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ARTICLE

Interfacial Bonding Mechanism and Mechanical Performance of Ti/Steel Bimetallic Clad Sheet Produced by Explosive Welding and Annealing

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Abstract: The microstructural characterization and interfacial shear tests of Ti/Steel bimetallic clad sheets were taken to study the interfacial bonding mechanism during the explosive welding process. The results show that the wavy interface with several vortexes forms between the dissimilar metal matrixes due to the interface deformation. A significant metal flow of steel matrix caused by the severe plastic deformation induces the continuous vortexes in the interface. The TEM and XRD analyses clarify that the nanoscale interfacial interlayer contains solid solutions and a small amount of intermetallic compounds. The shear strength of the interface along the explosive welding direction is enhanced by the wavy interface. The fracture of the bonding interface presents the ductile features on the vortex while brittle features on the smooth interface.

Key words: clad sheet; explosive welding; interface; TEM; intermetallic compounds

The clad sheets composed of dissimilar metals have been attracting much attention by combining the outstanding properties of dissimilar metals[1,2]. Particularly, the explosive welding technique is popular in the cladding field for its good capability of large deformation and high strain energy [3]. The study on the bond strength of explosive welded specimens reveals that, during explosive welding process, the interface is molten and has a remarkable atomic diffusion under the significant explosive impacting and deformation energy[4].

A good metallic bonding can be formed in the interface based on the control of explosive parameters[5]. After that, thermal annealing is necessary to remove the explosive residual work hardening[6]. A series of clad sheets can be produced by the explosive welding technique through designing the component material and thickness ratio[7]. In particular, Ti/Steel clad sheets were manufactured by Kundu, which can be applied in the heat-exchange facility based on the excellent heat conduction, mechanical strength, and corrosion resistance as well as low cost[8].

Nowadays, the microstructural characterization of the bonding interface has been wildly studied in the metallographic approach. Gulenc investigated the interfacial properties and weldability of aluminum and copper plates by the explosive welding method[9]. Kacar and Acarer reported the relationship between microstructure and mechanical properties of explosive welded duplex stainless steel-steel[10]. Kahraman systematically investigated the interfacial bonding quality of clad sheets using the tensile shear, bending and hardness tests [11]. The effect of explosive parameters on the cladding product has been summarized to guide the production in the future. The numerical simulation of explosive welding process has been reported to clearly understand the welding mechanism[12]. In addition, Acarer and Demir have studied the fundamental welding process and thermal kinetics in the explosive welded aluminum-dual phase steel[13]. However, the interfacial microstructure and fracture have not been deeply studied through the electron microscopy. The bonding mechanism of the welded interface in the explosive process

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is also lack of clear interpretation.

In the present paper, the interfacial microstructure and chemical phase were characterized through the optical and electron microscopy, and the X-ray diffraction analysis. The interfacial interlayer in high magnification was observed by the transmission electron microscope (TEM). The interface effect on the shear performance of explosive welded Ti/Steel clad sheets were studied according to the shear tests on the interface along the explosive direction.

1 Experiment

The raw materials were steel sheet SA516Gr.70 with thickness of 72 mm and titanium sheet SB265Gr.2 with thickness of 12 mm. They were fully annealed and obtained the initial shear strength of 265 and 200 MPa, respectively. They were assembled with a parallel distance of 12 mm. The powdery emulsion explosives with density of 0.84 $g\cdot cm^{-3}$ and thickness of 41 mm exploded from the center of clad layer at the velocity of 2460 $m\cdot s^{-1}$. Then the clad sheets were heat treated at 540 ^{o}C for 3 h. The metallographic preparation was taken on the longitudinal section along the explosive direction following the conventional methods.

The overall interfacial microstructures of the explosive welded clad sheet were observed by optical microscope (OM) and scanning electron microscope (SEM) SSX-550 equipped with energy dispersive X-ray detector (EDX). The phase constitution of the interfacial zone was measured through XRD analysis on the X'Pert Pro instrument with Cu target. Particularly, the interfacial characteristic was verified by the G2 TECAN TEM with a 200 kV accelerating voltage on the cross-sectional film which was thinned by precision ion milling.

The compression shear tests were carried out on the SANSCMT 5000 materials testing system at room temperature with the loading stress rate of 4 $MPa\cdot s^{-1}$. The load was taken along the interface. The samples with shear area of 5 mm × 25 mm were prepared from the center of clad sheet along the explosive direction according to ASTM 264. The compression shear schematic diagram is given in Fig.1. After that, the fracture observation was observed by SEM to analyze the interfacial failure.

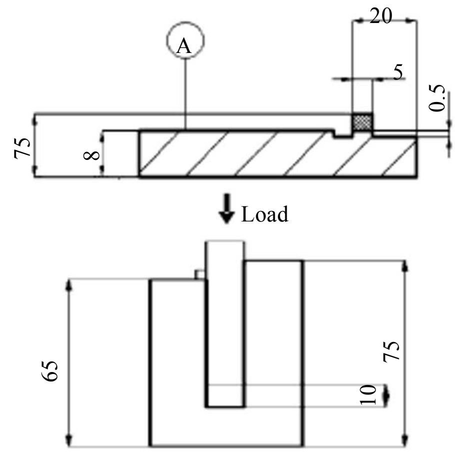

Fig. 1 Schematic diagram of the compression shear test for clad sheet

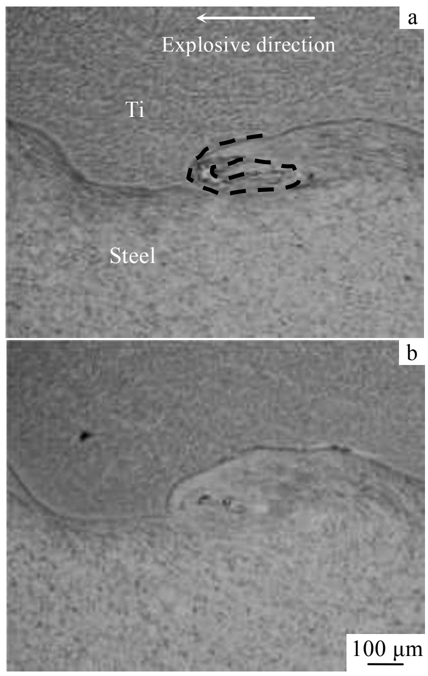

Fig.2 Interfacial macrostructure of Ti/Steel clad sheet: (a) clear path is illustrated by the dotted line in the interface and (b) a few of black molten objects are wrapped into the interfacial vortex

2 Results and Discussion

2.1 Interfacial microstructure of Ti/steel clad sheet

The Ti/Steel clad sheet, obtaining the significant work-hardening during the explosive welding process, must be annealed to get the optimal mechanical properties. In our previous investigations, applicable annealing parameters had been gotten and used in this experiment. Thus, only the annealed clad sheets are studied in the following sections. The interfacial zone of explosive welded Ti/Steel clad sheet after annealing is illustrated in Fig.2. It is revealed that some distinct wavy vortexes of steel exist on the interface with the elongated grains along the explosive direction.

As illustrated by the dotted line track in Fig.2, the whole deformation in the interface is clear according to the distribution of vortex. During the explosive welding process, the substrate steel plate gets a significant explosive impacting, which causes a severe deformation on the metal surface. Due to the lower melting temperature of steel than that of titanium, the deformation heat can soften steel, and then the surface layer of steel gets a prominent metal flow