Journal of Materials Processing Tech. 261 (2018) 24–30

Contents lists available at ScienceDirect

Journal of Materials Processing Tech.

journal homepage: www.elsevier.com/locate/jmatprotec

# Interfacial evolution of explosively welded titanium/steel joint under subsequent EBW process

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ARTICLE INFO

*Keywords:*
Titanium alloy
Mild steel
Explosive welding
Electron beam welding
Tensile strength
Residual stress

ABSTRACT

Electron beam welding of titanium alloy to mild steel with a transition joint prepared by explosively welding method was carried out. The interfacial structure of explosive weld and tensile strength of the joint were affected significantly by the distance between electron beam weld and explosive weld. When the electron beam weld was 1.5 mm away from the explosive weld, the explosive interface layer was liquefied during electron beam welding process, which was consisted of Fess, Fe + Fe2Ti eutectic, FeTi + Fe2Ti peritectic and Ti + Fe2Ti eutectic from the Fe side to the Ti side. When this distance increased to more than 3 mm, the thickness of interfacial intermetallic compounds in explosive weld decreased sharply from 40 μm to lower than 3 μm. The interface layer kept in solid state and diffusion of Ti and Fe atoms occurred across the interface. When the electron beam weld was located 6 mm away from the explosive weld, the maximum tensile strength of 418 MPa was obtained. In this case, the residual stress across the explosive interface induced by electron beam welding reached to the lowest value in this experiment.

## 1. Introduction

Because of metallurgical incompatibilities, the weldability of titanium alloy to steel is very poor. Solid-state joining is a viable solution to overcome this difficulty. Kundu et al. (2011) and Orhan et al. (2001) suggested that the brittleness of Fe-Ti and Fe-Cr-Ti intermetallics compromised the mechanical properties of diffusion bonding joints between titanium alloys and stainless steels. Aleman et al. (1993) reported that another factor for crack formation during diffusion bonding of titanium alloy to stainless steel was the internal stress induced by the differences in linear expansion and thermal conductivity between titanium and steel. Dey et al. (2009) and Fazel-Najafabadi et al. (2010) proved that Ti-Fe intermetallics formed in the interface during friction welding of titanium alloy to stainless steel. Fracture occurred at the TiFe-based interface and the tensile strength decreased with the thickening of the intermetallic layer. Chu et al. (2017) found that the explosion-bonded titanium/steel bimetallic joint can obtain a high strength of 540 MPa, with only a thin Ti-Fe intermetallics layer for the short welding time.

It is difficult to apply diffusion bonding and other solid state bonding methods to join titanium alloys and steels for some special components due to restriction of the complex geometric shapes. A feasible fusion welding method to join these two dissimilar metals is necessary for further development. Traditional arc welding methods are not feasible for joining Ti/steel joints. Satoh et al. (2013) investigated laser welding of grade 2 pure titanium to 316 stainless steel. Tensile strength of joint with brittle fracture was lower than those of base materials. Chen et al. (2014) showed that the highest tensile strength of laser welded Ti/Fe joint was 150 MPa at the optimized welding position and fracture occurred along the two adjacent interface layers. Wang et al. (2012) found that electron beam welded Ti/Fe joint ruptured immediately after welding due to the formation of continuous Ti-Fe intermetallics in the weld. Wang et al. (2012) and Tomashchuk et al. (2013) proved brittle intermetallic compounds were eliminated during electron beam welding by adding the copper or vanadium interlayer between Ti and Fe. Tensile strengths could be improved to 310–359 MPa with brittle fracture characteristics. Mitelea et al. (2013) also showed that copper foil interlayer could improve the tensile strength to 400 MPa for a laser welded Ti-6Al-4 V alloy to S5CrNi18-10 stainless steel joint with a mainly ductile fracture mode. The fusion welded joints of Ti/Fe dissimilar alloys could be improved with the adoption of interlayer alloys, but the tensile strengths were still limited.

In order to make full use of the flexibility of electron beam welding method and the high joining strength of explosive welded joint, a hybrid welding joint of electron beam welding (EBW) and explosive welding (EXW) was applied to further promote the application of Ti/Fe

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https://doi.org/10.1016/j.jmatprotec.2018.05.031
Received 10 January 2018; Received in revised form 14 May 2018; Accepted 28 May 2018
Available online 30 May 2018

