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Short communication

Friction stir selective alloying

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ABSTRACT

An attempt was made for the first time to selectively alloy aluminum with copper using friction stir processing. The objective was successfully accomplished and the copper-alloyed stir zone was found to respond well to artificial aging. Potential applications of friction stir selective alloying were outlined.

1. Introduction

Since the turn of this century, extensive work has been carried out using friction stir processing (FSP) for producingultra-fine-grained materials [1,2], for achieving compositional/microstructural homogeneity [3], for producing metal matrix composites [4], for producing integral channels for thermal management or heat exchange [5], for repairing cracked or defective components [6,7], and, most recently, for improving HAZ liquation cracking resistance [8,9] and for additive manufacturing [10]. Yet another possibility with FSP is "selective alloying" – addition of one or more alloying elements to the base material, just where they are needed – for achieving local enhancement in properties.

The use of FSP for selective alloying has not been explored till date. However, FSP can be expected to facilitate alloying in solid-state by both mechanical and thermal processes as it involves severe plastic deformation at high strain rates and high homologous temperatures. This conjucture is supported by the following. In an attempt to study diffusion and metal flow in friction stir welds, Gholami Shiri et al. [11] carried out friction stir butt welding of aluminum base plates by inserting thin foils of different materials (copper, zinc, etc.) at the joint line. Microstructural examination of these welds revealed some diffusion of the constituent elements of the foil material into the aluminum matrix, apart from chaotic mechanical mixing of the foil and the matrix materials. In another study, Li et al. [12] carried out FSP of titanium alloy Ti-6Al-4V in nitrogen atmosphere to obtain a hard and wear-resistant titanium nitride layer on the top surface of the processed region. Several investigators have also observed in-situ intermetallic formation during FSP. For example, Chuang et al. [13] carried out FSP of magnesium alloy AZ31 sheets stacked with pure aluminum and zinc foils in between. After multi-pass FSP, many different Mg-Al-Zn intermetallics were observed in the stir zone. Similarly, Ke et al. [14] attempted multi-pass FSP of a pure aluminum plate that contained some holes filled with pure nickel powder. During FSP, the nickel powder was found to react with the aluminum matrix resulting in the formation of Al_3Ni intermetallic. Further, friction stir welding of similar and dissimilar metals has been successfully demonstrated with filler metal addition [15].

The current work derives inspiration from the above investigations. In this work, the feasibility of selective alloying through FSP was investigated using aluminum-copper system as a test case. Behind the choice of copper as the solute are the following reasons: (i) copper and aluminum have decent mutual solid solubilities at temperatures typically encountered during FSP of aluminum, and (ii) copper addition to aluminum allows for exploiting precipitation hardening so that the strengthening effect in the processed region can be maximized.

2. Experimental work

A pure aluminum base plate (AA 1050) of 10 mm thickness (nominal composition in wt%: Al-0.4Fe-0.3Si-0.05Mn-0.1Zn-0.1Cu) and pure copper powder with an average particle size of ~ 60 ± 10 µm were used as the test materials. To begin with, a rectangular groove of 2 mm wide and 3 mm deep was machined in the aluminum base plate, which was subsequently tightly packed with the copper powder (the groove dimensions were arrived at targeting a copper content of 2–2.5 wt% in the stir zone). A capping pass was then performed over the copper-filled groove using a pin-less tool (made of H13 tool steel, 15 mm shoulder diameter). The process parameters used for the capping pass were: 1500 rpm tool rotation speed, 100 mm/min traverse speed, 2° backward tool tilt, and 0.3 mm shoulder plunge.

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The capping pass was meant to close the groove so that the copper powder does not fly away during actual FSP. Following this, FSP was carried out over and along the capped groove using a H13 steel tool consisting of a screw-threaded taper pin (6.7 mm length, 9 mm major diameter, 6 mm minor diameter, left-hand metric threads with 1 mm pitch) and a 3° concave shoulder (19 mm diameter). In the current study, the grooved region was FSPed for four times. The first pass was done using a tool rotation speed of 1500 rpm, a transverse speed of 100 mm/min, a plunge depth of 6.8 mm, and a backward tool tilt of 2°. For each of the three subsequent passes, the transverse speed was reduced by 25 mm/min to avoid defects in the stir zone. To facilitate better mixing of the copper powder in the stir zone, the processing direction was reversed for each pass. Similarly, after every pass, the base plate was allowed to cool to room temperature (to minimize equilibrium Al_2Cu (θ) formation).

Transverse sections cut from the FSPed base plates were metallographically polished, etched with Keller's reagent (1 ml HF, 1.5 ml HCl, 2.5 ml HNO_3 and 95 ml water), and examined using an Olympus inverted light microscope and an FEI Inspect-F high-resolution scanning electron microscope (SEM) equipped with energy dispersive spectroscopy (EDS). A JEOL JXA-8530F electron probe micro-analyzer (EPMA) was used for microchemical analysis and elemental mapping. Additionally, thin foil specimens were prepared (by mechanical thinning, dimpling, and ion milling) from the four-pass FSPed sample and were examined using a Philips CM-12 transmission electron microscope (TEM). Vickers micro-indentation hardness tests were carried out on the FSPed samples using a Matsuzawa MMT-7 digital microhardness tester (100 g load and 15 s dwell time). Room temperature tensile tests were also conducted (as per ASTM E8) on longitudinal specimens (2 mm thickness, 3 mm gauge width, 10 mm gauge length, 12 mm parallel length, 6 mm fillet radius, and 40 mm overall length) extracted from the friction stir copper alloyed aluminum samples in naturally aged and artificially aged conditions at a strain rate of 10^{-4} s^{-1}. Tests were also conducted on specimens extracted from the unalloyed FSPed aluminum samples as well as from the unprocessed base material for comparison.

