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Microstructure and mechanical characterization of re-melted Ti-6Al-4V and Al-Mg-Si alloys butt weld

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ABSTRACT

It is becoming increasingly difficult to improve tensile strength of dissimilar metals by controlling the formation of intermetallic compounds (IMCs) in the welding of Ti and Al alloys. In this study, a novel laser welding process based on welding-brazing process is proposed, referred to as local remelting process. Metallurgical bonding of incompatible Ti-6Al-4V and Al-Mg-Si alloys was successfully achieved and sound joint with well appearance was obtained. Tensile strength of the joint reached up to 78.6% that of Al substrate, typically the strength is lower than 70%. In order to reveal the effects of local remelting process on the microstructure and tensile strength, SEM, EDS and XRD were applied for the analysis and tensile strength was tested. In addition, FEM simulation was conducted to improve the comprehension of microstructural evolution involved in the process. The results indicate that the joint realized the metallurgical bonding by direct irradiation on aluminum sheet and heat conduction formed by welding on titanium sheet promoted the joining in the interface. Original ordered phase structure was destroyed and a thinner IMCs layer was formed. Both joints present brittle fracture characteristics, but for the joint of remelting process, parts of fracture surface were featured by dimples.

1. Introduction

Hybrid structures of Ti alloy and Al alloy are arousing a great deal of attention due to the possibility to make the most of the advantages of the materials for the industrial production [1–3]. The effective joint of Ti/Al dissimilar metals not only obtains superior comprehensive properties, like high thermal conductivity, electrical conductivity and strength-to-weight ratio et al., but also meets the requirements of light weight and low cost. Therefore, there would be a great and broad application prospects in the fields of aerospace, instrumentation, electronics, chemical industry and so on [4]. Wu et al. [5] reported an example the passenger seat track after AIRBUS conceptual design is manufactured with Ti and Al alloy by laser welding.

However, there is a considerable challenge for the manufacture of Ti-Al hybrid structure. Because of their significant differences of thermo-physical properties listed in Table 1, sound metallurgical bonding between the two metals has great technical difficulties. The formation of brittle intermetallic phases Ti_xAl_y existed at the bonding interface will seriously deteriorate the performance of the joint and cause brittle crack. Currently, general welding processes used for the connection of Ti/Al dissimilar metals has be widely conducted, such as laser welding [6–9], electron beam welding [10], arc welding [11], diffusion welding [12,13], friction welding [2,14] et al. These research prove that it is difficult to obtain a high strength joint of Ti/Al, mainly due to the poor metallurgical compatibility of these two atoms. Intermetallics of Ti-Al are brittle and disadvantageous to joints [8,9]. Typically the strength of Ti/Al dissimilar joint is lower than 70% of Al substrate strength, as shown in previous studies [2,9,15].

Kenevisi et al. [16] reported that Al7075 and Ti-6Al-4V alloys were successful welded using a novel 50 μm thick Sn-10Zn-3.5Bi foil as interlayer. Its results show that with the diffusion time increasing, multiple intermetallics were formed at the joint interface. The shear strength increases due to the sufficient atoms diffusion and favorable metallurgical bond. Song et al. [15] studied laser brazing of Ti-6Al-4V and A6061-T6 alloys by focusing laser beam on aluminum alloy side and indicated the interfacial intermetallic phase was $TiAl_3$ which metallurgically connected Ti-6Al-4V and A6061 plates together. Sun et al. [17] adopted an external axial magnetic field hybrid CMT welding process to join pure titanium TA2 and 6061-T6 alloy, and revealed that grain refinement and decreased Ti-Al intermetallic compounds could be realized and the tensile shear strength was improved. Above research indicated that sufficient atom diffusion is necessary for bonding of Ti/Al

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Table 1
Thermo-physical properties of titanium and copper.

Materials	Crystal lattice	Density kg·m^{-3}	Specific heat J·kg^{-1}·K^{-1}	Melting point K	Fusion heat kJ·mol^{-1}	Thermal conductivity W·m^{-1}·K^{-1}	Expansion coefficient 1E-6 K^{-1}
Ti	hcp	4540	544.2	1943	15.45	15.7	7.14
Al	fcc	2700	880	933	10.79	237	23.6

and the intermetallics are always present, however thickens and morphology can be controlled, the strength of the joint has great potential to be improved. Based on these conclusions, a new laser welding process of dissimilar Ti-Al joint is proposed to further enhance the performance. The validity of this process was confirmed in the application of electron beam welding of titanium and copper alloys [18]. This study revealed that by the combination of two welds, a less complex and thinner IMCs layer at the interface could be obtained and then tensile strength increased.

