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Evolution of microstructures and mechanical properties during dissimilar electron beam welding of titanium alloy to stainless steel via copper interlayer

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ABSTRACT

The influence of operational parameters on the local phase composition and mechanical stability of the electron beam welds between titanium alloy and AISI 316L austenitic stainless steel with a copper foil as an intermediate layer has been studied.

It was shown that two types of weld morphologies could be obtained depending on beam offset from the center line. Beam shift toward the titanium alloy side results in formation of a large amount of the brittle $TiFe_2$ phase, which is located at the steel/melted zone interface and leads to reducing the mechanical resistance of the weld. Beam shift toward the steel side inhibits the melting of titanium alloy and, so, the formation of brittle intermetallics at the titanium alloy/melted zone interface. Mechanical stability of the obtained junctions was shown to depend on the thickness of this intermetallic layer. The fracture zone of the weld was found to be a mixture of TiCu (3–42 wt%), $TiCu_{1-x}Fe_x$ (x=0.72–0.84) (22–68 wt%) and $TiCu_{1-x}Fe_x$ (x=0.09–0.034) (0–22 wt%). In order to achieve the maximal ultimate tensile strength (350 MPa), the diffusion path length of Ti in the melted zone should be equal to 40–80 μm.

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1. Introduction

The high quality dissimilar junctions between titanium alloys and stainless steel have many applications in chemical [1], cryogenic, [2], nuclear [3] and spacecraft [4] industries because of lower cost and weight of the details containing the titanium parts [5].

The main difficulty in joining titanium alloy with steel using fusion is the formation of zones containing the brittle $TiFe_2$ (hardness > 1300 HV [6]) and $TiCr_2$ intermetallics. That is why this approach is not suitable for the direct joining of these materials. The direct joining of this dissimilar couple can be performed only by solid state methods such as diffusion bonding [7–10], friction [3] and explosive [11] welding. The mechanical stability of the weld between titanium and steel can be enhanced by insertion of the intermediate metal foil that changes character of the interaction in the melted zone and leads to formation other phases than Ti–Fe-rich intermetallics.

The development of fusion methods for joining of titanium alloy to steel using an intermediate foil opens an attractive alternative to solid state joining since it allows higher flexibility in geometry of welds, faster welding process and easier preparation of junction surfaces. However, in order to obtain the highest mechanical strength of the joint the following conditions should be satisfied in this case, namely: the material of the inserted foil should be weldable with both alloys; the operational conditions should be optimized in order to maintain the integrity of this interlayer before the solidification; the local composition should be optimized to prevent the formation of large zones with brittle phases.

The conventional fusion welding methods such as arc welding are not suitable for this purpose because of the formation of long lifetime melted zones with strong mixing of the components. The instability of electric arc makes it difficult to maintain a continuous energy supply that in turn leads to local variations of the melted zone content. The high power beam methods such as laser and electron beam welding are more suitable for joining dissimilar alloys because they provide very local heat supply, rapid heating/cooling gradients and a perfect precision in the weld realization. Both methods were successfully applied for welding of different dissimilar couples in [12–14].

It is known that titanium does not form intermetallic phases with pure Zr, Nb, Mo, Ta, V and Hf, which could be tested as potential interlayers. Good result was also obtained in [15] with pure Ag as interlayer despite the formation of the AgTi intermetallic which is not brittle [16]. The high cost of all these metals

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and problems of their weldability with stainless steel result in use of more available materials such as Cu [5], Ni [17] and their alloys. However, in this case the risk of embrittlement of the weld due to intermetallic phase formation is high enough and titanium/foil interface appears to be the weakest part of the joint. Good results were obtained for infrared bonding of titanium to stainless steel with combined V/Cr/Ni interlayer (here Cr/Ni foil contacts with the stainless steel to prevent the brittle σ-phase of the V–Fe system and V foil contacts with titanium) [18]. The first attempts to use vanadium and tantalum interlayers for CO_2 laser welding have not being successful because of the oxidation problems and formation of the brittle phases [19].

Despite the formation of numerous intermetallic phases in the Cu–Ti system [20], copper is often used as interlayer material for joining titanium alloys to steels due to the compensation of local phase brittleness by ductility of copper. As the Cu–Fe system [21] does not contain intermetallic phases, it is easy to create mechanically stable copper–steel junctions both by solid state (diffusion bonding [22]) and fusion (electron beam [23] and laser [24]) methods. The formation of a narrow reaction zone between titanium and copper, in which the Cu–Ti intermetallics are formed, allows successful joining by explosion welding [25] and diffusion bonding [5,26]. In case of joining by fusion, thin copper foil cannot be able to prevent Ti–Fe interaction completely and therefore the whole Fe–Cu–Ti interaction takes place resulting in five ternary phases [27]. Because of numerous phases formed in the melted zone the optimization of phase composition of the joint becomes a difficult task.

