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Effect of heat treatment on tensile deformation characteristics and properties of Al3003/STS439 clad composite

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ABSTRACT

The tensile deformation and fracture behaviors of roll-bonded Al3003/STS439 clad composite were studied. The mutual constraint and interaction of joined Al and STS with different deformation characteristics tend to shape the deformed specimen geometry to appear similar and induce the simultaneous fracture of Al and STS. The examination of the fractured clad revealed more uniform deformation of less ductile metal layer was induced by co-deforming more ductile metal layer in the clad composite, enhancing the overall tensile ductility. The suppression of neck formation in STS layer of Al3003/STS439 clad composite was observed to be induced by the resistance to neck formation of joined Al layer, rendering the enhanced ductility of joined STS layer over the separated STS layer. Excellent interface bonding and absence of brittle intermetallics at the interface are prerequisites for the enhanced ductility of clad composites because constraint by the adjacent joined metal layer can be made by the stress and strain transfer through the interface. The strength of the roll-bonded Al3003/STS439 clad composite is in close agreement with that calculated from the rule of mixture.

1. Introduction

The clad metals, consisting of two or more metal layers, have been developed because of their unique combination of properties [1–3]. The properties of clad composite material are determined by the selection of component materials to be joined, the stacking structure of different materials with various thicknesses and the interface structure and the properties between different materials [3–5]. Clad composite material in which different metals and alloys with various properties are joined have been used in various industrial fields [3,6,7]. There has always been a need to develop materials with the optimum combination of superior specific strength and corrosion properties combined with good thermal conductivity [1,5,9]. One of the most widely used commercial clad products is a roll-clad composite structure consisting of stainless steel (STS) and aluminum sheets. Stainless steel (STS) provides high strength and excellent corrosion and abrasion resistance, while Al contributes to high thermal/electrical conductivity and weight reduction [1,6,9]. Al3003/STS439 (stainless steel) clad composite plate not only has sufficient strength and corrosion resistance required for structural materials but also provides other functions including high thermal and electrical conductivity, and still achieves cost-competitiveness and weight reduction [1,9]. Because of the favorable combination of properties, Al3003/STS439 clad composite finds its application in various fields such as automotive and aircraft components, maritime vehicles, electronic packaging, and cryogenic/chemical tanks [9]. Plate and wire forms of Al/steel clad composite are currently used as cookware material, messenger and conduction wires. The roll bonding method is currently the most common process for producing clad sheets because of its efficiency and economy, compared with other types of processes [1,8–10].

Mechanical properties of Al3003/STS439 clad composite have attracted the interest of many investigators [1,9–12] because it provides many attractive combinations of properties for engineering application. However, the effect of annealing on the deformation and fracture of Al3003/STS439 clad, is still not well understood. Lee and Kim [6] reported that the flow stress of STS/Al/STS sandwich clad metal followed the rule of mixture because of the negligible transverse stress compared with the longitudinal stress. Recently, Kim et al. [4] and Kim and Hong [10] reported that the ductility of clad composite did not follow the rule of mixture and exceeded it especially when the interface bonding between layers was excellent in Mg/Al/STS clad composite. Kim and Hong [10] observed that the fracture strain of STS layer was enhanced significantly whereas that of Mg layer was not greatly affected by the presence of ductile Al layer in the middle. In this study, the effect of post-roll-bonding heat treatment on the deformation and fracture of Al3003/STS439 clad composite was investigated. The behaviors of Al3003/STS439 clad were also compared with those of separated

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Al and STS plates to examine the effect of interface joining on the overall deformation behaviors.

2. Experimental method

The materials used in this work were 2-ply Al3003/STS439 clad metals produced by warm roll bonding at 350 °C with a reduction ratio of 60%. These final clad plates had a total thickness of about 1.5 mm and the thicknesses of Al and STS sheet were 1 mm and 0.5 mm, respectively. Al3003 plates have the composition of 1.0 wt % Mn, 0.7 wt% Fe, 0.6 wt% Si, 0.2 wt% Cu and 97.5 wt% Al and STS439 plates used in this study have the composition of 17 wt% Cr, 1.0 wt% Ti, 0.9 wt% Mn, 0.5 wt% Ni, 0.7 wt% Si and 79.9 wt% Fe. An Al3003/STS439 clad plate was heat-treated at various temperatures (200, 300, 400, 500, 550, 600 °C) for 1 h to observe the effect of the heat treatment. To investigate the mechanical properties of heat-treated clad composites at various temperatures, tension tests were performed using a Universal Materials Testing Machine (UNITED, US/SSTM) at room temperature. The gage length and gage width for the tensile testing sample were 15 mm and 3.5 mm, respectively. During the test, the strain rate was 1×10^{-3}/s. In order to precisely evaluate the contribution of each layer on the overall mechanical performance of 2-ply Al3003/STS439, each layer was separated from the clad Al3003/STS439 composite and mechanically tested independently to characterize the mechanical performance.

