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Hardness Development of Mechanically-Bonded Hybrid Nanostructured Alloys through High-Pressure Torsion

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Abstract. Processing through the application of high-pressure torsion (HPT) provides significant grain refinement in bulk metals at room temperature. These ultrafine-grained (UFG) materials after HPT generally demonstrate exceptional mechanical properties. Recent reports demonstrated the bulk-state reactions for mechanical bonding of dissimilar lightweight metal disks to synthesize hybrid alloy systems by utilizing conventional HPT processing. Accordingly, the present report provides a comprehensive summary of the recent work on processing of several UFG hybrid alloy systems including Al-Mg and Al-Cu by HPT under 6.0 GPa at room temperature and a special emphasis was placed on understanding the evolution of hardness. This study demonstrates a significant opportunity for the application of HPT for a possible contribution to current enhancements in diffusion bonding, welding and mechanical joining technologies as well as to an introduction of hybrid engineering nanomaterials.

Introduction

Non-ferrous metals including aluminum (Al) and magnesium (Mg) are conventional lightweight metals which are widely used for structural applications in the automotive, aerospace and electronic sectors. Copper (Cu) is also an important engineering material for such industries, especially in consideration of electrical properties. Thus, improvements in the mechanical properties and the development of additional functionalities for these metals and alloys are becoming indispensable for enhancing their future applications.

To convert coarse-grained bulk metals into a material with ultrafine or nanoscale grains, it is necessary to impose exceptionally high strain on the material which introduces a high density of dislocations. The dislocations subsequently re-arrange forming an array of grain boundaries in the microstructure. This "top-down" approach to produce severe plastic deformation (SPD) has been studied intensively for the last three decades. Among the studied SPD techniques, high-pressure torsion (HPT) processing is well recognized for producing engineering materials having true nanometer grains [1] and the fundamental principles of the HPT processing technique were well described in an earlier review [2].

In order to break through the saturation in microstructural refinement and thus mechanical properties in UFG metals, a recent study demonstrated the synthesis of high performance nanocrystalline materials by mechanically bonding dissimilar bulk metals during grain refinement through SPD techniques. Specifically, the present research uses conventional HPT processing to demonstrate mechanical bonding of Al with Mg and Al with Cu for producing multi-layered Al-Mg and Al-Cu systems and ultimately introducing intermetallic compound phases within the nanostructured bulk alloys at room temperature (RT). This report summarizes a series of recent reports for describing the examinations of the deformed structure and hardness. Special emphasis was placed for analyzing the hardness evolution to demonstrate a new model of the hardness development for the mechanically-bonded hybrid nanocrystalline Al alloy systems through HPT.

Synthesis of an Al-Mg Hybrid System by HPT

A unique approach for the mechanical bonding of separate Al and Mg disks by utilizing HPT was conducted for 5-10 turns [3-5] and for 20 turns [6] at RT by stacking three disks in the order of Al/Mg/Al for producing multi-layered structures in an Al-Mg system. Specifically, the applied Al and Mg disks were prepared from separate conventional metals of Al (Al-1050 alloy) and Mg (ZK60 alloy) and these were mechanical bonded by HPT under 6.0 GPa at 1 rpm using a unique sample set-up as schematically shown in Fig. 1(a) [3].

The cross-sectional microstructures are shown in Fig. 1(b) for the mechanically-bonded Al-Mg disks after, from top, 1, 5, 10 and 20 turns [3-6] where a brighter phase represents an Al-rich phase and a darker region represents a Mg-rich phase. The interfaces of the separate phases are well bonded without any segregation even in an early stage of HPT after 1 turn. A gradual mixture of the Al and Mg phases is apparent from the disk edges with increasing numbers of turns by observing the fragmentations of the Mg-rich phase at the disk peripheral regions. Significant grain refinement was achieved especially at the disk edges where the highest straining is introduced during HPT. A representative microstructure taken by transmission electron microscopy (TEM) was shown in Fig. 1(c) for the Al-Mg disk edge after 20 HPT turns [6]. The measurement showed the region achieved a reasonable equiaxed grain structure with an average grain size of $d \approx 60$ nm.

Further detailed examinations by TEM demonstrated that the fragmented Mg-rich phase was dissolved into the Al matrix at the disk edges after 10 and 20 turns [3-6]. Thus, no presence of Mg-rich phase was observed, but instead the existence of Al-Mg intermetallic compounds was observed at the disk edges after 10 and 20 turns [3,6]. Moreover, the presence of the Al-Mg intermetallic compounds was confirmed by X-ray diffraction (XRD) analysis for the Al-Mg system after HPT for 10 and 20 turns [3,4,6]. In practice, a large content of $Al_{12}Mg_{17}$ was observed in the obtained XRD profile taken for the disk edges after 20 HPT turns as shown in Fig. 1(d) [6].

