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On the role of intermetallic and interlayer in the dissimilar material welding of Ti6Al4V and SS 316L by friction stir welding

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Abstract. Joining titanium with stainless steel can lighten the structure of numerous industrial applications. However, a vast disparity of thermal, physical, and chemical properties between these alloys leads to defects in conventional arc welding techniques, viz., brittle intermetallic compounds, pores, cracks, etc. Friction stir welding (FSW) is a renowned solid-state joining technology for creating dissimilar material joints producing visco-plastic material flow at the interface. The present investigation compares the intermetallic layer thickness and properties as a function of the thickness of the Cu interlayer sandwiched in lap joints. Macrostructural and microstructural characterizations were carried out to understand the localized microstructural evolution comprising intermetallic, grain refinement, defects, etc. Mechanical properties were also evaluated for prepared lap joints.

Introduction

The idea of using the appropriate material in the correct location has sparked a rise in the use of multi-material components. This concept has led to the development of several cutting-edge technologies, such as additive manufacturing, solid-state joining and processing, and selective laser melting, which have numerous applications in industries such as space, chemical, shipping, automotive, and transportation[1, 2]. These technological advances offer vast potential for creating customized multi-material structures and components. It is difficult to fathom the production of a multi-material component without dissimilar material joining, yet despite the significant interest in these industries, many unanswered questions remain. Weight reduction translates directly to cost savings in these industries. Such multi-material components make the structure lighter and more cost-effective at the same time. However, these benefits do not come without challenges. The mismatch in coefficients of thermal expansion between Ti_6Al_4V and SS 316L, which are 8.6 $\times 10^{-6}$ /ºC and 17.2 $\times 10^{-6}$ /ºC respectively, leads to a joint with significant residual stress [3]. Moreover, the differences in properties such as density, melting point, and chemical affinity also create negative effects during joining. The formation of brittle intermetallic compounds (IMCs), such as TiFe, $Ti_5Fe_{17}Cr_5$, and $TiFe_2$, is inevitable due to extreme heat input during fusion welding [4, 5]. TIG, MIG, braze welding, diffusion welding, and laser welding technologies have been widely reported to fabricate dissimilar material joints [4, 6-8]. However, these joints often fail at the interface due to the presence of IMCs.

Efforts have been made to reduce heat input during joining and eliminate IMCs. One feasible solution is to use an interlayer that acts as a diffusion barrier to suppress the reaction between Fe and Ti [4]. Various interlayers have been reported for SS/Ti joints, including V and Ta in laser welding, Ni, Cu, Al, and Ag in diffusion bonding[9-14]**,** and Ag-Cu, Cu-Ti, Ag-Cu-Zn, Ag, and Ti-based alloys in brazing[15-17]**.** However, none of these investigations have reported a bonding interface free from IMCs or defects. In a nutshell, solid-state welding is more suitable than fusion-related methods since the major problems associated with melting can be eliminated. Nonetheless,

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it remains challenging to create high-quality dissimilar material joints, and further research is needed to develop effective solutions.

Over the last couple of decades, Friction Stir Welding (FSW) has emerged as a highly effective solid-state technique for producing joints that are free from defects, even when joining materials that have significant differences in properties and compositions [18-20]. This is achieved by employing low heat input mechanisms, which sets FSW apart from both conventional and modern fusion-based processes [21-23]. In a study conducted by Fazel et al.[24], a commercially pure Ti/SS 304 lap joint was produced using various processing conditions, ultimately resulting in a joint efficiency of 73%. Although the amount of IMC present (TiFe) was reduced when compared to other solid-state techniques (such as diffusion bonding), it was still not possible to eliminate it entirely. Additionally, it was reported that at elevated temperatures, the thickness of the IMC layer increased, and the formation of a Ti oxide layer contributed to a decline in joint properties. Therefore, it is highly desirable to identify a suitable interlayer and determine the lowest possible heat input parameters in order to achieve a successful Ti/SS FSW joint.

