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Optimisation of interface formation by shear inclination: Example of aluminium-cooper hybrid produced by ECAP with back-pressure

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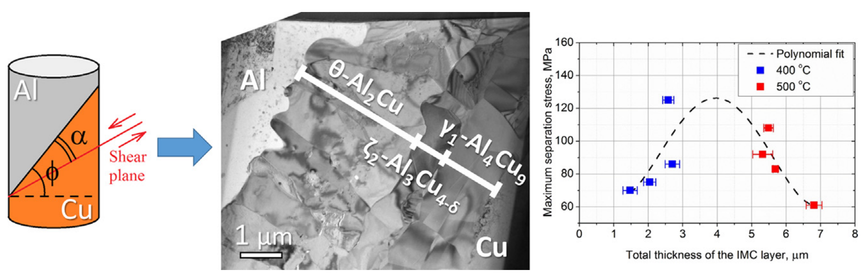
HIGHLIGHTS

- Detailed crystallographic analysis of intermetallic compounds on the Al-Cu interface after hot deformation was performed.
- Very rarely reported orthorhombic ζ_2-$Al_3Cu_{4-\delta}$ phase was identified as one of the compounds.
- The optimum thickness of the interface for high mechanical stability was found to be in the range of 3-5 μm.
- The interplay between the diffusion and recrystallization processes governs the formation of the Al-Cu intermixing zone.

GRAPHICAL ABSTRACT



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ABSTRACT

Hybrid materials present a convenient way of combining properties of more than one material in one product. However, there are problems associated with such manufacturing, particularly, in relation to the properties of the interface between components. Intermetallic compounds can potentially form in this area, whose size and composition can have a profound effect on mechanical properties of the product. In this work, we investigate the effect of temperature, mutual arrangement and hydrostatic pressure on the quality of the interface between Al and Cu parts, processed simultaneously by severe plastic deformation. We show that three intermetallic compounds - θ-Al_2Cu, ζ_2-$Al_3Cu_{4-\delta}$ and γ_1-Al_4Cu_9 - form on the interface. It is shown that the formation of these phases on the interface between aluminium and copper highly depends on the combination of diffusion and recrystallization process.

1. Introduction

The targets for material performance in modern world are set at a level that is difficult to achieve with conventional materials. Common approaches for improving material characteristics, for example, by alloying or thermomechanical processing are reaching their limits. In many cases, the set of the required microstructures and associated properties cannot be achieved in one particular material, prompting a development of concept of hybrid materials [1,2]. There are many techniques currently used to join dissimilar materials, but most frequently reported are friction stir welding [3], rotary friction welding [4] or explosion welding [5] techniques.

However, there are other processing techniques, which are capable of producing hybrid materials by newly emerging techniques of shear

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Table 1
Values of inclination angle used in experiment.

Φ - angle between contact plane and exit channel	0	30	45	60	90	120	135	150
α - angle between shear and contact plane	−45	−15	0	+15	+45	+75	+90	+105

mixing. Research within the ultrafine grain metals community over the past 15 years has shown that very large shear deformations imposed under concurrent high pressure can produce unique microstructures. Intense shearing introduces unique dislocation structures, but also alters the size and morphology of precipitates, dispersoids, and additional phases [6]. Moreover, it was shown that properties obtained by severe plastic co-deformation of dissimilar metallic materials are far outside of expected properties of composite materials [7,8].

Several review papers summarize metallic composite processing by severe plastic deformation [9–11]. They highlight achievements to date in advancing properties of nanocomposites by SPD methods. Most notably, they show that intensive straining to nanostructure the constituents results in unusual effects, such as formation of a supersaturated solid solution of chemically immiscible metals [12] or occurrence of solid state amorphous regions [13,14]. The extension of solid solubility in immiscible metals appears when the grain size is reduced to range of 10–20 nm by intense straining. This level of nanostructuring that is accessible in composites is shown to be unreachable in single constituent materials [15]. For example, severe plastic deformation techniques can consolidate particulate metals causing deformation-induced atom mixing and enhanced diffusion [16,17] to form interface layers with much higher hardness than the individual constituents, as shown in [7].

The idea of manufacturing material hybrids with simultaneous nano-structuring by different SPD methods is quite appealing and has been studied for several systems, for example, Al-Cu [18], Cu-Ag [19], carbon nanotubes (CNT-Al) [20], Al-IF steel [21] as well as metallic glasses [22]. However, the importance of interface formation and possibility to optimise the width and composition of intermixing zone, which define the properties of hybrid material, was not fully understood. A study of influence of high shear deformation mode and high hydrostatic pressure on the inter-diffusion and the physical mechanisms of interface formation was not performed.

