the mechanical properties of the Al-Zn-Mg-Cu base alloys. The zinc content of commercial 7075 alloy is about 5%, so an Al-5%Zn-1%Mg ternary alloy (referred as Al-5Zn-1Mg hereafter) is used as a standard alloy in the present study. The zinc content is increased to 10 % in the other alloys to study the effect of zinc on the strengthening. The content of magnesium is 1 % or 2 %, because 1 - 2.5 % Mg is often added to the commercial Al-Zn-Mg-Cu alloys. The copper has been known to increase the strength of the Al-Zn-Mg-Cu alloys, so an Al-10Zn-2Mg-2Cu alloy is used to examine the effect of copper addition.

Table 1 Chemical Compositions of the Specimens (mass %)

	Al	Zn	Mg	Cu
Al-5Zn-1Mg	bal.	5.4	1.0	
Al-10Zn-1Mg	bal.	10.9	1.0	
Al-10Zn-2Mg	bal.	10.7	2.0	
Al-10Zn-2Mg-2Cu	bal.	10.0	1.9	2.1

In general, small amount of manganese, chromium or zirconium has been always added to the commercial Al-Zn-Mg-Cu alloys to reduce the grains size after solution treatment. They often precipitate during prior homogenization process, and suppress the grain growth during solution treatment. They also affect the age-hardening behavior during aging which are intended to generate precipitation hardening, but only have indirect effect. In the present study, we focused on effects of zinc, magnesium and copper on the strengthening behavior by severe plastic deformation.

Disc specimens of 10 mm diameter and 1 mm height for HPT were prepared from the homogenized ingots. In the present study, cast and homogenized specimens were directly subjected to solution heat treatment and subsequent severe plastic deformation without intermediate hot or cold working. The disc specimens were solution heat treated at 450 ºC for 1 hour, and quenched into water. Some of the disc specimens were solution treated at 480 ºC for 5 hours, which is the same condition adopted in the previous studies. The solution treated disc specimens were placed between the upper and the lower anvils and torsion-strained by rotating the upper anvil with respect to the lower anvil at a rotation speed of 1 rpm under a compression stress of 2 GPa for 10 turns at room temperature. The torque and the compressive load, were measured during the HPT process. Small tensile test pieces were machined from the HPT processed discs to evaluate tensile properties at room temperature, where the parallel portion of the tensile specimens corresponds to the region 2.5 mm distant from the center of HPT processed disc specimens. In addition, polished surface of HPT processed disc specimens and fracture surfaces of the tensile specimens were observed using scanning electron microscope (SEM).

Results and Discussion

In the present study, mechanical properties were evaluated by torque generated during HPT process and tensile test after the HPT process. Figure 1 shows the measured torque during HPT process, which represents the resistance of specimens to plastic torsion. The specimens were deformed in torsion for 10 turns at a rotation speed of 1 rpm. The torque suddenly increases with the onset of torsion and reached at almost constant values within one turn of torsion. All the specimens show small cyclic change in torque which has the frequency of about 60 s, that is, 1 turn of torsion. This cyclic change can be attributed to inaccuracy in center position adjustment of upper and lower anvils. The shear strain of one turn appears to be large enough to saturate the work hardening in the disc specimens. However, saturating behavior was not the same in these specimens. The Al-5Zn-1Mg and Al-10Zn-1Mg alloys show slight work hardening up to 10 turns after sudden hardening within one turn. On the other hand, the Al-10Zn-2Mg and Al-10Zn-2Mg-2Cu alloys show some kind of yielding and subsequent stable flow. The disc specimen has significant strain gradient from the center to the edge after HPT process. The figure shows that higher torque was generated in the specimens with higher content of alloying elements. All the additives appear to be effective to increase the torque during HPT process.

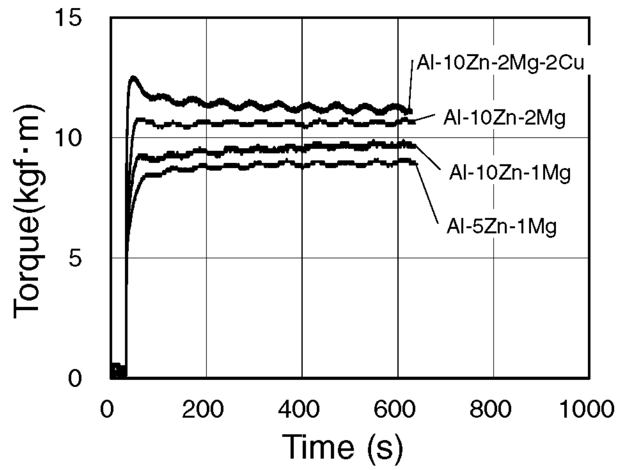

Figure 1. Torque vs. time plots during HPT process under compression load of 2GPa for 10 turns at 1 rpm in the disc specimens after solution treatment at 450 ºC for 1 hour.