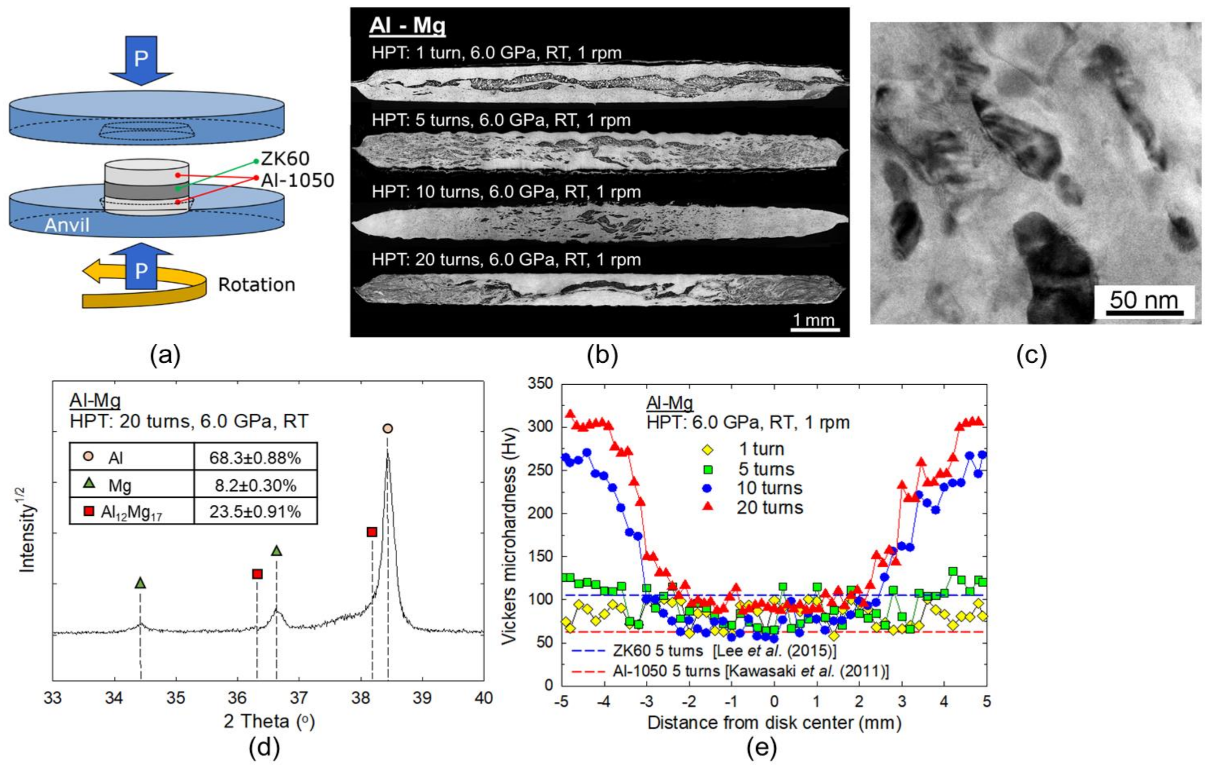

Figure 1. (a) Schematic illustration of the sample set-up for HPT processing [3], (b) an overview of the microstructure at the vertical cross-sections for Al-Mg after HPT for 1, 5, 10 and 20 turns [3-6], (c) a TEM micrograph and (d) XRD profile for the Al-Mg systetm after 20 HPT turns [6] and (e) values of the Vickers microhardness at the mid-sections on the cross sections for Al-Mg after HPT for 1, 5, 10 and 20 turns [3-6].

Vickers microhardness across the disk diameter was measured at the mid-sections on the Al-Mg system after HPT up to 20 turns and the hardness variations against the distance from disk center are shown in Fig. 1(e) [3-6]. The lower dots show the reference hardness values of UFG Al and Mg after grain refinement by HPT for 5 turns [7,8]. Contrasting the hardness variations with the microstructures in Fig. 1(b), it is concluded that exceptional hardness can be achieved by the severe mixture of Al and Mg through accelerated diffusion bonding leading to the formation of intermetallic compounds at the disk edges and the trend extends with increasing numbers of HPT turns up to 20.

