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Interfacial ferrite band formation to suppress intergranular liquid copper penetration of solid steel

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ABSTRACT

Intergranular liquid metal penetration, which is detrimental to the integrity of welded structures, has been widely investigated. Its mechanisms are now more clearly understood, but the suppression method is limited to optimizing processing parameters. In this paper, a metallurgical suppression technique by building an interfacial ferrite band to prevent intergranular liquid Cu penetration of solid steel was proposed. A ternary chemical potential prediction model was established and predicted that Si in liquid copper can accumulate at the interface and diffuse into steel during the interaction between molten Si-containing Cu and solid steel. This interaction can induce the formation of a ferrite band with a high resistance to intergranular liquid copper penetration of solid steel. A model for interfacial ferrite band formation based on Si diffusion during the interaction between solid steel and Si-containing molten copper was proposed and experimentally verified by welding-brazing copper to steel with Si-containing copper wire. The results indicated that long-range intergranular penetration was effectively suppressed, and harmless micropenetration appeared between the ferrite band and weld. The intergranular micro-penetration mechanism is considered a grain boundary liquidation phenomenon induced by Si diffusion, differing from classical wetting theory.

1. Introduction

Hybrid structures with dissimilar-metal welds have attracted more attention [1–3]. For example, Cu/steel structures has great potential for application because they can combine the excellent thermal and electrical conductivity of copper with the high strength and corrosion resistance of steel [4–7]. In the 1950s, such structures were used in the rotating bands of artillery projectiles manufactured by gas metal arc (GMA) surfacing deposition. Since then, components with Cu/steel have been used in more applications in manufacturing industries. These structures can be used in heat exchangers because Cu tubes can accelerate heat exchange via their excellent thermal conductivity. To meet the design requirements for extreme environments, high-performance alloys have been developed and deployed. For example, precipitation-hardened martensitic steels with high strength and corrosion resistance are used in hybrid Cu/steel structures for jet engine combustors. However, joining such high-performance steels with Cu alloy is challenging due to various weldability issues.

Although no brittle intermetallic compounds can form between Cu alloys and steel, fusion welding of the two alloys is problematic. First, a wide, metastable miscibility gap, in which metastable liquid phase separation occurs at an under-cooled condition, may induce welding cracks [8–10]. Second, macrosegregation can occur during welding of Cu/steel [11,12], which may negatively influence the mechanical properties of the joint. In contrast, brazing (or welding-brazing) with a partial heat source, such as laser brazing and arc brazing, can prevent liquid mixing of copper and steel and is a suitable solution. However, grain boundary penetration of molten Cu is a common issue when joining a Cu base alloy to steel using brazing with a partial heat source. Usually, penetration during furnace brazing is not problematic because no open gaps or cracks occur in the base metal. However, a tensile stress develops at the interface between the molten copper and solid steel when a partial heat source is used, which may induce open cracks with significant size near the solid/liquid interface in a steel substrate because of

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metal embrittlement (LME) [13].

Numerous researchers have investigated the phenomenon of Cu-induced hot cracking in steels. Asnis et al. [14] found that Cu will not wet ferritic steel, whereas pearlitic steel is readily wetted. They concluded that the cracks, which formed during the surfacing process, were initiated by a wetting process during steel brazing. Bredzes et al. [15] reported that copper penetration in low-C steel does not occur immediately and depends on diffusion of C to grain boundaries, whereas penetration is not delayed in eutectoid steels. W. F. Savage et al. [16] used the penetration depth and dihedral angle as characterization indicators and enhanced knowledge on the tendencies of molten Cu in penetrating steel grain boundaries. They found that alloy steels such as 4340, 4140 and Type 304 stainless steel are extremely susceptible to molten Cu penetration. Plain carbon steels, such as 1340, 1050, Armco iron, and carburized Armco iron, have penetration depths less than 1/3 that of the alloy steels previously mentioned as well as larger dihedral angles. More importantly, ferritic stainless steel (Type 430) is almost completely immune to Cu penetration, even at 1121 °C, when the matrix is ferritic (BCC) [16]. A. M. Bozhko et al. [17] found that when Cu is deposited on high-Si transformer steel that is also ferritic (BCC) at the melting point of Cu, the Cu penetration behavior is identical to that of Type 430 steel.

In general, the suppression of intergranular liquid Cu penetration into solid steel is limited by controlling the process parameters [4–8,16,18–21]. However, the metallurgical approach of preventing Cu penetration could be more effective. The above mentioned investigations indicate that ferrite has a greater intergranular penetration resistance to molten Cu penetration than austenite. As a result, intergranular penetration can be suppressed by introducing a thin layer of ferrite as a barrier. A convenient method is adding a ferrite stabilizer to copper to promote ferrite formation at the Cu/steel interface. Si could be used as an effective ferrite stabilization element. Its relatively large diffusion coefficient in steel is also beneficial to control the interfacial reaction. In addition, Si can improve the fluidity of molten Cu, which is an advantage to control weld appearance.