The first attempt to perform fusion welding of titanium alloy to steel with copper interlayer (1 mm thickness) was made by Wang et al. [28]. The junction was obtained by two-pass electron beam welding and melted zone was shown to contain $TiFe_2$ intermetallics dispersed in the copper medium. The mechanical resistance of the weld was equal to 224 MPa and the brittle fracture within intermetallic layer occurred near the titanium/melted zone interface. Previous study [29] of the welding of Ti6Al4V to austenitic stainless steel by both pulsed Nd:YAG laser and electron beam have shown the possibility of one-pass joining with a use of 0.5 mm thick copper foil. In both cases, the shift of heat source to copper–steel interface has allowed reduce the melting of the titanium alloy. The total metallurgical isolation of welded materials by copper interlayer was not achieved. However, the existence of the miscibility gap in the Cu–Fe system [30,31] and rapid cooling of the melt [23,31] resulted in formation of the immiscible flows and droplets between liquid copper and steel that enhanced the barrier function of the foil. The mechanical resistances of the electron beam and pulsed Nd:YAG laser welds were found to be similar (UTS about 350 MPa). This conformity was determined by similar structures of the inner intermetallic layers between Ti6Al4V and melted zone. Close result was obtained by Wang et al. [32] for welding of AISI 304L with Ti6Al2Mo2V2Zr alloy. By use of CO_2 laser Pugacheva et al. [33] have carried out welding of titanium and stainless steel via copper interlayer with injected of TiN and Y_2O_3 nanoparticles, which allowed to disperse brittle intermetallics and attain the UTS of 375 MPa. However, only a few welding conditions were tested in these studies.

In this paper, the influence of operational parameters of electron beam welding of titanium alloy to austenitic stainless steel with use of 0.57 mm thick copper interlayer is explored. The influence of heat source shift and of welding speed on weld morphology, phase content and mechanical resistance of the joint was studied in order to define the optimal structure of dissimilar interfaces.

2. Experimental procedure

2.1. Materials

2 mm thick austenitic stainless steel AISI 316L, 2 mm thick α–β titanium alloy and 572 ± 4 μm thick copper foil were used as raw materials. Their chemical and phase compositions are listed in Table 1.

2.2. Welding method

Electron beam welding was carried out in a key-hole mode using Techmeta S.A. welding machine with maximal beam power of 6 kW and spot diameter of 400 μm. The acceleration voltage of welding was 25 kV and beam current was 40 mA. The electron beam was focused at the surface of butt joint.

The welding configuration is given in Fig.1. The beam offset varied relatively to zero point in the center of the interlayer from 0.25 mm towards titanium alloy to 0.7 mm towards AISI 316L steel (offset to the titanium alloy side was considered as negative and to AISI 316L side – as positive). The constant offset values were used for each prepared weld (Table 2).

2.3. Characterization methods

The cross sections of the welds were polished and attacked by the Kalling's reagent. 20 mm large transversal cuts of the weld

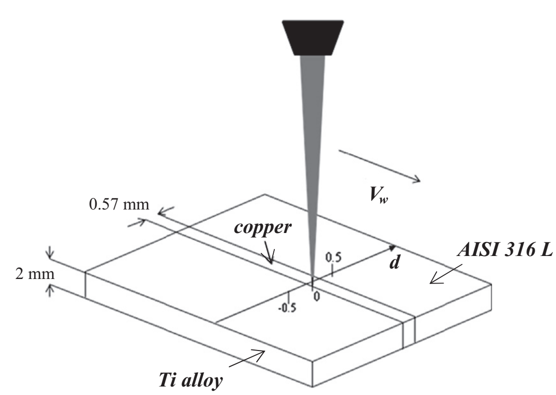

Fig.1. The configuration of welding with different beam offset (*d*).

Table 1
Chemical and phase composition of welded materials.

Material	Chemical composition (at%)									Phase composition and lattice constants (nm)		
	Al	Ti	V	Cr	Fe	Ni	Cu	Mn	Si	Phases	*a*	*c*
AISI 316L	–	–	–	20	68	7	0	balance		γ-Fe (100 wt%)	0.35937	–
Oxygen-free copper	–	–	–	–	–	–	100	–	–	Cu (100 wt%)	0.36146	–
Ti alloy	9	87	4	–	–	–	–	–	–	α-Ti (95 wt%)	0.29237	0.46685
										β-Ti (5 wt%)	0.32104	–

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