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Strength changes and bonded interface investigations in a spiral extruded aluminum/copper composite

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ABSTRACT

Fabrication of metal-based composites with concurrent grain refinement is an exciting and novel avenue in hybrid metal manufacturing. Copper clad aluminum rods, that were fabricated using Axi-Symmetric Forward Spiral Composite Extrusion (AFSCE) are investigated here as an example. Careful investigations of the bonding mechanism in the AFSCE samples are needed to control mechanical and physical properties of the composite material. In order to understand the mechanism of the bonding between copper and aluminum in the AFSCE process, morphological and micro-structural investigations were conducted by using a Scanning Electron Microscope/Focused Ion Beam (SEM/FIB) dual ion microscope and X-ray diffraction to study the nature of the interface. Hardness measurements across the interface region of the AFSCE sample were also produced to examine the deformation mechanism. A near flawless interface, without significant intermetallic or oxide layer, was identified. The strength variation in the copper region was characterized using micro-hardness tests which agreed well with the Electron Backscatter Diffraction (EBSD) observations of various sampling points. It was also found that the micro-hardness values near the interface and the outer periphery regions of the copper were higher than the hardness values at the middle region of the material, which is approximately equal to that of unprocessed copper.

1. Introduction

Severe Plastic Deformation (SPD) processes [1, 2], which are typically used to process single materials, have been recently applied to fabricate "architectured hybrid materials". SPD processes arguably provide one of the most potent methods of manufacturing bulk ultrafine grained materials [3]. Their concurrent grain refinement and production of "inner architectured metal-based composites" introduces a new paradigm of materials design [4]. These offer a synergistic effect by improving properties of the original constituent by combining two or more materials assembled in such a way that they have multiple attributes not offered by their individual components. In addition to the ultra-high strength of these hybrid structures, they also enable a large pool of new advanced materials, the architectured materials, to be designed and manufactured.

SPD processes can make a wide range of micro-structural changes in a material (see for example [1,5]). An interesting micro-structural change is the formation of Ultra-Fine Grains (UFGs) that enhances material strength through Hall-Patch effect by increasing the length of grain boundaries. For successful UFG formation, a significant portion of the deformation energy is used to create low angle grain boundaries and grain sizes smaller than 1 μm [6]. According to Valiev et al. [1], a "true" UFG can be defined as having a size of less than 1 μm and more than 70% high angle grain boundaries with a misorientation angle of greater than 15°. SPD processes can produce submicron grains at temperatures lower than $0.4T_m$ and nanocrystalline grains at temperatures below $0.2T_m$ [6]. However, a large hydrostatic pressure is needed to successfully produce nanocrystalline grains in most metals when the operating temperature is below $0.2T_m$ [6]. It has been reported that multiple processing of solid Ti-IF steel samples by Axi-Symmetric Forward Spiral Extrusion (AFSE) at room temperature can also produce submicron grain across the sample cross section [7].

Being a near zero shape change process, a solid single material can be produced using the AFSE process in multiple passes which allows more grain refinement [7]. It was shown that a variable pitch version of the extrusion die, for a single material, has significantly higher efficiency compared to the original AFSE process [8]. The Axi-Symmetric Forward Spiral Composite Extrusion (AFSCE)

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process involves extrusion of a composite sample through a die with engraved spiral grooves to produce a combination of shear and pressure in the composite material fabrication [9]. The AFSCE process can be easily performed in a single step and has good dimensional control. Contrary to many hot–warm bonding processes, a protective atmosphere is not essential during AFSCE. A case study of copper clad aluminum rod fabrication by AFSCE at an elevated temperature with backpressure was performed which proved to produce reasonably strong bonding between parent metals [9]. Other recent examples of Cu–Al based metallic composite fabrication include manufacturing of copper clad aluminum (Cu/Al) rod by Equal Channel Angular Extrusion (ECAE) [10] and Cu/Al tube by High Pressure Tube Twisting (HPTT) [11].

It has been suggested that the contact between the two materials at elevated temperatures with a high pressure process conditions may produce a material bond by inter-diffusions at the interface by facilitating atomic movements across the boundary [12–14]. Formation of Intermetallic Compounds (IMCs) at the interface has been reported for copper clad aluminum bonding cases [12,15–18]. Such intermetallic layer increases the strength of the interface, but limits the ductility as suggested by Sasaki et al. [19] and because of its brittle nature [13,19,20] reduces the bond strength as suggested by Bae et al. [20]. Moreover, joining Cu–Al has been recently investigated by many researchers, for example using brazing processes with various filler materials such as Zn–Al–Ce in [21], Al–Zn in [22] and Zn–3Al in [23]. However the brazing process produces significant amount of IMCs and makes significant micro-structural changes in the parent materials at very high temperatures which are not preferable.

