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MECHANICAL PROPERTIES OF Al-(8, 10)%Zn-2%Mg-2%Cu BASE ALLOYS PROCESSED WITH HIGH-PRESSURE TORSION

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Abstract

It has been reported that ultimate tensile strength of commercial 7075 alloy is improved up to about 1 GPa by high-pressure torsion (HPT), which is one of the typical methods of severe plastic deformation. In the present study, Al - (8, 10) % Zn - 2 % Mg - 2 % Cu - 0.25 % Cr - (0, 1) % Fe alloys, in mass %, were prepared by high-pressure die-casting (HPDC) or by gravity casting (GC) to study the effect of process conditions before HPT process on the mechanical properties after HPT. The tensile strength of the alloy HPTed at 2 GPa was increased up to 900 MPa, irrespective of process conditions before HPT. On the other hand, the process conditions affected the tensile elongation; the specimens prepared by HPDC show higher ductility than those by GC. This result is related to size and distribution of second-phase particles.

Introduction

Generally, the strength of aluminum alloy is effectively raised by precipitation hardening. Typical conventional high-strength aluminum alloys such as 2000 and 7000 series alloys are strengthened by aging, which is a heat treatment required for precipitation hardening. However, recent researches on severely deformed aluminum alloys have revealed that cold working is more effective method to strengthen the aluminum alloys than aging. It has been reported that the strength of age-hardenable Al-Zn-Mg-Cu based alloy, commercial 7075 and 7475 alloy, has been improved significantly by applying high-pressure torsion (HPT), one of the typical severe plastic deformation methods [1-3]. The ultimate tensile strength (UTS) of 7075 alloy has been raised up to 840 - 1000 MPa by HPT process without any 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 [2]. 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. On the other hand, Valiev et al. reported that grain boundary segregation is the dominant factor to raise the strength of their 7475 alloy processed with HPT for 10 turns at room temperature [3]. The present authors also have studied the microstructure of the HPTed 7075 alloy, and revealed that zinc, magnesium and copper significantly concentrate to the grain boundaries [4].

In addition to the mechanism for strengthening, the effect of alloying element on the mechanical properties and microstructure formation has not been known in the strengthening behavior of Al-Zn-Mg-Cu alloys processed with HPT, either. This is because the previous studies [1-4] are performed only on the 7075 or 7475 alloy with a specific chemical alloy composition. Regarding this, the present authors have reported the effect of alloying elements on the mechanical behavior in HPT processed Al-Zn-Mg-Cu alloys [5]. In the previous paper, we focused on effects of zinc, magnesium and copper addition on the mechanical properties, because these elements are known to be important on the strengthening in the Al-Zn-Mg-Cu alloys using precipitation hardening. We found that the Al-10Zn-2Mg-2Cu alloy exhibited very high UTS after HPT for 10 turns, 875 MPa, which is similar to that in the HPTed 7075 and 7475 alloy [1-4]. The results in our pervious study also showed that significant strengthening can be achieved by HPT process in the specimens with the rather disadvantageous initial state of coarse as-cast microstructure. However, the effects of initial microstructure before HPT process on the mechanical properties have been unknown. The present small paper is intended to examine the effect of chromium and iron additions on the mechanical properties of HPTed Al-Zn-Mg-Cu alloys, since these additives are known to form second phase particles, which affect the mechanical behavior.

Experimental Procedure

Four ingots of Al-Zn-Mg-Cu-Cr base alloys were prepared by high-pressure die-casting (HPDC) or by gravity casting (GC) to study the effect of process conditions before HPT process on the mechanical properties after HPT. The chemical compositions are shown in Table I, where the one of the commercial 7075 aluminum alloy is also shown as a reference. They were heated to 450 °C at a rate of 35 °C/min, homogenized at 450 °C for 18 hours and furnace cooled to room temperature to eliminate microscopic segregations during solidification process. A part of the homogenized GC ingots were cut into rectangular bars of 20 x 20 x 100 mm^3 and subjected to hot rolling at 400 °C to reduce the defects introduced during casting process. The reduction of hot rolling is 50 %. The hot rolled specimens are referred as GCHR, gravity cast and hot rolled.