Based on the information and studies elaborated it is evident that FSW has the potential to produce efficient Ti/SS joints accompanied by limited literature on producing defect-free joints. Therefore, the main aim of this study is to explore the possibility of creating a defect-free Ti_6Al_4V/SS 316L FSW joint through experimentation with the introduction of different Cu interlayer thicknesses. In addition, the study aims to analyze joint strength, microhardness, and microstructural features such as grain morphology and intermetallic compounds.

Materials & Methods

Dissimilar lap joints were created between 2 mm thick austenitic stainless steel AISI 316L and 2 mm thick titanium alloy Ti_6Al_4V employing pure Cu interlayer with 3 different thicknesses viz. 0.05, 0.1-, and 0.2-mm. The chemical compositions of the as-received material are mentioned in Table 1. Both the skin and stringer plate was maintained at an identical size of 140 × 90 mm. When employing FSW on high-strength alloys such as titanium alloys, selecting the appropriate tool material is crucial. The author has illustrated the effectiveness of W25Re compared to conventional tungsten carbides alloys like K10 and K10-K30 in this regard.[25]. The tool design is represented schematically in Fig. 1. The experiments were conducted at VR of 16, wherein the TR was 600 rota. min^{-1} and 37 mm min^{-1}, with varying the cu interlayer thickness from 0.05 – 0.2.

Table 1 *Chemical compositions for the substrates*

WT %	Ti	Al	V	Fe	C	Cr	Mo	Mn	Ni	Si	Other
Ti-6Al-4V	87.7÷91	5.5÷6.75	3.5÷4.5	<0.4	<0.08	-	-	-	-	-	<2.1
SS 316L	-	-	-	61.9÷72	<0.03	16÷18	2÷3	<2	10÷14	<1	<9.1

The microstructure specimens were prepared as per the standard metallographic specimen preparation standard. Kroll's reagent (HF 2 ml + HNO_3 6 ml + H_2O 92 ml) was used for etching Ti_6Al_4V sections, while Carpenters reagent ($FeCl_3$ 8.5gm + $CuCl_2$ 2.4 gm, HCL 122 ml+ HNO_3 6ml + C_2H_6O 122 ml) for AISI 316L section. Various microstructural features such as grain morphologies, material flow patterns, intermetallic particles, fractured particles, and other compositional elements were examined through the use of optical microscopy (OM) (OLYMPUS, Model-Inverted Metallurgical Microscope GX51), scanning electron microscopy (SEM), and energy dispersive spectroscopy (Zeiss, Model: Ultra-55 SEM).

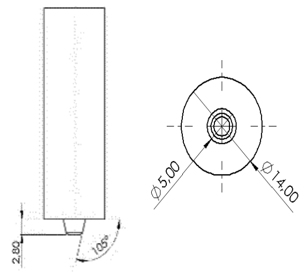

***Fig. 1** W25Re tool geometry for FSW*

To investigate microhardness, an Eseway 4302 Vickers hardness tester was used, following the ASTM E-384 standard. A square-based pyramid diamond indenter (136° intersects) was utilized with a 5 kg load and 15 seconds dwell time. For tensile tests, specimens with a width of 10 mm were employed in a conventional tensile testing machine with a velocity of 2 mm/minute.

Result & Discussion:

Microstructural Characterization

The macrostructures of the prepared Ti/SS lap joints are displayed in Fig. 2. It is evident from the micrographs that as the thickness of the interlayer increases, there is a marked increase in the penetration of SS to Ti in the form of a hook. Such hooks are formed due to distinct material flow patterns ensuing from distinctive mechanical properties. The profile of the hook has a significant impact on the resulting properties because of the interlocking between the skin and stringer materials. It is interesting to note that the phenomenon is prominent on the retreating side (RS). Two factors contribute to the formation of "hook" (i) material flow and (ii) heat flow. During FSW, the rotating tool pin pushes the stringer material underneath it, which extrudes in the opposite direction. Eventually, as the stringer material flows further upward being constrained and surrounded by the skin material, an extruded hook is engendered close to the thermo-mechanically affected zone (TMAZ). An identical phenomenon ensuing "extruded hook", has been reported during FSW of Al-Ti lap joint configurations[26].