In our previous investigation, Al–Cu hybrid metal composite was successfully fabricated by AFSCE at 300 °C with a 200 MPa backpressure and a dedicated blanking test was performed to measure the bond strength of the fabricated composite samples [9]. The process conditions with a high pressure and an elevated temperature could lead to the formation of both IMCs and ultra-fine grains at the interface. It is known that the concurrent shear deformation, high pressure and temperature create a bond at the interface during the AFSCE process but due to the inaccessibility of the interface, very limited direct observations can be made at the interface zone. The exact mechanism behind the creation of bonding is not clear. Therefore, in order to understand the bonding mechanism and the parameters that affect properties of the hybrid metal composite require further investigation.

In the current study Scanning Electron Microscope/Focused Ion Beam (SEM/FIB), X-Ray Diffraction (XRD) and Electron Backscatter Diffraction (EBSD) techniques are used to investigate the nature of the interface. Moreover, the strength changes across the sample due to the AFSCE process are determined using micro-hardness tests and the copper region hardness changes are compared with the EBSD micro-structural results. It is found that the bonding is a near flawless mechanical interlocking at the interface which agrees well with bonding shear strength measurement. The bonding shear strength at the interface is higher than shear strength for the pure aluminum. The deformation mechanisms in various regions were also accommodated by a formation of UFGs and crystal orientation changes in various regions of copper sleeve, were confirmed by micro-hardness distribution across the copper region and the EBSD results from various sampling points.

2. Experimental methods

2.1. Interfacial preparation and investigation using FIB

Copper clad aluminum composite sample was produced using the AFSCE process at 300 °C with a 200 MPa backpressure. Two parent materials used in this experiment were a commercially-pure copper (Cu) annular and a commercially pure cast aluminum (Al) solid rod. Details of the process and constitutive behaviors of these materials can be found in Sapanathan et al. [9].

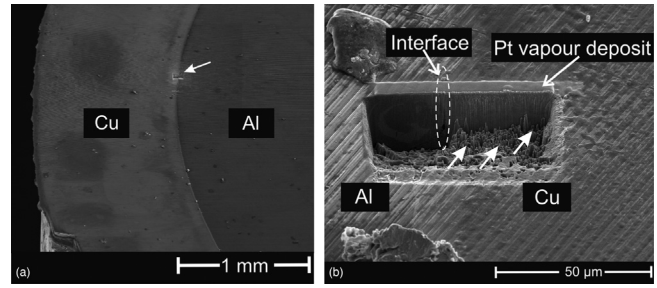

Fig. 1. (a) FIB location of the interface (b) intermediate milling step prior to final finishing.

To avoid dissection artifacts at the bonding interface, which could be introduced by standard mechanical grinding and polishing, a Focused Ion Beam (FIB) technique was utilized in this work to study interfacial features using an FEI Quanta 3D FEG FIB microscope. To minimize alteration of the interface and the formation of mechanical dislocations near the surface during the preparation, the FIB sample was cut from the middle section of the AFSCE extruded copper clad aluminum sample along the transverse section normal to the extrusion axis using a Buehler IsoMet low speed saw machine equipped with a diamond blade. The FIB milling location and the milled surface of the specimen are respectively shown in Fig. 1a and b.

Two approaches were chosen to reveal areas of interest. In the first approach, in order to prevent a collapse of the dissection, a thin layer of platinum was deposited across the dissection interface using FIB assisted chemical vapour deposition. The position of the thin layer on the transverse section is shown in Fig. 1a and the vapour deposition is shown in Fig. 1b. The second approach, without the platinum vapour deposition, was adopted to minimize the possible unwanted micro-structural changes by the local heating to the sample. Initially a large beam current of 30 keV was used to quickly remove and mill the material across the interface. The high beam current milling produced a "curtaining effect" on the surface with debris in the milling area and uneven rate of milling in copper and aluminum regions (shown in Fig. 1b by arrow marks). To improve the surface finish of the FIB dissection, a subsequent fine layer was milled by 5keV low beam current sputtering using a slicing method. In order to identify the formation of IMC, oxide or carbide, Energy-dispersive X-ray spectroscopy (EDS) investigations along the interface were also carried out using 5keV exciting voltage at the FIB dissected region without Pt deposition.

2.2. Micro-hardness measurements

Micro-hardness measurements on the transverse section were carried out to study mechanical property changes across the AFSCE composite sample in the radial direction particularly in the vicinity of the interface. Three samples were tested to investigate the hardness behavior along x and y directions and their average values were used to plot the hardness behavior as shown in Fig. 6. The Vickers micro-hardness was measured according to ASTM: E384 11e1 standard across the radial direction along the two perpendicular radii for aluminum and copper shown in Fig. 2. Given the kinematics of AFSE/AFSCE, a finer spacing was chosen near periphery of the die. A Wolpert Group Micro-Vickers hardness tester with 100 gf load was used. Measured hardness values of unprocessed materials were used to compare the hardness changes in the composite material. Dotted lines are used in Fig. 2 to show the deviation of the sample transverse section, groove and valley, from a real axi-symmetric (circular) section.