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Research on explosive welding of aluminum alloy to steel with dovetail grooves

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ABSTRACT

In order to explore a new method for the explosive welding of aluminum alloy to steel, a 5083 aluminum alloy plate and a Q345 steel plate with dovetail grooves were respectively employed as the flyer and base plates. The parameters adopted in the explosive welding experiment were close to the lower limit of weldable window of 5083 aluminum alloy to Q345 steel. The bonding properties of 5083/Q345 clad plate were studied through mechanical performance tests and microstructure observations. The results showed that the aluminum alloy and steel plates were welded under the actions of metallurgical bonding and meshing of dovetail grooves. The tensile shear strength of 5083/Q345 clad plate met the requirements of the bonding strength of Al/Fe clad plate. The interfaces between aluminum alloy and the upper and lower surfaces of dovetail grooves were mainly welded through direct bonding, and discontinuous molten zone emerged in the local region; while the interface between aluminum alloy and the inclined surface of dovetail grooves was bonded by continuous molten layer. The brittle intermetallic compounds $FeAl_2$ and Al_5Fe_2 were generated at the bonding interfaces of 5083/Q345 clad plate. The fracture surface of the tensile specimen exhibited ductile and quasi-cleavage fractures.

1. Introduction

With the development of modern industry, single metallic constituents cannot meet the requirements of utilization. Instead, with the respective merits of two metallic components, the bimetallic clad plate is capable of obtaining the performance that single metallic constituents fail to provide. Explosive welding employs explosive energy to make metal surface produce intense plastic deformation and to achieve metallurgical bonding between metal plates. Metallurgical bonding formed at the interface possesses higher shear strength, and the metallic materials used for explosive welding are unconstrained. Explosive welding is widely used in the manufacture of bimetallic clad plate, and researchers have successfully achieved such welding of hundreds of homogeneous or heterogeneous metallic materials [1–5].

Aluminum alloy exhibits excellent performances such as small density, good conductivity, high thermal conductivity, and good corrosion resistance. Aluminum-clad steel is widely applied to the fields of aerospace, ship-building, machine manufacturing and chemical engineering, etc. However, it is difficult to directly achieve explosive welding of aluminum alloy to steel, especially Al-Mg alloy to steel with sound welding quality. At present, a thin aluminum, nickel, titanium or steel plate as intermediate plate is inserted between them to achieve explosive welding of aluminum alloy to steel [6–8]. Welded with each other, the metal plates are then processed into a clad plate with multi-layers.

In Wang et al.'s work, the aluminum alloy-aluminum-steel clad plate was manufactured by explosive welding. The results showed that metallurgical behavior was achieved at the bonding interfaces between aluminum alloy and aluminum and between aluminum and steel, among which the bonding interfaces between aluminum alloy and aluminum presented regular sine waves; while the bonding interfaces between aluminum and steel was line-shape [7]. In Hokamoto et al.'s study, the explosive welding of aluminum alloy to stainless steel could be achieved by inserting a thin stainless steel plate as the intermediate transition layer between the two metal plates. The intermediate transition layer of the Al/Fe clad plate was composed of Al and Fe_4Al_{13} [8]. An AA5083 aluminum alloy plate and a SS41 steel plate adopted an AA1050 aluminum alloy plate as the transition layer, and were welded together by using explosive method. The results showed that the interfacial transition zone comprised intermetallic compound $FeAl_3$, which was deemed as a crack source at the bonding interface of 1050/SS41 clad plate. The shear strength of the clad plate gradually decreased as the increase in thickness of transition layer [9]. Muneshwar et al. reported that aluminum alloys and austenitic stainless were often used for construction of cryogenic pressure vessels owing to their attractive properties at cryogenic temperatures. Pure aluminum sheet were used as an interlayer between aluminum alloy and steel to achieve a satisfactory bond [10]. Aceves et al. studied that there were lots of difficulties in directly explosive welding joining of 6061 aluminum alloy to 304 stainless steel, thus interlayer was used to prevent interaction of the

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aluminum alloy and stainless steel and minimize brittle intermetallic phase formation. Titanium (Ti), copper (Cu), and tantalum (Ta) were selected as the dissimilar metal interlayer materials. Results of the characterization of the three interlayer bonds showed that Ti produced the best strength joints, Ta produced the most ductile joints, and Cu produced a joint that failed with low ductility at the Al/Cu interface. The Ti and Ta interlayer bonds both appear to have sufficient strength and ductility for the intended use [11]. Guo et al.'s results showed that aluminum/316 L stainless steel bimetallic pipe with excellent metallurgical bonding quality could be achieved by explosive welding. They claimed that the bonding quality of aluminum/316 L bimetallic clad pipe was excellent. In addition, the Al-316 L SS clad pipe could endure the second plastic forming [12].