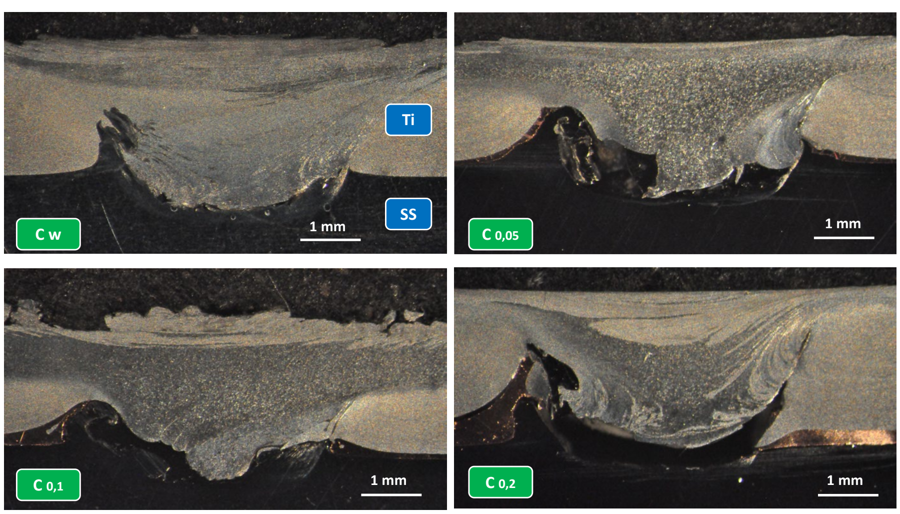

***Fig. 2.** Macrostructures of the prepared Ti/SS lap joints*

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On the one hand, the joints prepared without interlayer exhibited a limited SS material penetration to Ti skin accompanied by minimal defect generation. On the other hand, the joints prepared with the Cu interlayer exhibited comparatively larger SS material penetration to the Ti skin in the form of a hook. Simultaneously, the larger inflow of the SS material engenders a larger void into the stringer material and leaves behind a large cavity or a wormhole. Moreover, with the increase in the thickness of Cu interlayer, the size of the void enlarges owing to the mechanical deformation superimposed upon supposed material mixing at elevated temperature. Such a phenomenon can be justified by the heat transfer incurring for the two cases, one without interlayer and with interlayer as schematically represented by Fig. 3 (a) and (b) respectively.

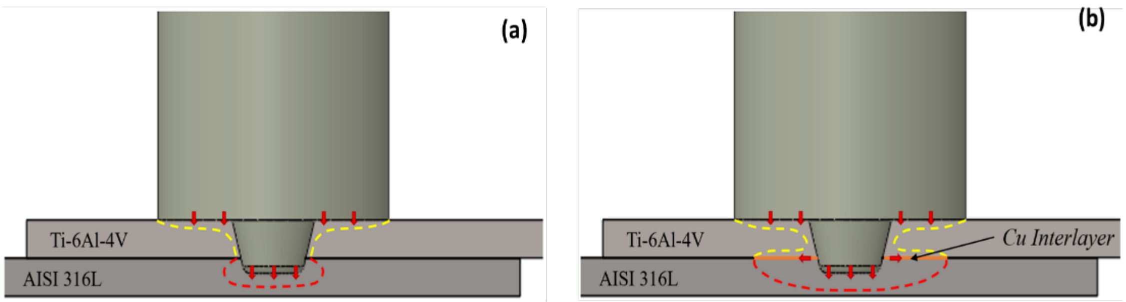
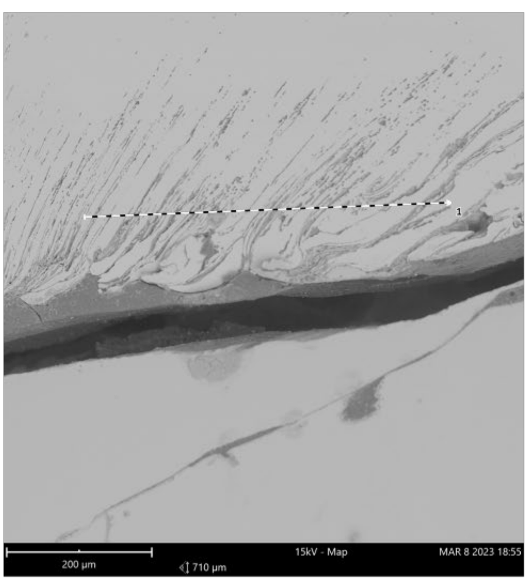