In order to clarify how the intermetallic compounds layer is affected by the temperature field, a common method referred to as FEM simulation was implemented to support the analysis. Numerical simulation is a powerful tool to study the physical transport phenomena of welding process [19]. Casalino et al. [20] reported that FEM calculation can well predict weld shape, the thermal and mechanical evolutions in the weld bead. With the help of ANSYS parametric design language (APDL) [21] and COMSOL Multiphysics [22], temperature field and interfacial microstructure of Ti-Al laser welding were studied. Donati et al. [23] investigated friction welding process by FEM and simulation results were used for the analysis of welding quality and the microstructure evolution. FEM simulation could provide a full comprehension of the welding process which is hard to state by theoretical analysis. Therefore, a FEM model for the new laser welding process on titanium sheet was created to obtain the behavior of the laser source. Micromorphological changes were assessed to validate the model.

As a summary, there is a problem of brittle IMCs, causing the failure of joint, in the dissimilar metals welding of titanium and aluminum alloy. Present studies state that the problem is very difficult and technological innovation is necessary. In the paper, a new laser welding process was studied. The process in butt configuration was carried out by focusing the laser on the top surface of aluminum sheet and then shifting the laser on titanium sheet. the joint realized the metallurgical bonding by direct irradiation on aluminum sheet and heat conduction formed by welding on titanium sheet promoted the joining at the interface. A satisfactory structure and distribution of IMCs, as well as high tensile strength of joint, were obtained. Microstructural development and mechanical properties in the weld were investigated.

2. Experimental procedure

2.1. Materials

Ti-6Al-4V and 6082 A l plates with the size of 100 × 50 × 4 mm and no groove were used. Chemical compositions and mechanical properties of Ti and Al alloys were shown in Table 2. The top and faying surfaces of materials were polished by steel wire brushing and sanded by papers of grit sizes (240#, 400#, 600#) to remove the oxide layers.

Table 2
Chemical compositions (wt.%) and mechanical properties of Ti and Al alloys.

Materials	Elements (wt. %)					Hv	δ	Rm/MPa
6082 A l	Al	Mg	Si	Fe	Mn	60–90	≥15	210
	Bal.	1.0	0.8	0.5	0.4			
Ti-6Al-4V	Ti	Al	V	Fe	C	250–300	≥10	895
	Bal.	6.38	4.12	0.05	0.02			

Specimens were firmly hold in butt configuration and cleaned by absolute alcohol before laser welding.

Shielding gas was used. Insufficient gas flow will cause serious oxidation but excessive gas flow will cause turbulence, so it is disadvantageous to weld joint property in both cases. In order to prevent the adverse effects of air, 99.99% argon shielding gas with the flow rate of 15 L/min was adopted. The angle between vertical middle line and gas flow direction was 45°.

2.2. Welding process

Schematic diagram of the new laser welding process and macrograph of a weld are shown in Fig. 1. It shows that there are two welds, one is the traditional welding-brazing seam formed by the laser beam focusing on Al sheet and another is the seam of new process called as local remelting formed by the laser beam focusing on Ti sheet. 3 kW SPI fiber laser was used and the parameters of welding-brazing on aluminum side were set as 2.8kw, 10 mm/s and offset by 1.5 mm. The new local remelting weld occurs very close to the welding-brazing seam, but the welds are not merged together and there is a distinct gap between the two seams. The parameters of local remelting process on titanium side were set as 2.5kw, 10 mm/s and offset by 2.8 mm. The metallurgical bonding is realized by direct laser irradiation on aluminum sheet, and high temperature field formed by the local remelting process promotes Ti-Al interface reconstruction and optimization of IMCs.

2.3. Characterization methods

In order to analyze the microstructure of the welds, specimens with the dimensions of 10 mm × 5 mm × 4 mm was obtained by wire-electrode cutting from the welded joints. Cleaned specimens were grinded, following a 120-240-400-800 grits sequence. Etching solution of Ti-6Al-4V alloy and 6082 A l alloy were kroll reagent consisting of 1 vol% HF, 6 vol% HNO_3 and 93 vol% H_2O for 10s and aqueous solution of NaOH, respectively. A Zeiss optical microscope and a Quant 250FEG scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectrometry (EDS) system were applied for the observation of microstructure and chemical composition under the chamber pressure of 1.89e-3pa and gun pressure of 1.50e-7pa. The phase structures in the interface of welds were detected by a Bruker-AXS D8 Advance X-ray diffractometer (XRD) with the time interval of 0.2s and step size of 0.02°. Tensile strength were evaluated by a tensile testing machine with the speed of 3 mm/min at room temperature according to GB/T228-2002. Four tensile samples of each kind of joint were tested and average strength was recorded.

2.4. FEM simulation

The remelting process on Ti sheet promoted the Ti-Al joining. Phase structure and interface morphology at the Ti-Al interface were changed under the effect of temperature.

In order to clarify the evolution process of phases, the temperature distribution of joints was studied and FEM method was used. The basic idea of FEM is to discrete the solving area into a unit combination which units are connected to each other in a certain way and then solve these finite elements by piecewise interpolation. The results of FEM can