Traditional aluminum alloy and steel are hard to be directly welded by explosive method. What's worse, it has the shortcomings such as complex process, lower efficiency and higher cost. In this study, an aluminum alloy plate and a steel plate with dovetail grooves are used for the explosive welding. It is a new method for the explosive welding of aluminum alloy to steel.

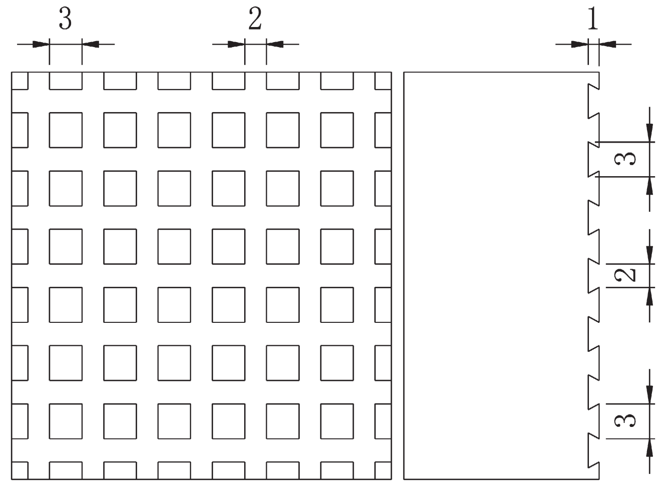

Fig. 1. Schematic diagram of the base plate with dovetail grooves.

2. Experimental materials and methods

2.1. Experimental materials

The flyer and base plates used in this study were respectively made of 5083 aluminum alloy and Q345 steel, whose corresponding dimensions were 4 mm × 430 mm × 430 mm and 15 mm × 400 mm × 400 mm. The physical and mechanical properties of the flyer and base plates are given in Table 1.

Dovetail grooves were cut along the transverse and longitudinal of the base plate. The upper side length, the lower side length and the height of dovetail grooves were 2 mm, 3 mm and 1 mm successively. All the intervals between dovetail grooves were 3 mm, as shown in Fig. 1.

Honeycomb structure is advantageous at aspects such as stable structure, good flatness, high strength and stiffness. The material of honeycomb panel was 3003H24 aluminum alloy with a thickness of 50um, and the honeycomb holes were of regular hexagon with a length of 8 mm, as shown in Fig. 2.

The aluminum honeycomb explosive consisted of emulsion explosive filled with honeycomb holes, as shown in Fig. 3. Aluminum honeycomb panel could ensure that the thickness of welded explosive was identical in different positions, and its dimension could be selected according to the explosive charge.

A parallel installment structure was applied in the explosive welding set-up, and a non-electric detonator was located at the center of the explosive, as shown in Fig. 4.

2.2. Experimental methods

The specimens for tensile and tensile shear tests were prepared according to GB/T6396-2008 [13]. The tensile tests and the tensile shearing tests were both performed on an MTS-810 type universal testing machine, and the speed was respectively 2 mm/min and 0.5 mm/min. The metallographic specimens were ground and polished to 1um finish. The etchant of 5083 aluminum alloy consisted of 1 mL HF and 100 ml H_2O, and the etchant of Q345 steel consisted of 4 mL HNO_3 and 96 mL anhydrous alcohol. A Carl Zeiss Axio Imager A1m type optical microscope (OM) and an XL-30 type scanning electron microscope (SEM) were used for the microstructure observation at the interfaces of 5083/Q345 clad plate. An ESCALAB 250 type energy-dispersive X-ray spectrometry (EDS) and a TTR-III type X-ray diffraction (XRD) analysis were used to analyze the distribution of the phases at the interfaces of 5083/Q345 clad plate. The fracture characteristics of the tensile specimens were examined through an XL-30 type scanning electron microscope (SEM).

Table 1
Physical and mechanical properties of metallic materials at room temperature.

Material	T/°C	ρ/g · cm^{-3}	HV	σ_s/MPa	σ_b/MPa	C/m · s^{-1}
5083 aluminum alloy	570 ~ 640	2.72	61	125	270	6300
Q345 steel	1523	7.85	168	385	609	6000

Note: T is the melting point of metallic material; HV is the Vickers hardness of metallic material; C is the sonic speed of metallic material.

3. Explosive welding parameters

3.1. The dynamic parameters

The crux of achieving explosive welding and acquiring excellent welding quality is to choose reasonable parameters [14–16]. The process of explosive welding was affected by dynamic parameters like the collision angle, the collision point velocity and the collision velocity.

Fig. 2. Aluminum honeycomb panel.