

Review of Ti to Steel Dissimilar Joining



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Introduction

Dissimilar metal joining of Ti alloys to steels has gained considerable attention in the design of lightweight structures. However, it is difficult to produce robust and reliable Ti/steel joints by fusion welding (e.g., arc [1] and laser welding [2,3]) or solid-state joining methods (e.g., friction [1,4], friction stir [5-7], and diffusion bonding [8-11]) due to the significant mismatch in thermal physical properties and poor metallurgical compatibility between the two materials. The major metallurgical challenge of joining Ti alloys to steels is the formation of hard and brittle intermetallic phases regardless of the dilution ratio, such as FeTi and Fe₂Ti, which could lead to cracking and thus reduced joint strength.

Without the usage of an interlayer material as a diffusion barrier, no satisfactory results have been reported for direct joining of titanium and steel using various methods. Failures occurred at the joint interface during tensile testing across all types of joints due to the presence of a significant amount of brittle intermetallic compounds. For instance, Dey et al. [4] evaluated dissimilar Ti-6Al-

4V to stainless steel joints using laser beam welding, as illustrated in Figure 1a & 1b.

Brittle compounds including FeAl, FeTi, Fe₂Ti and Ti₅Fe₁₇Cr₅ were observed in fusion zones marked as Layers I-IV in Figure 1c & 1d. Spontaneous cracking occurred immediately after welding, due to the formation of a significant amount of these intermetallic compounds and sufficiently high tensile residual stress as the laser beam was offset toward the titanium side, as shown in Figure 1b. The highest achievable tensile strength was about 150MPa by offsetting the beam 0.6mm to the stainless steel side; brittle fracture occurred between the two adjacent Layers I and II during tensile testing across the weld. The improved weldability for the case with laser offset toward stainless steel was believed to result from the higher thermal conductivity of stainless steel (12.1W/m.K at 20 °C) than that of titanium alloy (5.44W/m.K at 20 °C). Such observations indicate time at temperature, transport (diffusion or convection) and chemical potential gradients dictate the extent of intermetallic formation.

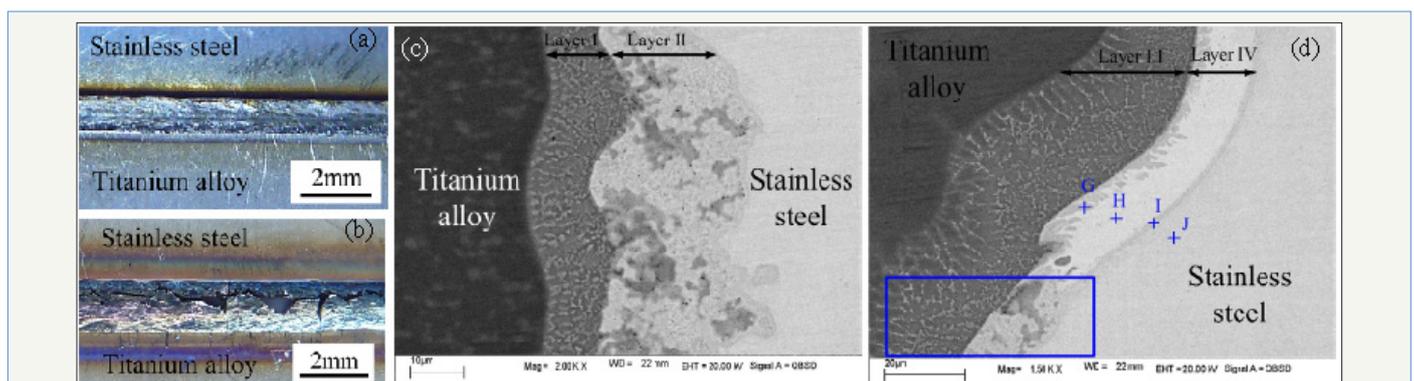


Figure 1:

1a & 1b: Macrographs of the titanium alloy to stainless steel dissimilar joint by laser welding with the beam offset toward stainless steel

1c & 1d: Macrographs and microstructures of the titanium alloy to stainless steel dissimilar joint by laser welding with the beam offset toward the Ti-6Al-4V Dey et al. [4].