Fig. 3. *Proposed heat flow during Ti/SS FSW for specimens prepared (a) Without Cu interlayer (b) With Cu interlayer.*

The thermal conductivity of the titanium alloy is almost half that of stainless steel (k_Ti=6.70 W/(m K), k_SS=15 W/(m K)). This means that heat conducts more easily in SS substrate than Ti, resulting in a larger thermally-influenced layer compared to titanium when no interlayer is present. Whereas, for the Ti skin the heat is concentrated at the center only with a very limited heat span. In the absence of an interlayer, the thermal layer in titanium remains near the interface, while in steel, there is a slight expansion of the thermal layer at the sides and under the pin. Introducing copper interlayer having very high thermal conductivity than the other two substrates the rate of heat dissipation increases and conducts the frictional heat away from the stirring zone resulting in mechanical deformation instead of supposed material mixing at elevated temperatures.



Element Symbol	Atomic Conc.	Weight Conc.
Fe	48.44	52.94
Cr	13.22	16.32
Ni	12.81	6.44
Al	3.66	2.25
Ti	21.87	22.05

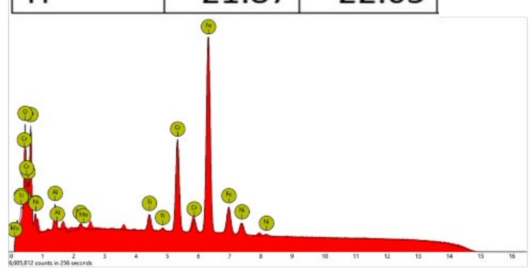


Fig. 4. *Line scan near Ti/SS interface displaying the $Ti_5Fe_{17}Cr_5$ intermetallic.*

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After selecting the most promising sample, it was subjected to SEM and EDS mapping. The resulting SEM-EDS analysis uncovered the existence of a $Ti_5Fe_{17}Cr_5$ IMC layer that was extremely thin and sporadic, found close to the interface of Ti/SS (See Fig. 4). Remarkably, the thickness of the IMC layer may be considered relatively thin compared to the observed thickness in conventional arc welded joints [26, 27]. However, a thicker layer of intermetallic was observed in the vicinity of the extruded SS hook. On the contrary, when the extruded SS hook penetrates the Ti, the temperatures of both substrates increase, resulting in Ti-Fe diffusion and the development of a thick IMC layer. $Ti_5Fe_{17}Cr_5$ was the predominant IMC phase detected in NZ. The mechanical characteristics of the FSW joints produced are significantly impacted by the location, size, and quantity of these IMCs. However, the specimens prepared with Cu interlayer did not exhibit such IMCs along the interface.

Apart from that, highly diverse grain morphologies were observed in the different zones of the FSW joints. Surprisingly, the nugget zone (NZ) majorly occupied by the Ti skin was characterized by larger grains as compared to the parent material (PM). This can be attributed to the lower heat transfer coefficient of Ti which does not allow the heat to dissipate fast ensuing the larger grains led by the slow cooling rate. The TMAZ was characterized by distorted and elongated grains, whereas heat affected zone (HAZ) with the finer grains as compared to the NZ. Several defects such as porosity, tunnels, and voids were evident in the NZ owing to a greater mismatch of the properties for skin and stringer materials.

Mechanical Properties

The tensile test results for all specimens are in Fig. 5a. On the one hand, specimens prepared without Cu interlayer exhibited the highest shear strength of 421 N/mm. On the other hand, the moderate shear strengths of 150, 370, and 250 N/mm were obtained for the specimens prepared with Cu interlayer thicknesses of 0.05, 0.1, and 0.2 mm respectively. The lower strengths recorded in those specimens can be attributed to defects such as porosity, cavities, wormholes, and recesses. However, the dimensions of the hook in those specimens have greatly influenced the shear strength results owing to the mechanical interlocking achieved. The specimens prepared with the 0.1 mm interlayer thickness offered the highest strength among the Cu interlayer specimens. Such an increase may have resulted from the two predominant mechanisms: (i) Longer hook (ii) Reduction in the amount of Fe_3Ti brittle IMC.

