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Lap joining of TC4 titanium alloy to 304 stainless steel with fillet weld by GTAW using copper-based filler wire

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ABSTRACT

TiFe and $TiFe_2$ intermetallic compounds (IMCs) were effectively suppressed with copper-based filler wire when joining TC4 titanium alloy to 304 stainless steel by gas tungsten arc welding (GTAW). A Ti/Cu reaction zone, consisting of various IMCs like Ti_2Cu, $AlCu_2Ti$, TiCu, Ti_3Cu_4 phases, formed between TC4 substrate and the weld. Increasing welding heat input induced the formation of TiFe, $TiFe_2$ and complex Ti—Cu—Al—Fe IMCs in the Ti/Cu reaction zone. The highest shear fracture load occurred at welding heat input of 2.34 kJ/cm reached 341 N/mm corresponding to 107 MPa in shear strength, and the microhardness in the Ti/Cu reaction zone was about 619 HV. Further increasing welding heat input deteriorated the shear fracture load and increased the microhardness in the Ti/Cu reaction zone. All joints fractured at the Ti/Cu reaction zone with cleavage characteristics on the fracture surface due to the brittle IMCs and micro cracks generated in the Ti/Cu reaction zone.

1. Introduction

Dissimilar joining can combine the advantages of titanium alloy and stainless steel, therefore the hybrid joints between these two materials are of interest. For instance, the dissimilar joint of stainless steel to titanium alloy can be applied in accessories in oil rig, cryogenic plumbing and welding aircraft engine blades (titanium) to discs (stainless steel), and the lap joining configuration between stainless steel and titanium alloy has be applied in electric heater where doesn't suffer a high load. However, when directly joining titanium alloy to stainless steel, the high residual stress induced by the large differences in physical properties of these two materials can promote cracks to generate and propagate through the brittle TiFe and $TiFe_2$ intermetallic compounds (IMCs), which eventually deteriorates the mechanical performance of the resultant joint.

To suppress the formation of brittle Ti—Fe IMCs, brazing and solid-phase welding methods, such as diffusion bonding, friction welding, friction stir welding, and explosive welding, have been used to join titanium alloy and steel. Dong et al. (2013) have studied the effect of braze time on the mechanical properties of dissimilar joint of TiAl alloy with 40Cr steel, and it was reported that longer braze time promoted the diffusion between filler and base metal, improving the joint strength. Following research reported by Dong et al. (2015a) revealed that less Ti and more V were appropriate for brazing TiAl alloy to 40Cr steel. The diffusion welding method was applied to join titanium alloy with stainless steel. Kundu et al. (2011) reported the diffusion bonding of TC4 alloy with micro-duplex stainless steel, and the maximum tensile strength reached 520 MPa when joined at 900 °C. But TiFe IMCs still formed at the interface. Ni interlayer was used to prevent the formation of Ti—Fe IMCs, as reported by Kundu et al. (2013) and Sam et al. (2012). Dey et al. (2009) and Dong et al. (2015b) studied friction joining of titanium alloy with steel, they found that post weld heat treatment could greatly improve the mechanical properties of the dissimilar joint. Friction stir welding is another method to join titanium alloy with steel. Gao et al. (2015) found that the probe length was the key to control the interface microstructure. More thermal input occurred if the probe length into the steel substrate increased, resulting in formation of Ti—Fe intermetallic phases. It suggested that direct contact between molten 304 stainless steel and TC4 titanium alloy should be avoided during GTAW of these two materials to suppress the formation of brittle Ti—Fe IMCs. Moreover, explosive welding can also be used to fabricate titanium/steel bimetallic sheets (Akbari Mousavi and Farhadi Sartangi, 2008). However, these methods are restricted by the joint configuration or inferior mechanical properties.

Recently, more attention is paid to the fusion welding of titanium alloy and stainless steel for the acceptable flexibility in weld configuration and geometry, easy pre-weld preparation and high welding productivity. Due to the high energy density and rapid heating/cooling rate, electron beam welding (EBW) and laser beam welding (LBW) have been applied to join titanium alloy and stainless steel. However, it is difficult to obtain an admirable dissimilar joint when directly joining titanium alloy to stainless steel by fusion welding, because of the