It should be noted that the mechanically-bonded Al-Mg alloy disks up to 20 HPT turns form a gradient-type microstructure or a heterostructure [9] which involves gradations of not only grain and phase sizes but also phase fractions and compositions. However, a very recent report presented an achievement of homogeneous microstructure and hardness distributions with d = 30 nm and Hv ≈ 330, respectively, across the mechanically-bonded Al-Mg disk when HPT processing was applied for an extended rotation towards 100 turns under 6.0 GPa [10].

Synthesis of an Al-Cu Hybrid System by HPT

For examining the feasibility of the mechanical bonding by HPT processing, a further examination was conducted for producing an Al-Cu system through 10, 20, 40 and 60 turns by HPT under 6.0 GPa at RT from the commercial purity Al and Cu by stacking them in the order of Al/Cu/Al [11]. Overviews of the cross-sections of the Al-Cu disks are shown in Fig. 2(a) for 10-60 turns. The mid-height regions with light-grey color denote the Cu phase, bright color regions locating mostly at the central disk surfaces denote the Al phase, whereas the dark grey color at the disk edges may describe a complete mixture of Al and Cu.

The Al-Cu system demonstrated a consistent trend of microstructural evolution with the Al-Mg systems during HPT with increasing numbers of turns. Specifically, the Al-Cu disks showed a multi-layered microstructure in a wide central region up to a distance from disk center, r, of ~ 3-4 mm while the disk edge at r > 4 mm contained a mixture of very fine Cu phases within the Al matrix after 10 HPT turns. With increasing numbers of HPT turns for 20 and 40, a gradual expansion was observed in the severely mixed edge regions. HPT processing through 60 turns demonstrated a significant reduction in the central region to r <2 mm and instead formed the widened peripheral region with a severe mixture of Al and Cu.

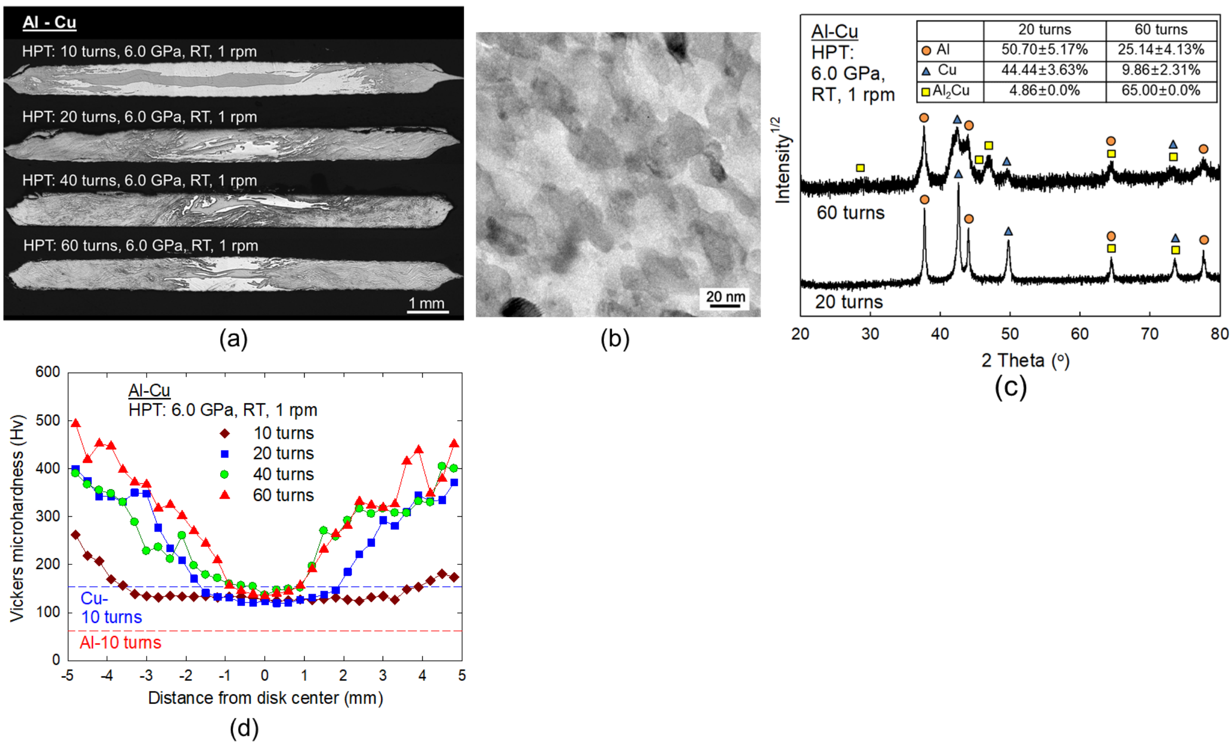

Figure 2. (a) An overview of the microstructure at the vertical cross-sections for Al-Cu after HPT for 10, 20, 40 and 60 turns, (b) a TEM micrograph at the edge of the Al-Cu 60 turns disk, (c) XRD profile after 20 and 60 HPT turns and (d) values of the Vickers microhardness at the mid-sections on the cross-sections for Al-Cu after HPT through 60 turns [11].