Table I. Chemical Compositions of the Specimens (mass %)

Sample	Al	Zn	Mg	Cu	Cr	Fe
8Zn-0Fe	bal.	8.0	2.0	1.9	0.26	0.12
8Zn-1Fe	bal.	8.1	1.9	2.0	0.26	1.06
10Zn-0Fe	bal.	9.9	2.0	2.0	0.27	0.12
10Zn-1Fe	bal.	10.0	2.0	2.0	0.26	1.10
7075	bal.	5.6	2.5	1.6	0.23	<0.5

Discs of 10 mm diameter and 1 mm height for HPT were prepared from the HPDC, GC and GCHR specimens. The disc specimens were solution heat treated at 480 °C for 5 hours, and quenched into water. 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 1 or 10 turns at room temperature. There was no evidence of slippage on the surface of the HPT-processed specimens, so we consider that compressive stress of 2 GPa is enough to prevent the slippage between the anvils and the specimen. 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 distance from the center of HPT processed disc specimens. In addition, polished cross-sectional surface of the disc specimens along their diameter was subjected to micro-hardness measurement and observed using scanning electron microscope (SEM).

Results and Discussion

In the present study, mechanical properties were evaluated by micro-hardness measurements and tensile tests after the HPT process. Figure 1 shows the examples of hardness map obtained in the HPTed specimens, which represents the inhomogeneous distribution of mechanical strength after HPT process. This inhomogeneity is attributed to the strain gradient which exists in the disc specimen [6]. In the present study, we evaluate tensile properties from the region 2.5 mm distant from the center of HPT processed disc specimens, where the averaged hardness is raised up to HV232 after 1 turn, and HV240 after 10 turns of HPT process in the case of 10Zn-0Fe GCHR specimen shown in the figure. Results on other specimens, which are not shown in the figure, revealed that the averaged hardness in such region was ranging from HV210 to HV260 after HPT process. The 10Zn series specimens tend to show higher hardness than 8Zn series specimens, though the effect of the process conditions before HPT was not clear.

The tensile properties after 1 turn of HPT process are compared in Fig. 2. The UTS, as shown in Fig. 2(a), is ranging from 700 to 900 MPa. It is surprising that even 1 turn of HPT process can raise the UTS very effectively. However, the effect of process conditions before HPT is not clear, which is basically the same tendency as the results of hardness measurement. The elongation to failure is shown in Fig. 2(b), which reveals that addition of iron suppresses ductility. In addition, process condition also affects the elongation; GC specimens tend to have lower ductility. In many cases, HPDC and GCHR specimens have higher ductility than GC specimens. This implies that second-phase particles containing iron promotes the premature failure at smaller tensile strain in GC specimens. The effect of second-phase particles will be discussed later.

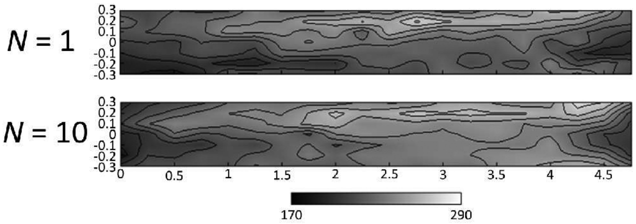

Figure 1. Micro-Vickers hardness distribution in the 10Zn-1Fe (GCHR) specimens after 1 turn (N = 1) and 10 turns (N = 10) of HPT process. Results of measurement are shown as 2D maps.