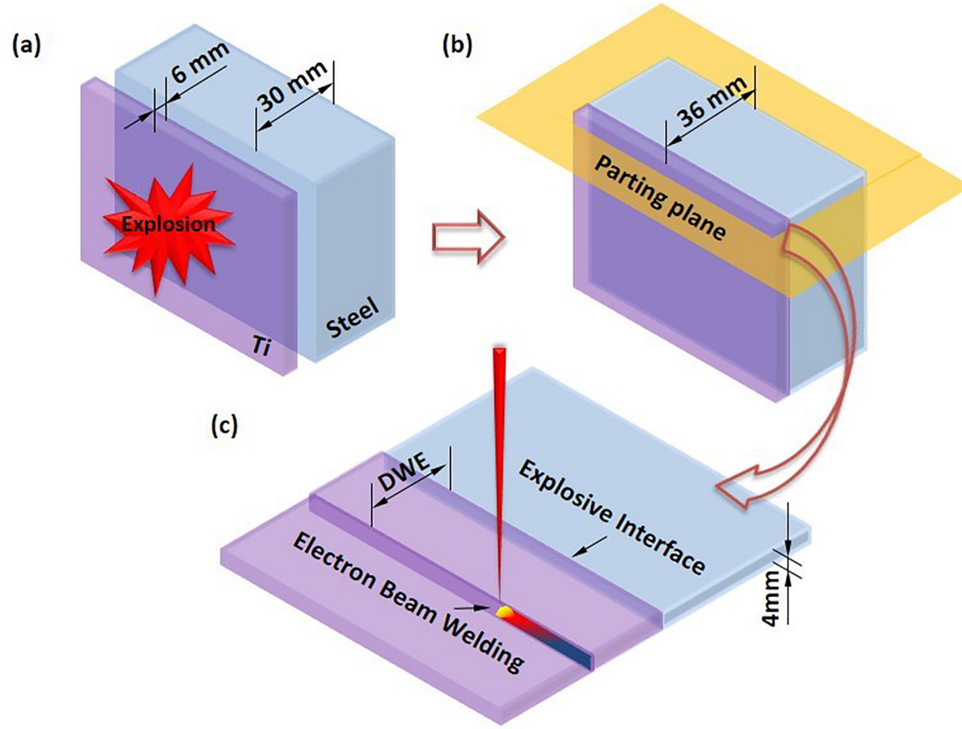


**Fig. 1.** Schematic diagram of welding process with hybrid electron beam-explosive welding joint. (a- Formation of the explosive welding joint, b- Fabrication of the Ti-steel composite plate as transition joint, c- Formation of the hybrid electron beam-explosive welding joint.).

dissimilar joint. The influences of distance between EBW and EXW on the interface and mechanical properties of the hybrid Ti/Fe dissimilar joints were investigated. The strengthening mechanism of the Ti/Fe dissimilar joint was analyzed.

## 2. Materials and methods

TA10 (Ti-0.3Mo-0.8Ni) titanium alloy and Q345 (Fe-0.20C-0.55Si-1.30Mn-0.02Al) mild steel were used as the base metals. TA10 plates with thickness of 6 mm and Q345 plates with thickness of 30 mm were firstly welded by explosive welding. The parameters of explosive welding were shown as follows: detonation velocity was 2200 m/s and the density of explosive material was 900 kg/m$^3$, applied stand-off distance was 6 mm and impact angle was 12.2 °. Then the explosion-welded TA10/Q345 composite plates were cut vertically to the explosive welding interface to obtain transition joints with thickness of 4 mm. The as cut plates were then electron beam welded with TA10 plates. The schematic diagram of the welding process is shown in Fig. 1. The distance between EBW and EXW is abbreviated as DEW in this paper. The DEWs were selected as 1.5 mm, 3 mm, 4.5 mm and 6 mm at Ti side. The welding parameters used in electron beam welding were optimized as beam current of 35 mA, welding velocity of 800 mm/min and high voltage of 70 kV.

All samples cut off from the welded plates were prepared with standard grinding and polishing. Fractional corrosion method was used for the different base metals. The Ti side was etched by Kroll reagent (2 ml HF + 4 ml $HNO_3$ + 94 ml $H_2O$) and steel side was etched by a solution of 4% nitric acid and 96% alcohol. Microstructure and chemical composition were observed by an optical microscope and a scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectrometry (EDS) system. The intermetallic phases existing on the fracture surface of the explosive weld were detected by X-ray diffractometer (XRD). To evaluate the mechanical properties of the hybrid welding joints of TA10 to Q345, UTS was conducted on a universal testing machine with the speed of 1.5 mm/min at room temperature. The geometric dimension of UTS sample is shown in Fig. 2 and three samples were tested for each condition.

A 3-D thermal-structural finite element model was built to simulate the thermal field and residual stress of the electron beam welding process. The effects of temperature on the material properties, including elastic modulus, yielding strength, specific heat, thermal conductivity and linear expansion coefficients, were taken into consideration during the simulation process. The thermal-physical properties of TA10 and Q345 used in this study were referenced from Mousavi and Al-Hassani (2005) and Chu et al. (2015). The initial temperature was set as 20 °C and the heat transfer coefficient was 40 W/ (m$^2$ K). The finite element model and calculation method were described in the former published article (Zhang et al., 2012). The TA10-Q345 composite plate was considered as a whole plate. The interface layer in the explosive weld was ignored in the FEM model, because it was too thin to test the physical properties.

## 3. Results

The optical micrographs of explosive interfaces after electron beam welding are shown in Fig. 3a–d. All the explosive interfaces exhibit slight waviness. The explosive interface layer thickness (EIT) decreases with the increase of DEW. Electron beam welding does not obviously affect the microstructures of the explosive interfaces when DEW ≥ 3 mm. The EITs under different DEWs are respectively 3 μm, 2.5 μm and 2.3 μm according to the EDS results shown in Fig. 4. But the subsequent electron beam welding process influences the explosive interface significantly when DEW = 1.5 mm and the EIT increased to 40 μm, as shown in Fig. 3a.

The typical explosive interfaces are shown in Fig. 5a–b obtained under the conditions of DEW > 1.5 mm. The morphologies of the interface layers do not change with the increase of DEW, which are the same as that of the explosive welded Ti/Fe joint obtained by Akbari Mousavi and Farhadi Sartangi (2009). Thin layer of FeTi and $Fe_2Ti$ formed in the explosive interface is mainly attributed to the atomic diffusion. The explosive interface obtained under the condition of DEW = 1.5 mm shows eutectic solidification characteristics, as seen