A refined microstructure at the Al-Cu disk edge through 60 HPT turns is shown with a representative TEM micrograph in Fig. 2(b) [11]. Significant grain refinement was achieved to demonstrate true nanostructure with an average grain size of $d = 30$ nm in an equiaxed microstructure. In the wide peripheral region, the Cu phase was completely dissolved into the Al matrix and there was no evidence of the Cu-rich phase. With the activated diffusion activity, the nucleation of Al-Cu intermetallic compounds was observed by XRD where the XRD line profiles are shown in Fig. 2(c) for the Al-Cu disk edges after HPT for 20 and 60 turns [11]. Although there is a detection of Cu which may be removed completely due to the inhomogeneous distributions of the phases, a significant reduction in the Cu phase and instead an increase in the volume of an Al_2Cu intermetallic compound was observed at the disk edges with increasing HPT turns from 20 to 60.

The Vickers microhardness was measured at the mid-height along the disk diameters of the Al-Cu disks after HPT for 10, 20, 40 and 60 turns. A summary of the hardness distribution is shown in Fig. 2(d) where the hardness of the base metals of Al and Cu after 10 HPT turns are denoted by the dashed lines at Hv ≈ 65 and ~150, respectively [11]. The central regions of r <3-4 mm after 10 turns, r <2 mm after 20 turns and r <1 mm after 40-60 turns holding the layered microstructure as seen in Fig. 2(a) demonstrated the lower hardness which is consistent with the hardness of the base material of Cu processed by HPT for 10 turns. However, the hardness at the peripheral regions recorded exceptional hardness values of Hv ≈ 250, 400 and 500 with increasing numbers of turns to 10, 20 and 40, and 60, respectively. Overall, a consistent trend in structural changes and the hardness development was observed in the mechanically-bonded hybrid Al-Mg and Al-Cu systems.

Hardness Development Model for the Mechanically-Bonded Hybrid Al Alloys

It was defined that there are three different models of the hardness developments for UFG metals processed by HPT depending on the melting temperature, T_m, of the material [12]. Specifically, the behavior depends on the computed homologous temperature of processing (T/T_m) where the processing temperature, T, of HPT is generally at room temperature. Many engineering metals and alloys show a behavior of hardening without recovery where the hardness values increase logarithmically with increasing straining by HPT. The base metals of Al-1050, ZK60 Mg alloy and commercial purity Cu demonstrate a consistent hardness development when they are processed by HPT separately and these metals show the hardness saturations with increasing straining by HPT [7,8,11]. The other two hardness models of softening with recovery and weakening without peak hardness are demonstrated by high-purity metals and the materials having low T_m, respectively [12].

In order to evaluate the hardness evolution of the mechanically-bonded alloy systems, the measured Vickers microhardness values as shown in Fig. 1(e) for Al-Mg and Fig. 2(d) for Al-Cu are evaluated with increasing equivalent strain [2] calculated based on the locations of the hardness measurements. Plots of hardness versus equivalent strain were then constructed and these are shown in Fig. 3 (a) for Al-Mg after HPT for 10 and 20 turns and (b) Al-Cu after 20, 40 and 60 HPT turns.