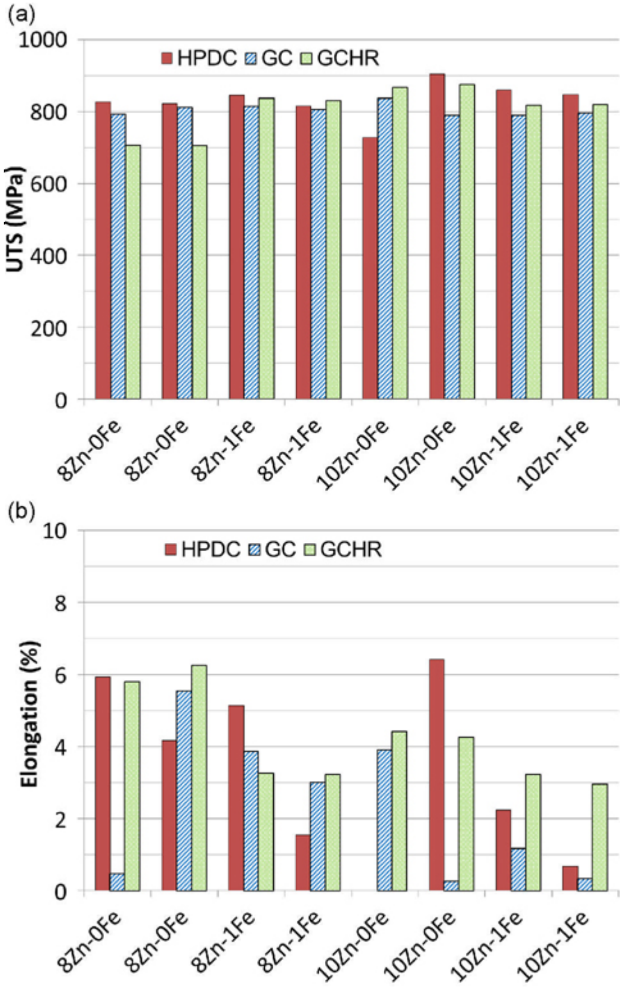

Figure 2. Results of tensile tests in the specimens processed with HPT for 1 turn. (a) UTS, (b) elongation.

The tensile properties after 10 turns of HPT process are compared in the Fig. 3. Some of the GCHR specimens have large cracks and tensile test could not be made. The UTS, as shown in Fig. 3(a), is ranging from 400 to 900 MPa, which implies that hardening by HPT processing saturates after 1 turn of HPT and the specimens were processed under a steady state after that. The elongation to failure is shown in Fig. 3(b), which reveals that ductility is generally lower in these specimens than in those after 1 turn of HPT process shown in Fig. 2. The ductility is too small for the applied stress to reach the yield point in some specimens; their UTS are very small since they failed during elastic deformation. These results imply that huge amount of strain causes large cracks during 10 turns of HPT processing, resulting in small tensile ductility. However, it is noted that HPDC specimens generally show high UTS and two of them show good ductility.