3. Results and discussion

Fig. 1 shows the progression of alloying from the first pass to the fourth pass. Microstructural examination of the stir zone after the first pass revealed many non-uniformly distributed, undissolved copper particles (Fig. 1a). The stir zone showed some dark-etching regions, which were found to be alloyed with copper in varying amounts (up to 1.8 wt%, based on EDS spot analysis). The light-etching regions of the stir zone, on the other hand, showed no copper content. Microhardness measurements showed that the dark-etching regions were harder than the light-etching ones due to copper alloying (Fig. 1a). After the second pass, the stir zone showed more dark-etching copper-alloyed regions, but still contained some random bands of light-etching unalloyed regions. The undissolved copper particles in the stir zone appeared finer and fewer as well as more uniformly distributed than in the first-pass stir zone. The copper content and the hardness of the dark-etching regions were also found to be slightly higher (Fig. 1b). After the third pass, the etch contrast in the stir zone appeared more uniform, but still some very thin bands of unalloyed light-etching regions could be seen (Fig. 1c). Across the stir zone, the copper content as well as the hardness showed considerable variation (the high copper content at some points is due to the presence of fine undissolved copper particles within the EDS sampled volume). After the fourth pass, however, the stir zone showed very uniform etch contrast within the bulk of the stir zone and practically no undissolved copper particles (Fig. 1d), implying

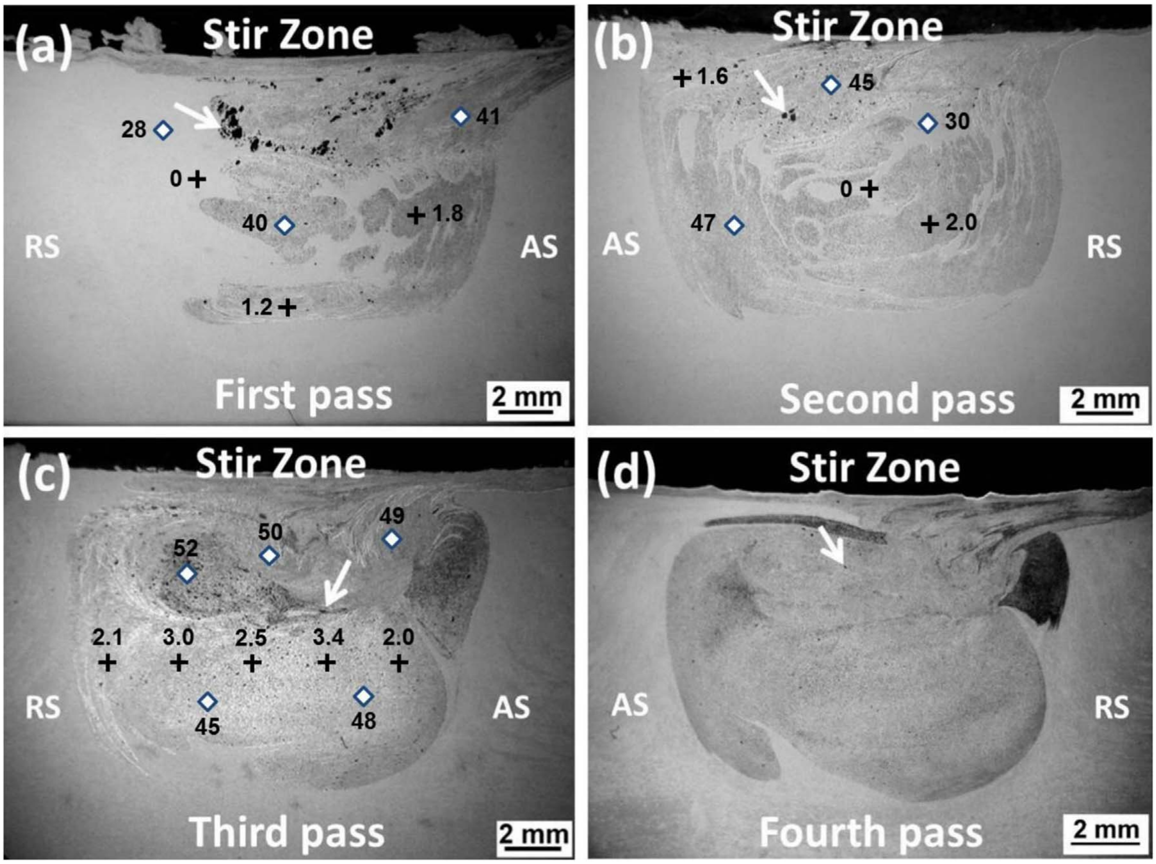

Fig. 1. Stir zone macrographs (after Keller's etch): (a) First pass, (b) Second pass, (c) Third pass, and (d) Fourth pass (AS: advancing side, RS: retreating side). Arrows show undissolved copper particles. Note uniform etch contrast within the bulk of the stir zone after fourth pass. In (a), (b), and (c), the Cu content at locations shown by plus marks is reported in wt% (based on EDS spot analysis). The diamond marks show the locations of microhardness testing. The hardness values are reported in HV.