One of the feasible approaches to produce successful Ti-to-stainless steel joining so far is to use an interlayer as a diffusion barrier, preventing reaction between Fe and Ti. Various types of interlayer materials have been investigated for joining Ti to stainless steels based on either their solubility in the base metals or

their availability as commercial fillers. These include

1. Vanadium and tantalum in laser welding [2]
2. Ni[12,13], Cu[14,15], Al[16] and Ag[17] based alloys in diffusion bonding; and

3. Ag-Cu[18-21], Cu-Ti[22], Ag-Cu-Zn[23], Ag[24], and Ti[24] based alloys in brazing.

However, none of these studies produced bonding interfaces completely free of intermetallic compounds (IMCs) and/or defects.

The solid-state joining processes with reduced peak temperatures and reduced transport kinetics did not suppress the formation of detrimental brittle layers with significant success in comparison to fusion welding. For instance, Fazel-Najafabadi et al. [5] reported a peak temperature of 1077 °C (equal to 0.7T_{m,Ti} in K) during FSW of pure titanium to 304 stainless steel, and Ghosh et al. [8] used diffusion bonding at a temperature between 850 and 950 °C (about 0.6T_{m,Ti} in K) to join the same couple. In all of these cases, brittle fracture occurred at the joint interface during tensile testing across the joints. However, the intermetallic layer thickness by FSW was significantly reduced to under 5 μm [5-7], while the fusion techniques typically generated layers wider than 20 μm. It is worth noting that amongst all of the solid-state joining techniques, explosive welding was reported as the viable solution to produce a thin and discontinuous layer of intermetallic compounds [1] or in some cases even avoided their formation [25,26]. This achievement was attributed to the extremely rapid joining rate generated by the explosion (i.e., as fast as the speed of

sound), the low peak temperature, the extremely fast heating and cooling rates in comparison to fusion welding processes. Little or no evidence for inter-diffusion was observed at the joint interface [27]. Hence, failures were not constrained within the interface for these explosive welded cases. However, application of explosive welding is very limited due to the safety concerns and restrictions in joint designs. Explosive welding is more commonly used to produce clad plates from which components are extracted.

More recent studies towards application/development of new solid-state welding technologies have presented promising results. For instance, Liu et al. [28] used vaporizing foil actuator welding method, which is a solid-state impact welding technique, to join Ti-6Al-4V alloy to AISI 1018 steel, using a four layer system, Ti-Nb-Cu-Fe. By optimizing the input parameters, IMC-free joints were produced. As shown in Figure 2, the right two columns of plots represented the line EDS mapping of element distribution before and after the heat treatment at 910 °C for 24 hours. The joint was demonstrated to be stable at such postweld heat treatment conditions. Gould et al. [29] evaluated the feasibility of using resistance mash seam welding and upset welding techniques to create sheat-metal-based Ti-to-steel joints with a thin Nb interlayer, and was able to achieve joint strengths ranging from 200 to 300MPa from both processes.

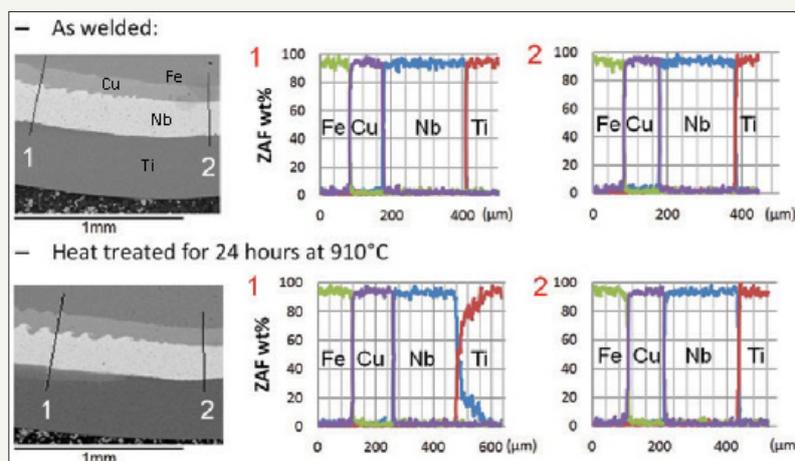


Figure 2: Line EDS mapping in vaporizing foil actuator welded region before and after heat treatment for 24hrs at 910 °C Liu et al. [28].

Conclusion

The development of new solid-state welding technologies and the use of effective diffusion barrier interlayers enabled robust and reliable joining of Ti alloys to steels. Great needs still exist for exploration of economic and flexible welding solutions, such as development of new filler metals with multiple principal components and innovative consumables that reconcile the large difference in coefficient of thermal expansion for residual stress control.

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