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Interfacial microstructure and properties of copper clad steel produced using friction stir welding versus gas metal arc welding

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ABSTRACT

A preliminary study compares the feasibility and microstructures of pure copper claddings produced on a pressure vessel A516 Gr. 70 steel plate, using friction stir welding versus gas metal arc welding. A combination of optical and scanning electron microscopy is used to characterize the grain structures in both the copper cladding and heat affected zone in the steel near the fusion line. The friction stir welding technique produces copper cladding with a grain size of around 25 μm, and no evidence of liquid copper penetration into the steel. The gas metal arc welding of copper cladding exhibits grain sizes over 1 mm, and with surface microcracks as well as penetration of liquid copper up to 50 μm into the steel substrate. Transmission electron microscopy reveals that metallurgical bonding is produced in both processes. Increased diffusion of Mn and Si into the copper cladding occurs when using gas metal arc welding, although some nano-pores were detected in the FSW joint interface.

1. Introduction

Overlay welding or cladding is often used to provide corrosion or wear resistance to steel components. However, this encounters some challenges in the case of copper claddings. Dissimilar welding of these materials is hampered by the fact that copper and iron form an immiscible binary system, while another key issue is liquid metal embrittlement that arises from the molten copper in contact with the steel, which is able to wet the steel austenite grain boundaries at high temperature [1]. This may lead to sub-surface cracking [2], and cracking of the copper cladding can also readily occur upon cooling due to thermal stress caused by the drastically different conductivities and thermal contraction coefficients of the two materials. Furthermore, high heat input is required to overcome the high thermal diffusivity of the copper, and processes such as electron beam welding (EBW) offer such capability [3]. However, poor mixing of the materials and some defects such as porosity and micro-cracking were observed in EB welded copper–stainless steel [4]. Meanwhile, the interface diffusion control is a key point in Cu/steel dissimilar metal welding process with high heat input, because the mechanical properties of the weld will be deteriorative due to enhanced interface diffusion capability [5].

Due to the problems encountered with cladding copper on steels, solid state processes such as explosive welding are more generally preferred [6,7]. A few studies have shown that laser welding of copper and steels is feasible [8]. However, the need for higher productivity and material deposition rates has also driven the study of hot-wire tungsten inert gas welding [9]. Although the deposition rates were reported to be 3.1 kg/h, poor wetting to the steel substrate occurs with low arc current, and excessive iron dilution into the copper layer was noted at higher arc currents. It has also been shown that iron dilution into copper will further promote microcracking in the solidified material [10]. Since many issues stem from the interaction of the molten copper with the steel, solid state welding processes may provide a beneficial alternative for joining of these materials.

Friction stir welding (FSW) was developed in 1991 by The Welding Institute (TWI) for joining heat treatable aluminum alloys and other materials which are difficult to join by arc welding [11]. The process of FSW involves plunging a rotating cylindrical tool into the interface between two plates, and generating sufficient frictional heat and deformation to consolidate the two materials together [12,13]. FSW has been shown to be applicable for joining dissimilar materials such as Al/Mg alloy [14], Al/Fe alloy [15] and Al/Cu alloy, because the formation of low melting point intermetallic compound (IMC) was limited, and metallurgical bonding was confirmed at the interface [16]. The strength of the weld is drastically reduced when IMCs involving AlCu, Al_2Cu and Al_4Cu_9 form at the Al/Cu interface [17–19]. Meanwhile, defects such as microcracks and voids were observed in the weld [17].

The use of FSW has been demonstrated to join pure copper in sections up to 50 mm thick [20–23], where defect-free welds were produced, and tensile strength of the FSW copper joint was higher than that made by EBW [22], with a joint efficiency of 94% reported [22,24]. FSW also has been developed for sealing copper canisters for the storage of

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nuclear waste, since the copper provides excellent corrosion protection [25]. Furthermore, FSW has been applied to join copper to steel in both lap and butt weld configurations with no defects, where mechanical mixing and metallurgical bonding conformed at the Cu/St interface in lap weld configuration [26,27].

The present work provides the first comparison between FSW lap welding of copper cladding sheets to a steel substrate versus cladding by pulsed-current gas metal arc welding (GMAW). The FSW process provides a method of potentially applying a cladding layer by staggering a series of lap-joints on a sheet of cladding material. This can potentially be highly productive since a copper sheet with quite high thickness can be employed, however the bonding microstructures and bonding mechanisms have yet to be examined and compared to conventional overlay fusion welding methods.

2. Experimental details

For the case of FSW, lap welding was performed on a 2.1 mm thick C10200 copper sheet with a hardness of 70 HV, and a 25.4 mm thick A516 Gr. 70 steel substrate with a hardness of 155 HV. The tooling during FSW was a Co–WC cermet, consisting of a 12 mm shoulder, and a smooth 2.1 mm long pin with a tapered geometry (where the diameter increased from 4 to 5 mm), as shown in Fig. 1a. A second '3-flat' tool with the same geometry was also investigated, with the exception of three 0.5 mm flat surface ground into the pin at equal 120° spacings (see Fig. 1a). The 3-flat geometry was considered in order to compare the effect of enhanced mechanical deformation and strain compared to a smooth pin tool. Co-axial alignment of the FSW in the holder was measured to be within 0.035 mm. A tool rotation speed of 1120 RPM and travel speed of 31.5 mm/min was used, with a tool tilt angle of 2.5°, and the tool penetration ranged from 0.06 to 0.60 mm into the steel substrate. It should be noted that in preliminary trials, parameters were also compared using different combinations of 900 RPM and travel speeds of 90 mm/min, however only superficial bonding was produced. The parameters applied appeared to be the minimum required for bonding using the FSW equipment used. No preheating was applied during FSW. Initially two single pass welds were reproduced using varied penetration depths. The microstructures of both single-pass FSW lap welds were compared multiple pass FSW joints staggered at 4 mm intervals, with 5 passes of 100 mm length were produced adjacent to each other using the smooth pin tool with a penetration of 0.25 mm. No tool wear was apparent after the 5 adjacent passes.