Fig. 1 shows the schematics of the suppression of intergranular penetration cracks by building a ferrite band when the liquid copper interacts with the solid steel. Molten Cu diffuses into the grain boundaries of austenite, which weakens the strength between the grains. The crack appears under the thermal stress induced by the welding process, as shown in Fig. (a). When Si, a ferrite promoter, is added to the molten Cu, a ferrite band can form between the liquid Cu and solid steel due to diffusion of Si from the Cu into the steel, as shown in Fig. 1b. The ferrite band acts as a barrier to liquid Cu penetration. Therefore, intergranular crack formation is suppressed although the interface suffers residual thermal stress.

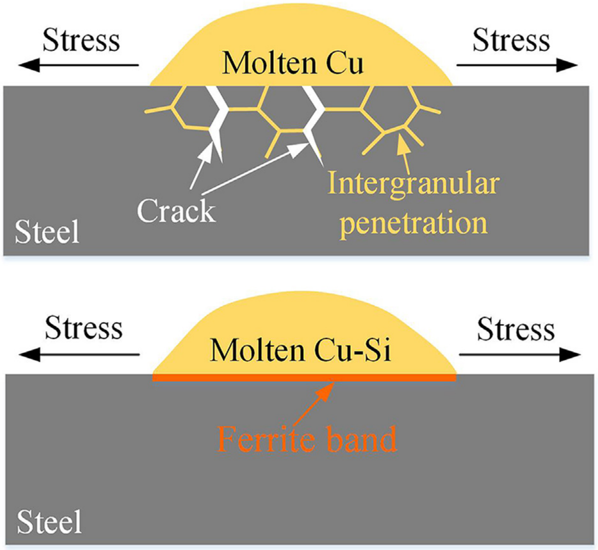

Fig. 1. Mechanism suppressing intergranular liquid copper penetration of cracks in steel by building a ferrite band: (a) without Si in molten Cu and (b) with Si in molten Cu.

To prove the ferrite band could be built by adding Si to the copper and suppress intergranular liquid copper penetration of solid steel, this paper focuses on the influence of Si on interaction between the liquid copper and the solid steel. A chemical potential prediction model for a ternary system was built to evaluate Si diffusion behavior in the near field of the interface between Si-containing liquid copper and solid steel. Furthermore, a model suppressing intergranular penetration of Si-containing molten copper into steel was established. The model was verified by designing cold metal transfer (CMT) welding-brazing of Cu to precipitation-hardened stainless steel with a Si-containing filler wire. When Si in molten Cu diffuses to the steel, the tendency to form a ferrite layer was analyzed. Interfacial phenomena during the interaction between solid steel and the Si-containing liquid copper were discussed.

2. Experiments

To verify the models suggested in the current investigation, a CMT welding-brazing experiment with Cu/steel dissimilar metals was designed. A schematic of the experimental setup is shown in Fig. 2. TPS4000 CMT welding equipment was used. The wire tip was aligned at the edge of the Cu plates.

A precipitation-hardened martensitic stainless steel (S06) and a chromium bronze (QCr0.8) were selected as the experimental materials. Their compositions are listed in Table 1. Plates of steel with dimensions of 100 mm × 80 mm × 8.0 mm and copper with dimensions of 100 mm × 80 mm × 2.5 mm were prepared for CMT welding-brazing. A Si-containing S201 wire was used as the filler metal. The compositions of the welding wire are listed in Table 1.

Welding currents ranging from 120 A to 180 A, which have been confirmed by experiments to ensure good weld appearance and stable welding process, were used to investigate the influence of the heating input on the microstructure and grain boundary penetration. After welding, the samples were cut from their start, middle and end positions to obtain 3 specimens for the grain

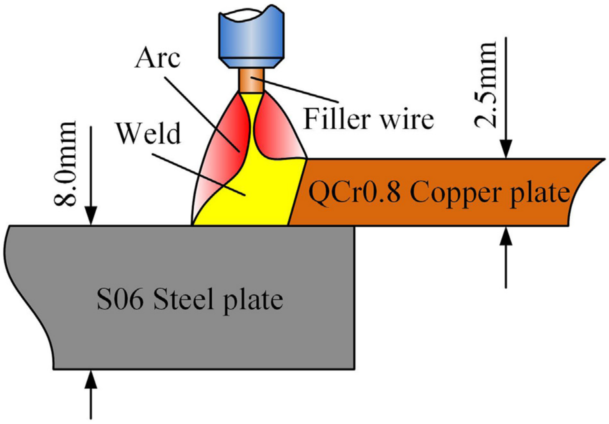

Fig. 2. Schematic of CMT welding-brazing process.