In this paper a research of Al/Cu hybrid material produced by equal channel angular pressing (ECAP) at different inclination angle between shear direction and the contact area, different temperatures and levels of hydrostatic pressure is presented.

2. Experimental

Electrolytic Tough Pitch (ETP) copper rods of 99.9 wt% purity and commercially pure Al 1050 with an average grain size of around 28 μm and 52 μm, respectively, were used in this study. The rods of 12 mm diameter were cut along the length of the rod with different inclination angles Φ ranging from 0° to 150°, Table 1, and hybrid sample was made by putting together two matching halves made from aluminium and copper (Fig. 1a). Fig. 1a also shows an angle α between the contact plane and the shear place of the ECAP process (Fig. 1b). Considering the direction of shear, the value of angle α was varying from −45° to +105° (Table 1). Prior to ECAP, the Al/Cu contact area was cleaned with acetone and roughened with a file.

The hybrid samples were pressed through 90° ECAP die with zero radius (Fig. 1b) at four different temperatures (20°, 400°, 450°, 500°) and five levels of hydrostatic pressure, created by application of backpressure (230, 385, 615, 925, 1080 MPa). The ECAP rig with backpressure has two hydraulic cylinders applying independent pressure to forward and backward punches. The forward punch moves with a constant pre-defined velocity deforming the sample through the die against pre-set pressure applied by a backward punch. Both velocity and level of back pressure are computer-controlled. Use of backpressure creates uniform hydrostatic pressure within deformation zone as discussed in our previous publications [23,24].

The strength of the bond has been checked by a separation stress test. Rectangular tests samples with dimensions 35 mm × 5 mm × 1.5 mm (L × W × T) were wire-cut from ECAP-processed cylinders perpendicular to the shear plane. Samples were fixed in the grips of Instron 4505 testing machine and tensile stress was applied along their major axes. The stress required to separate the parts was identified as maximum separation stress.

For microstructural analysis, a cross-section of samples was obtained using focused-ion beam technique at FEI Quanta 3D FEGSEM scanning electron microscope (FEI, The Netherlands). Samples were subsequently analysed in JEOL JEM 2100F FEGTEM transmission electron microscope (JEOL, Japan). To obtain diffraction from zone axes, samples were tilted in the column by double-tilt specimen holder. PDF4+ software package (ICCD, USA) was used to generate diffraction patterns for known phases to compare against obtained diffraction data to determine the intermetallic phases. Chemical analysis was performed using TEM EDX detector. Molybdenum lift-out grids were used for lamella fixation instead of conventional copper grids to avoid excessive Cu noise signal from the samples.

3. Analytical model and an optimum inclination angle Φ

Force applied by the forward punch during ECAP can be decomposed into two components normal, $\boldsymbol{N}$, and shear, $\boldsymbol{T}$, to the contact plane, Fig. 1c, which are calculated as follows:

$$N = F\cos\Phi \qquad T = F\sin\Phi \tag{1}$$

The contact area between two materials is not ideally smooth, it consist of the array of asperities with different shape and height, which under normal pressure form the junctions defining the real

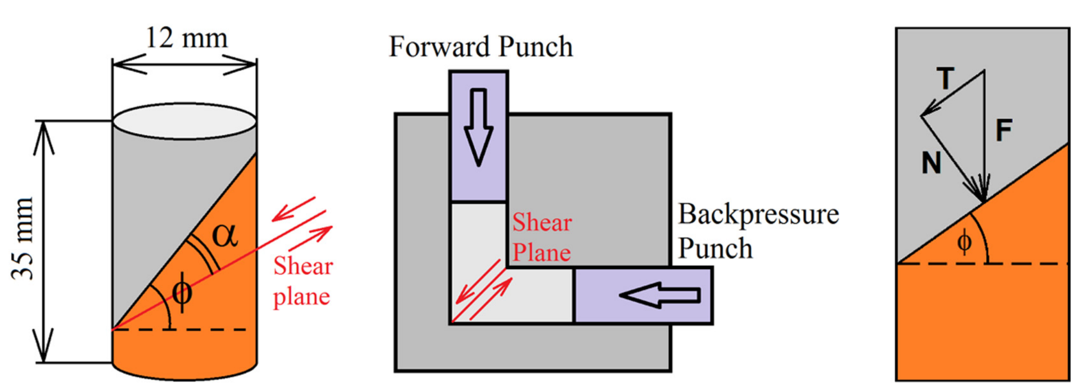

Fig. 1. Schematic of hybrid samples (a), ECAP process (b) and decomposition of the ECAP force at the contact plane between the parts (c).