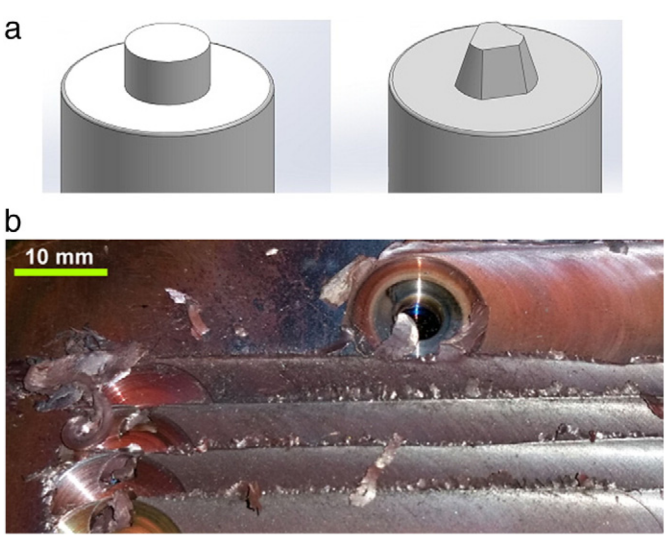

Fig. 1. (a) Schematic illustration of the tool geometry, (b) photo of the Cu/steel FSW multi-pass lap joint surface.

The GMAW claddings were produced using pulsed current deposition with a 1.14 mm diameter AWS A5.7 ERCu composition wire, travel speeds of 7.45 mm/s, heat input of 725 J/mm, wire feed speeds of 7.37 m/min, and an inter-bead spacing of 4.0 mm. The initial preheat during GMAW was 100 °C with inter-pass temperatures maintained below 300 °C.

Standard metallographic preparation techniques were applied, with final polishing using 1 μm diamond slurry. Specimens were first etched using 2% Nital to reveal the steel microstructures, then etched with 60% Nital to reveal the copper grain structure. The joint microstructures were examined by a combination of optical metallography, scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The SEM analysis was performed on a JEOL 6460 instrument equipped with energy-dispersive X-ray (EDX) spectroscopy and operated at 30 keV. TEM analysis involved using a focused ion beam to extract the copper/steel interfacial region in both claddings, and analysis of the thinned foil was performed using a Titan LB instrument. In addition, Vickers microhardness measurements were conducted in both samples to detect any possible embrittlement of the heat affected zone (HAZ) of the steel.

3. Results

3.1. FSW Cu/steel lap joint

The copper sheet was adhered to the substrate with minimal flash ejected from the surface as shown in Fig. 1b, and multiple FSW passes could be staggered adjacent to each other without severe accumulation of the flash on the surface. In an individual pass, it is clear that a wave-like or 'hook' feature is formed in which the steel has been displaced into the upper copper sheet (see Fig. 2a), which provides strong mechanical interlocking at the Cu/steel interface. The bonded area occurs across the interface which spans this intermixed region, roughly corresponding to the diameter of the tool pin. It is clear that the Co–WC FSW tool penetrated into the steel, and the bonding occurs only along the width of the pin in this displaced region.

The cross-section of the Cu/steel interface in the bonded region is shown in Fig. 2b when using the smooth pin tool and a penetration of 0.25 mm. A smooth interface is observed near the centerline of the joint, while a series of ridges or ripples with a 10 μm-amplitude occurs near the sides of the interface, as shown in high magnification in Fig. 2c & d. These ridges appear to promote interlocking between the two materials, similar to that observed in explosion welds [28]. The origin of these ridges appears to be related to the oscillations imposed during the rotation of the tool since their spacing increases towards the outer edges of the bonded interface [29]. The spacing of the ridges becomes finer towards the outer periphery of the stir zone (Fig. 2c), which is likely due to overlapping material flow staggered at finer spacings near the sides of the pin. This can be visualized in a prior work explaining the recirculating flow during FSW [30].

Multiple FSW passes (all beginning at the same side) were traversed in the same direction on the lapped Cu/steel, at a spacing of 3 mm between passes with varying pin penetration depths. The first passes were made using both the smooth pin tool, and then later passes were made using the 3-flat tool pin geometry in order to determine how tool penetration and pin geometry influence the microstructure of the bonded interface. Fig. 3 shows the interfacial region between the two passes made using the smooth pin tool with 0.15 and 0.19 mm of penetration, respectively. It can be noted that 0.15 mm of pin penetration did not promote complete bonding with the steel substrate, and in both cases a large number of steel fragments were noted in the stir zone of the welds. A void can also be noted between the boundaries of the two passes.

In order to determine if bonding could be improved with different tool geometry, a 3-flat pin was investigated. Welds were made at progressively increasing plunge depths from 0.06 to 0.60 mm using the 3-