As the hardness results are concerned, Ti_6Al_4V and SS 316L substrates displayed a hardness of ~275 HV and ~180 HV, respectively. The NZ of the Ti skin specimen recorded a marginal rise of ~ 15% as compared to the substrate as indicated graphically in Fig 5b. The improved hardness values can be attributed to the Ti-SS composite structure, and IMCs present in the NZ of the welded samples. However, several peaks in the hardness values were recorded in the vicinity of TMAZ for the specimen prepared without Cu interlayer, owing to the presence of hard and brittle IMCs. While the sudden fall in the hardness values can be attributed to the softer SS 316L hook formed near the TMAZ region. The observed increase in hardness values could be attributed to the effectiveness of shear lag and dislocation strengthening mechanisms. On the one side, the shear lag mechanism involves the transfer of load from the Ti matrix to the hard TiFe3 IMC present in the NZ. This generates shear stress at the interface, which restricts dislocation movement and improves material properties. On the other side, during the cooling period post-thermos-plastic deformation caused by FSW, geometrically inexorable dislocations are formulated in the vicinity of the Ti/SS interface and IMCs due to the significant mismatch of coefficient of thermal expansion between two substrates. These dislocations impede crack propagation, which results in increased shear strength and hardness. In summary, the observed "dual" metallurgical-mechanical bonding mechanism can be effective in producing dissimilar Ti/SS lap joints via FSW, making it a promising method for producing lap joints using dissimilar materials.

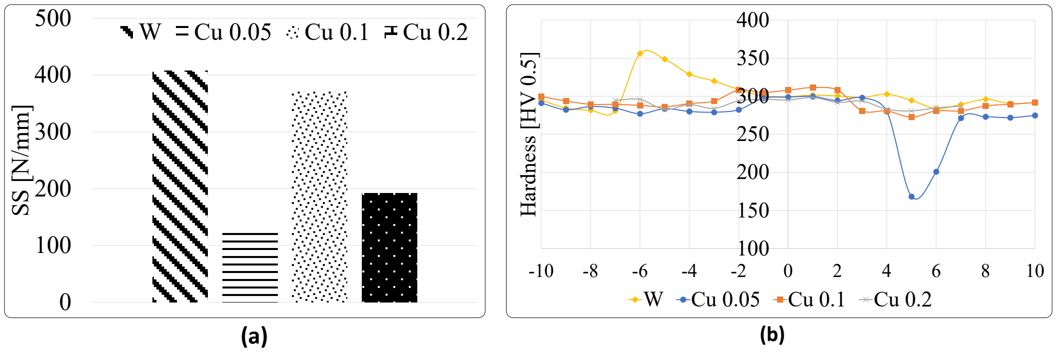

Fig. 5. *Specimen comparison for (a) Shear strength (b) Hardness Distribution*

Conclusions

This study documents the successful fabrication of dissimilar lap joints utilizing Ti_6Al_4V and SS 316L substrates. The effects of the thickness of the Cu interlayer on the joints' macrostructural, microstructural, and mechanical properties were thoroughly explored. The following conclusions were reached:

- The joints prepared without Cu interlayers exhibited superior properties owing to almost defect-free NZ.
- The dissimilar material Ti/SS joint displayed interesting material flow patterns. The development and geometry of the extruded hook were found to be critical to mechanical interlocking, resulting in improved joint strength. However, Cu interlayer specimens were characterized by multiple defects such as cavities and recesses owing to heat dissipation by the highly conductive Cu interlayer to the surrounding zones.
- The highest shear strength of 421 N/mm was recorded with the specimen prepared without Cu interlayer owing to minimal defect rate. The prepared Ti/SS lap joint hardness values were marginally increased by 15% attributable to the strengthening mechanisms led by IMCs.

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