Separated STS sheets from the joined clad composite plates were obtained by dissolving the Al layer in NaOH solution for 24 h at room temperature. Stainless steel is considered resistant to any concentration of sodium hydroxide below 353 K (80 °C) [10]. Indeed, the surface of the separated STS plate in NaOH was found to be clean. After chemical separation, the STS sheet was mechanically polished with care before tensile testing. In order to exclude the effect of temperature-dependent intermetallic formation and its effect on the surface properties of separated sheets, each layer was annealed after separation. If Al/STS clad plates are annealed at high temperatures as they were bonded, the intermetallic layer is likely to form, which would deteriorate the surface properties of separated Al sheets. The Al sheet was separated by mechanical polishing of the SST sheet away from the outer surface using a material polisher. All samples after mechanical polishing were observed to be clean and no visible defects were observed using a stereo microscope. The mechanical testing was repeated at least 3 times for each condition to ensure that the results in this study are reliable, and the average strength and strain values were used for the rule of mixture calculations. The variation of the data under the same experimental condition was negligibly small. To analyze the interfacial microstructure after heat treatment and cross-sectional fracture surface of clad material, Optical Microscope and FE-SEM with EDS were used. XRD analyses were carried out to identify the interfacial reaction products between Al and STS. The identification of phases was done by matching the XRD results to the JCPDS card.

3. Result and discussions

Fig. 1 shows the optical micrographs of the as-roll-bonded and heat-treated Al3003/STS439 interface at various temperatures (200–600 °C) for 1 h. For as-rolled Al3003/STS439 clad and those heat-treated at 200–500 °C, no visible interfacial reaction layer was observed, suggesting that the bonding interface between Al and STS is intact. At 550 °C and 600 °C for 1 h, a fatal crack was observed at the interface, which led the clad to separation into Al and STS sheets during handling after heat treatment. The interfacial

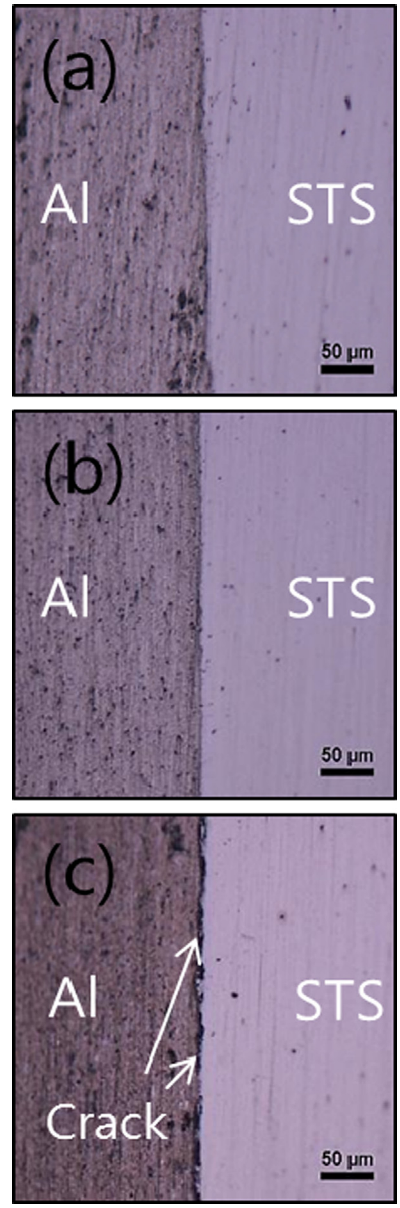

Fig. 1. Interface region of the as-roll bonded (a) and heat-treated Al3003/STS439 composite at 500 °C (b) and 600 °C (c) for 1 h.

cracks were also observed in Al3003/STS439 clad composite annealed at 550 °C for 1 h. It suggests the formation of brittle intermetallic layer between Al and STS above 500 °C. Because of the significant difference of the thermal expansion coefficients between Al (23.2×10^{-6}/K) and STS (12.5×10^{-6}/K), the thermal stress is large enough to induce the interface cracks along the brittle intermetallics layer developed after annealing above 550 °C. If the elastic moduli of iron aluminides are close to those of STS (204 GPa) [3,13], the thermal stress develops in a temperature cycle from 500–600 °C to room temperature and was calculated to be 100–120 MPa, which is not sufficient enough to initiate cracks in bulk iron aluminide intermetallics [14]. The interfacial cracking after annealing above 500 °C may indicate that the interfacial crack could occur at the interface of intermetallics and metal substrates in the presence of intermetallics. The thickness of the intermetallic layer in Al3003/STS439 clad annealed at 600 °C for 1 h. was observed to be ~4 μm in Fig. 1, which is compatible with the thickness (5–6 μm) observed by Tortorici and Dayananda [2] in Al/430STS heat-treated at 600 °C for 3 h. The absence of interfacial