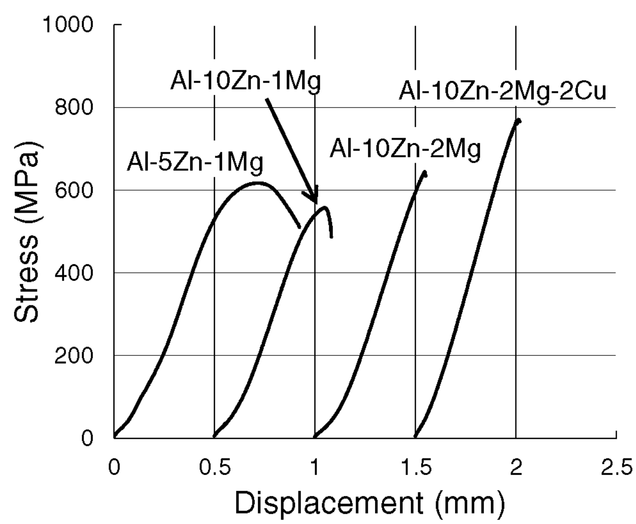

Figure 2. Stress vs. displacement curves during tensile testing in the specimens HPT processed in the same condition shown in Figure 1.

Figure 2 shows stress-displacement curves during tensile tests in the specimens after HPT processing of 10 turns. The authors expected higher tensile strength in the specimens with higher torque during HPT process. However, the result was a little different. The Al-10Zn-1Mg alloy showed lower tensile strength than the Al-5Zn-1Mg alloy with the lowest torque value during HPT, as shown in Figure 1. This can be rationalized by considering the difference in scales of strength evaluation in torque during HPT process and load during tensile tests. The measured torque represents the averaged value of resistance to torsion in the whole disc specimens during HPT process. On the other hand, the tensile load is a local value of a small tensile specimen machined from the specific part of the disc specimens. In this situation, inhomogeneous microstructure would affect the tensile properties of the small tensile specimens. Optical micrographs of the HPT processed disc specimens showed that the microstructure was very inhomogeneous where deformation appeared significantly inhomogeneous. This may be attributed to the coarse as-cast microstructure. In the present study, any hot or cold working was not conducted to characterize the mechanical properties under the simplified manufacturing procedure. So, such inhomogeneous nature of the present specimens will be removed if hot and cold working process will be done before solution treatment.

Figure 1 and 2 show that increasing amount of alloying elements generally increases the strength during and after HPT process. Among the tested specimens, Al-10Zn-2Mg-2Cu alloy exhibit very high UTS after HPT for 10 turns, 780 MPa, which is far higher than that in the precipitation hardened 7075 alloy at peak-aged state, 570 MPa. However, this value is smaller than the previously reported value of UTS in HPT processed 7075 alloy, 840 - 1000 MPa [7, 8]. Since the reason for this difference is considered to be lower solution treatment temperature in the present study, solution treatment at higher temperature was conducted on the Al-10Zn-2Mg-2Cu alloy. Figure 3 compares the stress-displacement curves of the alloys HPT processed for 10 turns after solution treatment at 450 ºC for 1 hour and at 480 ºC for 5 hours. This figure shows clearly that raising solution treatment temperature increases the tensile strength of the HPT processed specimen. The UTS of the alloy is as high as 875 MPa when solution treated at 480 ºC for 5 hours before HPT, which is comparable to the data in the previous studies.

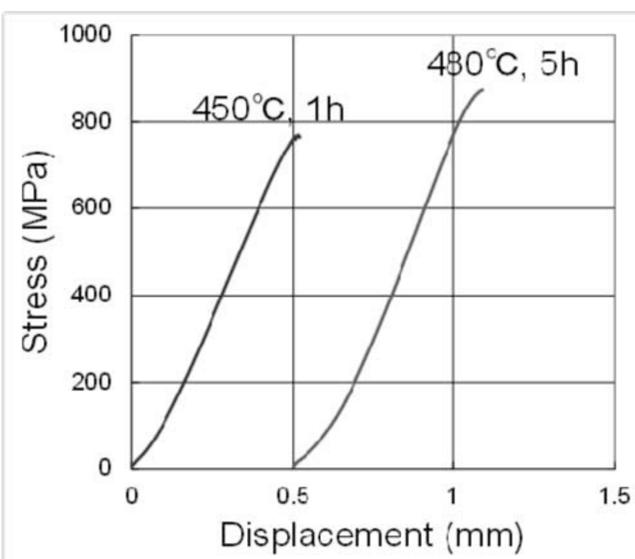

Figure 3. Stress vs. displacement curves during tensile tests of the Al-10Zn-2Mg-2Cu specimens.