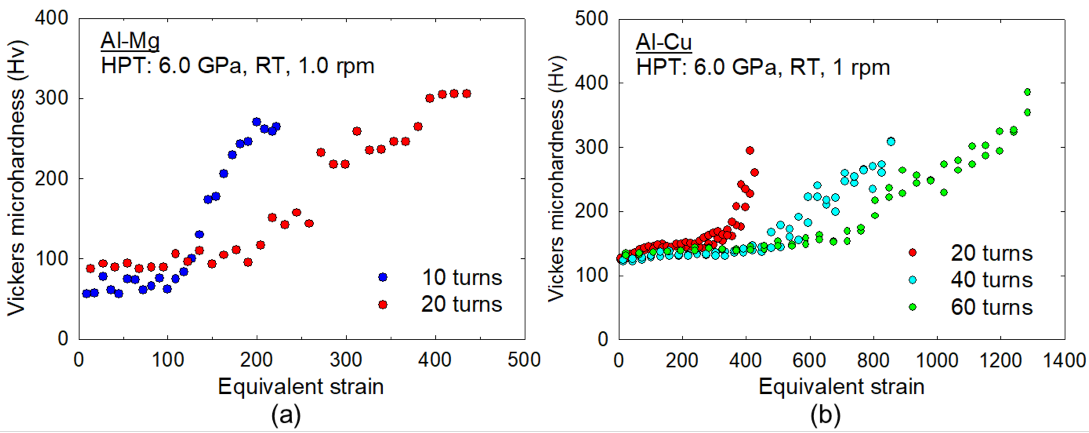

Figure. 3 Variations of microhardness with equivalent strain for (a) the Al-Mg system after HPT for 10 and 20 turns and (b) the Al-Cu system after HPT for 20, 40 and 60 turns.

Three important trends are observed for the mechanically-bonded hybrid alloy systems. First, both HPT-induced Al-Mg and Al-Cu systems demonstrated a plateau in their hardness values up to equivalent strains of ~100 and ~200 for the Al-Mg and Al-Cu alloys, respectively, thereafter these are followed by a logarithmic increase in hardness with increasing equivalent strain for all HPT processing conditions.

Second, while general UFG metals and alloys demonstrate hardness saturation after 5-10 turns by HPT [13], the maximum achievable hardness increases without any saturation for both hybrid Al-Mg and Al-Cu alloy systems under the current HPT processing conditions. Therefore, the mechanical bonding by utilizing HPT processing shows a considerable potential for the synthesis of a variety of hybrid nanocrystalline alloy systems which can achieve exceptional hardness when applying extreme straining.

Third, higher values of equivalent strain tend to be required for obtaining a specific hardness value for the sample with higher HPT turns. For instance, Hv = 250 can be achieved at equivalent strain of ~170 for the 10 turns Al-Mg disk while strain of ~300 is required for the 20-turn Al-Mg disk, and Hv = 300 is achieved with an equivalent strain of ~300 in the Al-Cu disk after 20 HPT turns while equivalent strains of ~850 and ~1200 are required for the Al-Cu disks after 40 and 60 turns, respectively. This behavior may be due to the inevitable heat generation during HPT that is attributed to the friction between the anvils and a disk sample. In practice, the processing temperature slowly increased from room temperature up to 70 ˚C in the first 15-20 minutes including the compression stage to the following anvil rotation for up to 20 turns and it remained constant during the rest of processing for both mechanically-bonded alloy systems. Thus, the generated heat may cause a microstructural recovery in the introduced UFG microstructures and this may explain the required higher equivalent strain to achieve the specific hardness values with higher numbers of HPT turns.

Nevertheless, these mechanically-bonded hybrid systems of Al-Mg and Al-Cu showed a successful improvement in hardness without any softening. As was noted earlier, extensive HPT turns to 100 turns [10] led to achieving an homogeneous extreme hardness of Hv = 330 which is higher than the highest hardness after 20 HPT turns for the Al-Mg system, and thus it is anticipated these Al-Mg and Al-Cu systems are able to achieving an extreme homogeneous hardness without any softening after receiving severe straining by HPT. On the contrary, it should be noted that there is a recent report demonstrating the synthesis of a Zn-Mg alloy system by the mechanical bonding by HPT for 30 turns at 6.0 GPa where the highest equivalent strain reaches 650 and the alloy system demonstrated a strain softening behavior after significant hardening towards microstructural homogeneity across the disk diameter [14]. The mechanical bonding by HPT used two pure metals of Zn and Mg which generally deform and show the hardness change with a model of softening with recovery [12]. Thus, it is anticipated that a hardness development of a mechanically-bonded alloy strongly depends on the separate base metals. Further analyses are necessary to define the hardness development behaviors for a variety of mechanically-bonded alloy systems.

Summary

Mechanical bonding of dissimilar metals was conducted by utilizing HPT processing at room temperature to synthesize hybrid UFG alloy systems of Al-Mg and Al-Cu. Significant grain refinement and severe phase mixture by HPT led the metals to demonstrate significant grain refinement, formation of intermetallics and extreme hardness especially at the disk peripheries. The hardness development behavior with a logarithmic increase was observed for the mechanically-bonded Al alloy systems with increasing equivalent strain. This processing approach demonstrates a significant contribution to developments in the synthesis of advanced engineering metals.

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