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Interfacial microstructures and mechanical property of vaporizing foil actuator welding of aluminum alloy to steel

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ABSTRACT

Different from traditional collision welding methods in driving principle, vaporizing foil actuator welding (VFAW) was developed to weld 3003 aluminum alloy (Al) to 4130 steel (Fe). The interfacial morphology and microstructures of VFAW were investigated, and the effect of the impact angle on interfacial morphology was analyzed through a groove die with a special angle. Results showed that irregular interfacial waves were formed between Al and Fe, confirming that the VFAW achieved metallurgical bonding. The range of impact angle forming interfacial irregular waves was from 8° to 24°, which meant the impact welding of 3003 Al to 4130 Fe has relatively wide weldable range of collision angle. The formation of irregular interfacial waves considered to be related to match between the density of the flyer and the ultimate static strength of the target. A very thin layer with intermetallic compounds, composed of continuous $Al_{86}Fe_{14}$ and massive Fe_4Al_{13} and FeAl, was formed in the trough of interfacial waves. The layer with intermetallic compounds was formed by very thin liquid metal, which was the residual liquid metal of the jet flow along the interface. The highest anti-shear capacity of the joint exceeds 200 N/mm.

1. Introduction

Composite structure steel (Fe) and aluminum alloy (Al) have advantageously combined the good mechanical property of Fe and the lightweight and corrosion-resistance properties of Al. Thus, these materials have high potential for application in the automobile, aerospace, and aviation industries. However, the welding of Al to Fe using the traditional fusion-welding method is difficult because of the formation of mass of intermetallic compounds.

Recently, the task of combining Al with Fe has focused on the solid-phase welding methods that enable the effective suppression of the formation of intermetallic compounds, compared with fusion-welding method. Diffusion and friction welding, which are typical solid-phase welding methods, have been used to join Al to Fe. As a novel solid-phase welding method, friction stir welding has several advantages in joining Al to Fe. Kimapong et al. [1] and Chen et al. [2] reported that the butt- and lap-joint welding of an Al plate to an Fe plate was achieved easily and successfully. Several experiments on joining Al to Fe were published. The consumption of stirring head, which frays severely because of the high hardness of steel, is a challenge for fraction stir welding of Al to Fe.

Collision welding such as explosive welding (EXW) and magnetic pulse welding (MPW) is a solid-state process; thus, the technologies are favorable to joining Al to Fe. The EXW is a typical collision-welding method with significant advantage for manufacturing a large area of an Fe/Al composite plate. Recently, explosive cladding method has focused on bi-metallic steel/aluminum pipes. Sun et al. [3] prepared an Fe/Al-clad tube by the EXW and found that the bonding interface of clad tubes had higher shear strength than pure aluminum, which meant the bonding interface of clad tubes could withstand both axial and radial deformation. Zamani et al. [4] produced bi-metallic corrosion-resistant steel pipes through the EXW. This investigation showed the wavy interface transformed into a smooth decreasing explosive load. Sui et al. [5] investigated through finite element simulation and experiments the bonding mechanism of an Fe/Al-clad tube prepared via the EXW. It is found that radial contraction and slope collision through continuous local plastic deformation are necessary for the good bonding of tubes. Guo et al. [6] prepared the clad pipe adopted by different mould materials to evaluate the effect of the constraint on the clad quality of the bimetal pipe prepared via explosive cladding. When the steel mould was adopted, the outer diameter of the clad pipe was uniform from head to tail and the

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metallurgical bonding was formed.

Magnetic pulse welding (MPW) is a solid state and high rate welding (joining) process derived from magnetic pulse forming. One of the promising welding methods for Fe/Al joints, the MPW process meets the requirements of automobile manufacturing. This method is suitable for welding of tube configuration because of the convenience it allows in MPW actuator design. Yu et al. [7] investigated the mechanical property and microstructure of an Fe/Al tube joint via magnetic pulse welding. Metallurgic bonding between Fe and Al was obtained by discharge voltage of 15 kV and preset angle of 4°. In addition, Yu et al. [8] manufactured a aluminum-clad steel tubes by the MPW. The results show that the proposed MPW process is able to form sound cladding bonds and could be applicable to a tubular clad component with a high axial length. Raoelison et al. [9] investigated the weldability of Al 6060T6 tubular assembly welded via magnetic pulse welding. The weld variance presented in a charging voltage/gap diagram displayed the curve limit with convex shape tendency for the straight/wavy transition and the isovalues of high-amplitude waves. Kore et al. [10], Lee et al. [11] and Zhang et al. [12] developed MPW seam linear welding. These methods tended to use much less energy than those for tube welding. For example, Kore et al. [10] found that the energy needed to weld a 1 mm-thick Al plate to Fe plate was only about 1.4 kJ because of the very rapid rise times (time for the actuator to reach maximum primary current) in the capacitor discharge circuit.