Figure 4 shows the results of polished surface observation by SEM. In the specimens solution treated at 450 ºC, large particles exist after 1 turn of HPT, and they appear to be divided into smaller pieces after 10 turns of HPT. On the other hand, amount of particles are smaller in the specimens solution treated at 480 ºC, and the size of the particles does not change by HPT process. This means that increasing solution treatment temperature is effective to dissolve the part of the large particles during solution treatment and increase the solute content of the alloying elements after quenching at room temperature. Anyway, the results obtained in the present study indicate that higher solution content in the initial state leads to higher strength after HPT process.

As shown in Figure 3, the tensile ductility of HPT processed Al-10Zn-2Mg-2Cu alloys is not so large even in the specimen solution treated at 480 ºC for 5 hours with reduced amount of second phase particles. This may be also due to the inhomogeneous deformation microstructure mentioned above. SEM observations on the tensile specimens revealed that the fracture surface was covered by numerous microdimples which indicate that the fracture basically proceeded with a ductile fracture mechanism. However, SEM observations in lower magnifications revealed that large cracks of from 100 μm to some mm exist on the fracture surface. These large cracks seem to be formed during HPT process and spoil the tensile ductility in subsequent tensile tests.

Regarding the strengthening mechanisms in the present specimens, we have to consider the effect of grain refinement, increase in dislocation density, nano-cluster formation inside the grains and grain boundary segregation during HPT processing. The results in the present study shows that significant strengthening can be achieved by HPT process in the specimens with higher solute content even with the rather disadvantageous initial state of coarse as-cast microstructure. This substantial effect of solute content implies that nano-cluster formation inside the grains or grain boundary segregation during HPT processing has a significant role in strengthening. Further considerations will be required to make clear the strengthening mechanism in the present study.

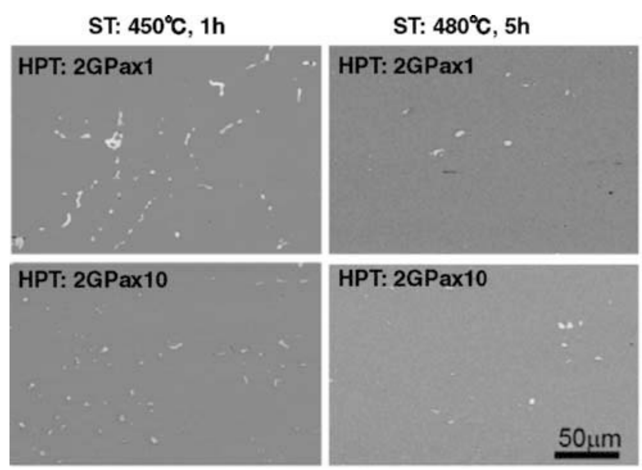

Figure 4. SEM images of the Al-10Zn-2Mg-2Cu specimens.

Summary

The present research has been performed to study the effects of alloy compositions and process conditions on mechanical properties in Al-Zn-Mg-Cu alloys processed with HPT. Mechanical properties were evaluated by torque generated during HPT process and tensile test after the HPT process.

1. The shear strain of one turn appears to be large enough to saturate the work hardening in the disc specimens. However, saturating behavior was not the same in these specimens.
2. The Al-10Zn-1Mg alloy shows lower tensile strength than the Al-5Zn-1Mg alloy with the lowest torque value during HPT. This can be rationalized by considering the difference in scales of strength evaluation in torque during HPT process and load during tensile tests.
3. The Al-10Zn-2Mg-2Cu alloy exhibits very high UTS after HPT for 10 turns, 780 MPa, which is far higher than that in the precipitation hardened 7075 alloy at peak-aged state, 570 MPa. However, this value is smaller than the previously reported value of UTS in HPT processed 7075 alloy, 840 - 1000 MPa.
4. Raising solution treatment temperature increases the tensile strength of the HPT processed specimen. The UTS of the alloy is as high as 875 MPa when solution treated at 480 ºC for 5 hours before HPT, which is comparable to the data in the previous studies.
5. The results in the present study shows that significant strengthening can be achieved by HPT process in the specimens with higher solute content even with the rather disadvantageous initial state of coarse as-cast microstructure.

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