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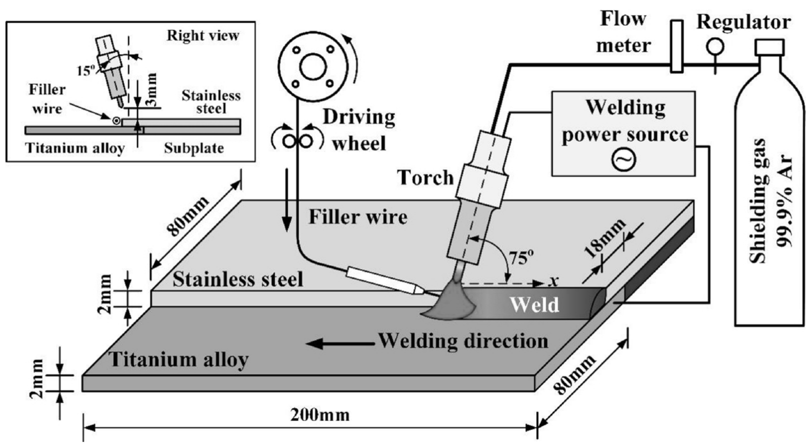

Fig. 1. Schematic illustration of lap joining for TC4 titanium alloy/304 stainless steel with fillet weld by GTAW.

Table 1
Nominal compositions of 304 stainless steel, TC4 titanium alloy and ERCuAl-A1 filler wire (wt.%).

Grade	Elements										
304	C	Cr	Ni	Mn	Si	P	Cu	Mo	Ti	S	Fe
	≤0.08	18.070	8.112	1.15	0.418	0.023	0.021	0.018	0.003	0.003	Bal.

Grade	Elements				
TC4	Al	V	Fe	Si	Ti
	5.865	3.567	0.136	0.012	Bal.

Grade	Elements				
ERCuAl-A1	Al	Mn	Zn	Si	Cu
	6.0–8.5	≤0.5	≤0.2	≤0.1	Bal.

Table 2
Welding parameters and welding heat input during TC4 titanium alloy/304 stainless steel lap joining with ERCuAl-A1 filler wire.

Sample (No.)	Welding current (A)	Welding speed (mm/s)	Filler wire feed speed (mm/s)	Welding heat input (kJ/cm)
1#	60	2	14	2.34
2#	80	2	14	3.12
3#	80	3	20	2.08
4#	100	2	14	3.90
5#	100	3	20	2.60

spontaneous cracks induced by the formation of brittle and hard $TiFe_2$ (~1000 HV) and TiFe (~600 HV) IMCs due to the low solubility of Fe in α-Ti (less than 0.1 at.% at room temperature), as stated by Akbari Mousavi and Farhadi Sartangi (2008). Chen et al. (2014) reported that the laser beam offset greatly affected the mechanical properties and microstructure of the butt joint between TC4 titanium alloy and 201 stainless steel. The highest tensile strength was only 150 MPa when the laser beam was 0.6 mm offset towards stainless steel, and the mixed IMCs of $FeAl + \alpha - Ti$ and $TiFe + TiFe_2 + Ti_5Fe_{17}Cr_5$ formed at the interface.

Various interlayer materials, such as vanadium, copper, silver and nickel etc., have been used in EBW and LBW to constrain the formation of brittle Ti−Fe IMCs. Gao et al. (2012) studied the laser welded TC4 titanium alloy/304L stainless steel joint with Mg as interlayer material, and the tensile strength was elevated to 221 MPa. $Mg_{17}Al_{12}$ IMC was detected at Ti/Mg interface but no IMCs formed at Mg/steel interface. Tomashchuk et al. (2011) found that the ultimate tensile strength of butt joint between TC4 titanium alloy and 316L stainless steel with copper interlayer could reach 337 MPa and 359 MPa by EBW and LBW, respectively. The application of copper interlayer effectively inhibits the formation of Ti−Fe IMCs, resulting in the improvement of mechanical properties of the hybrid joint. Zhang et al. (2016) reported that the tensile strength of laser welded TC4 titanium alloy/SUS301L stainless steel joint using Nb sheet as interlayer was up to 370 MPa. The Nb/steel interface consisted of eutectic Fe_7Nb_6 and Fe_2Nb and no Ti−Fe IMCs were detected in the joint as well as other IMCs. According to the Ti−V and Fe−V phase diagrams stated by Okamoto (2002), V can produce continuous solid solutions with Ti, but brittle σ- phase will form between Fe and V. Tomashchuk et al. (2015) joined TC4 titanium alloy to 316L stainless steel with V interlayer. It was found that the undesirable σ phase did not appear due to the fast cooling rate, and two-pass welding drastically improved the UTS of joint to 367 MPa.

However, the high equipment cost and accurate welding assembly restrict the extensive application of LBW and EBW, especially the complicated vacuum condition for EBW enlarges the complexity of this welding process. Arc welding is a widely used welding process for the advantages such as low expense, convenient operation and high flexibility to various joint types. But only a few investigations about GTAW of titanium alloy and steel were reported. Liu et al. (2016) joined TA15 titanium alloy to 18-8 stainless steel with GTAW, and massive brittle IMCs formed in the interfacial reaction zone, such as Ti_3P, Ti_2Cu_3 and