Daehn et al. [13,14] developed the novel collision welding method called vaporizing foil actuator welding (VFAW). A 0.0762 mm-thick Al foil was vaporized by a strong electric current in an extremely short time using a capacitor bank. The pressure created from the vaporizing Al foil drove the flyer to collide with the target, and then both metals were joined. The study concluded that a robust collision welding technique can successfully weld various dissimilar metal pairs. The VFAW could create similar welds made by the EXW, but at much smaller length scales. Compared with the MPW, the VFAW could drive the flyer to higher impact velocity, which indicates higher potential for welding. In addition, there is no issue of coil longevity, and even low conductivity materials can be launched without the use of a driver sheet.

As a novel joining technology, the VFAW of Fe/Al dissimilar metals is not investigated. The microstructures, interfacial morphology and mechanical property of Fe/Al dissimilar metals joint by the VFAW are not understood. The insight into the characteristics of Fe/Al dissimilar metals has significance in the application of VFAW.

In the current study, the 3003 Al was welded to the 4130 Fe via the VFAW. Through the design of a groove die experiment, the proper range of the impact angle was obtained and the characteristics of interfacial morphology and microstructures were investigated. Influence of processing parameters on anti-shear capacity of the joint was analyzed. Furthermore, the formation mechanism of interfacial waves and interfacial intermetallic compounds in the VFAW were discussed.

2. Experimental methods

The 3003 Al was selected as the flyer after H14 heat treatment, and its reference condition was ASTM B209. The target was 4130 Fe with reference condition of AMS 6350-6351 after the annealing process. The chemical compositions are shown in Tables 1 and 2, respectively. The mechanical properties are presented in Table 3. Flyers that are 0.508 mm thick and targets that are 6.35 mm thick were squares with side length of 76.2 mm. A 0.0762 mm-thick Al foil insulated by an adhesive polymer tape was placed under the flyer. The ends of the aluminum foil were connected to the terminals of a capacitor bank. The active area of the foils was 50.8 mm long and 12.7 mm wide, as shown in Fig. 1a. A standoff was preset between the flyer and the target, as shown in Fig. 1b. The target was backed by a heavy Fe block, and the specimens were fastened by four bolts at four corners. When the capacitor bank was discharged, a strong current in the order of 100 kA flowed through the foil. Thus, the foil was vaporized in tens of microseconds. Therefore, the collision forces by the foil vaporizing drove the flyer sheet to a high speed toward the target sheet at a standoff distance. The target impacted obliquely by high-speed flyer generated jets under a proper preset angle. The wave interface morphology was formed on both sides, as shown in Fig. 1b. Finally, Al was welded to Fe via VFAW.

Shear tests were performed to evaluate the mechanical properties of the joint. It is difficult to measure the shear area of the joint in this paper. Hence, the anti-shear capacity is expressed by highest shear load per length, N/mm. The specimens were cut to shear test by line cutting device. The width of specimens is 20 mm. Every specimen was cut from center line because there are two seams. The anti-shear capacity is average value of two specimens. The shear tests were conducted by means of a specially designed fixture at a cross head rate of 1 mm/min, as shown in Fig. 2. The maximum gap between the outer surface of Fe part and the inner surface of the fixed jaw has been restricted in very low level by accurate machining because the thickness of the flyer is only 0.5 mm. The fixture was manufactured by high strength steel to avoid its abrasion and deformation. The steel and the fixture were clamped by testing machine to ensure that the Fe part as well as the Al part are not deviated from the shearing surface during the compression load.

The specimens for OM observation were first mechanically grinded with abrasive paper up to 1000 grits followed by final polish with 1 μm Al_2O_3 suspensions. The microstructures of the specimens before and after tensile tests were observed using scanning electron microscopy (SEM) equipped with an energy-dispersive X-ray spectrometer (EDS). The crystalline phases in the interfacial layer of the joint were identified by micro-beam X-ray diffractometer (XRD).

3. Results

3.1. Interfacial morphologies

The macro-cross section of the specimen perpendicular to the axis of the foil is shown in Fig. 3. The Al and Fe seem to be close contact; however, strong metallurgical bonding is achieved only in the partial zone along the foil perimeter. The target at the center directly collides with the high-speed flyer. When the flyer hits the target in the center, the impact angle is zero. The oblique impact that is necessary to form weld is not reached. In addition, no jetting is formed when the impact angle is zero. The weld is difficult because contaminants and oxide film on the metal surface are not removed. The two sides of the flyer sheet opposite the active foil area collapse from that area to two sides of the target. When the angle and velocity of the impact fall within an appropriate range, metallurgical bonding occurs at the interface between the flyer and the target, as shown in Fig. 3.

Fig. 4 illustrates the interfacial morphology at the joining zone. The interfacial morphology has slight waves, which means that reliable metallurgical bonding is achieved successfully. In Fig. 4, the motion direction of the collision point is from left to right. Irregular interfacial waves are formed along the interface between 4130 Fe and 3003 Al. The wavelength of the interfacial wave increases along the motion direction.