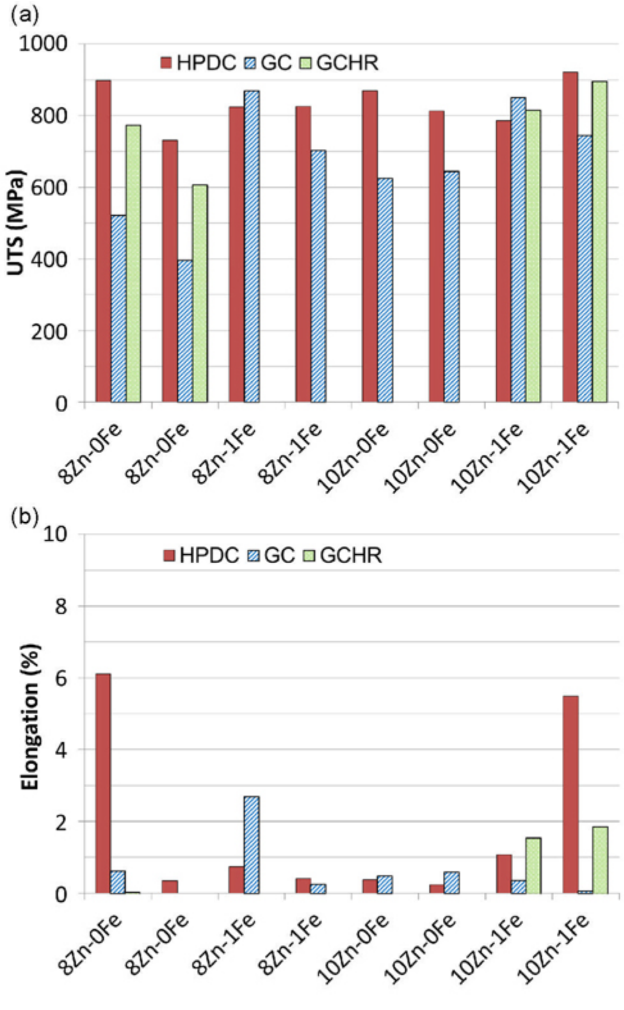

Figure 3. Results of tensile tests in the specimens processed with HPT for 10 turns. (a) UTS, (b) elongation.

Some stress-strain curves during tensile tests of 10Zn-0Fe and 10Zn-1Fe HPDC specimens are shown in Fig. 4. The 10Zn-0Fe specimen after 1 turn of HPT process exhibits very high UTS of 900 MPa together with 7 % of total tensile elongation. It is noted that such effective strengthening with good ductility has never been reported before in the specimens with only 1 turn of HPT processing. In many cases, such strengthening can often be achieved by 10 or more turns of HPT processing [2, 3]. So the present data is very important in the practical point of view.

The same alloy specimen after 10 turns of HPT process has almost the same strength but smaller elongation. SEM observations of this specimen 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. On the other hand, the 10Zn-1Fe specimen shows large ductility even after 10 turns of HPT process. It shows very high UTS of 920 MPa and 5.5 % of total tensile elongation. SEM observations of this specimen revealed that the fracture surface is covered with ductile dimples and there is no large crack on the fracture surface.

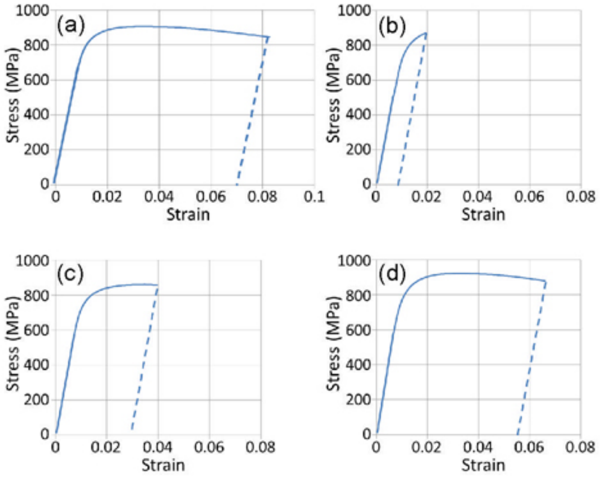

Figure 4. Stress-stain relationship during tensile tests for the (a), (b) 10Zn-0Fe and (c), (d) 10Zn-1Fe specimens. (a), (c) $N = 1$, (b), (d) $N = 10$.

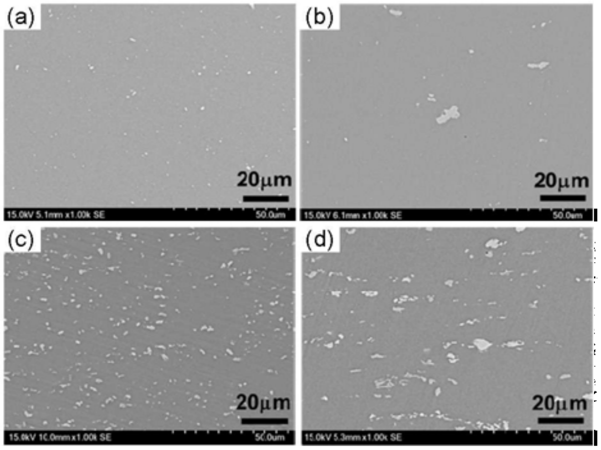

Figure 5. SEM images of the polished surface of (a), (b) 10Zn-0Fe and (c), (d) 10Zn-1Fe specimens after 10 turns (N = 10) of HPT process. (a), (c) HPDC, (b), (d) GC specimens.

Figure 5 shows the results of polished surface observation by SEM. Here we compare the effect of iron addition in 10Zn series specimens. The iron content in the 10Zn-0Fe specimens is 0.12 % whose origin is pure aluminum ingot with 99.7 % purity. These 10Zn-0Fe specimens have small amount of iron containing second-phase particles as shown in Fig. 5 (a, b), which formed during solidification process. The size of the particles is larger in the GC specimen, which can be attributed to the slower cooling rate in gravity casing. The 10Zn-1Fe specimens have large amount of such second-phase particles as shown in Fig. 5 (c, d). The size of the particles is larger in the GC specimen, which is similar tendency in the 10Zn-0Fe specimens. The size and distribution of the second-phase particles in GCHR specimens are basically the same as those in GC specimens, though the results are not shown in the figure.

The results of tensile tests in the present study indicate that tensile ductility is strongly affected by second-phase particles. Especially, in the GC and GCHR specimens with larger particles tend to show small ductility after 10 turns of HPT process. The large particles are likely to act as initiation sites for cracking during HPT process, and such cracks deteriorate the tensile ductility. GCHR specimens show good ductility after 1 turn of HPT process, which may be attributed to the decrease in large pores by hot rolling. So the strain accumulated by 1 turn of HPT process may not be enough for generating large cracks in the GCHR specimens. On the other hand, second-phase particles in HPDC specimens are small, even in 10Zn-1Fe specimens, which results in larger tensile ductility. Amount of defect like pores would be smaller in HPDC specimens, which also contributes to suppress cracking during HPT process.

In the present study, the increase in revolution failed to produce any further strengthening effect after 1 turn of HPT, as shown in Figs. 2 and 3. It is possible that the hardening by HPT processing saturates after 1 turn of HPT and the specimens were processed under a steady state, as mentioned above. This behavior must be confirmed by further experiments in future, since there has been no report on the strength of Al-Zn-Mg alloys in the initial state of HPT processing. However, significant strengthening with good ductility in the present specimens with 1 turn of HPT, as shown in Fig. 4, is very important, since such strengthening with smaller amount of cold work is potentially favorable for practical use.

Summary

The present research has been performed to study the effects of second-phase particles on mechanical properties in Al - (8, 10) % Zn - 2 % Mg - 2 % Cu - 0.25 % Cr - (0, 1) % Fe alloys processed with HPT. The alloys were prepared by high-pressure die-casting (HPDC) or by gravity casting (GC), and part of the GC samples were subjected to hot rolling (GCHR) to study the effect of process conditions before HPT process on the mechanical properties after HPT. Mechanical properties were evaluated by hardness measurement and tensile test after the HPT process.

1. The ultimate tensile strength of the alloy HPTed at 2 GPa for 1 turn increases to 700-900 MPa irrespective of process conditions before HPT. The process conditions affect the tensile elongation; the specimens prepared by HPDC and GCHR show higher ductility than those by GC.
2. The ultimate tensile strength of the alloy HPTed at 2 GPa for 10 turns increases to 400-900 MPa. The specimens prepared by HPDC show higher strength than those by GC and GCHR.
3. The size of the particles is larger in the GC and GCHR specimens, which can be attributed to the slower cooling rate in gravity casing. Such large particles deteriorate ductility.
4. The 10Zn-1Fe specimens have large amount of such second-phase particles, but the tensile ductility in the HPDC specimen is not spoiled by the particles. This can be attributed to smaller size of the particles in the HPDC specimens.

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