INFLUENCE OF THE PROCESS PARAMETERS OF ELECTRON BEAM TO THE WELDABILITY OF ALUMINUM AND TITANIUM ALLOYS

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Abstract

Electron beam welding offers many advantages over other methods of fusion welding. High current density of electron beam is one of the advantages. Energy delivered on the surface of welded components allows rapid melting and evaporation of base materials. It is possible to weld materials with the different thermophysical properties under condition of appropriately adjustment of process parameters. One of the examples is welding of aluminum and titanium alloys, which provides suitable combination of physical and mechanical properties, especially for aerospace and automotive industry. Fusion welding of these materials is associated with the formation of intermetallic phases during mixing of basic materials and subsequent solidification and cooling of weldment. In this work was evaluated influence of welding speed, oscillating frequency, beam focus and offset of electron beam on the structure and integrity of welded joints. The resulting weld joints were evaluated by using light and electron microscopy. Type of intermetallic phases observed in the welds was determined by EDS analysis. Estimation of mechanical properties was carried out on the base of measurement of microhardness profile across weld joints.

Keywords: Electron beam welding, intermetallic phases, aluminum alloy, titanium alloy, dissimilar weld

1. INTRODUCTION

Light metals such as aluminum and titanium and their alloys are important construction materials with a high strength-to-weight ratio. This relates to demand for dissimilar joints of these materials, especially in the airspace and automotive industry. Aluminum alloys lead to saving of weight and energy. On the contrary, titanium alloys provide required strength and improve the corrosion resistance. Nevertheless, the fusion welding of aluminum and titanium alloys is a difficult task due to the different physical properties, especially due to a large difference of melting points. These differences lead to the formation of brittle intermetallic (IMC) phases at the weld interface or after significant dilution of base materials (BMs) [1, 2].

As describe above, fusion welding results in formation of undesirable IMC phases such as TiAl, $TiAl_3$ and Ti_3Al which causes an embrittlement and decrease of strength of dissimilar joints. This problem can be resolved by other techniques such as riveting, clinching and screwing. These are still widely used techniques. However, these techniques require additional machining and use of another material which could increases the resulting weight. In recent years, laser welding, diffusion welding, friction welding and ultrasonic welding have been used to produce the lightweight Al/Ti structures [1]. The successful welding of titanium to aluminum especially requires control above all the formation of IMC phases. A lot of experiments about welding titanium to aluminum were already done. For example, Jiangwei et al. [4] carried out diffusion welding of Ti/Al alloys, Dressler et al. [5] used friction stir welding and Majmudar et al. [6] performed crack-free Ti/Al welds by CO_2 laser. Direct keyhole laser welding of Ti/Al alloys was published by Tomaschuk et al. [2]. Further possibility was used of modified welding method. Bang et al. [7] presented gas tungsten arc welding supported by hybrid friction stir welding of Ti6Al4V/AA6061-T6 alloys. Chan et al. [8] improved the reaction at Ti/Al interface by laser welding-brazing process. These methods relate to the effort to reduce dilution and changes in chemical composition of BMs to avoid the formation of IMC phases.

An alternative for welding titanium to aluminum is the use of electron beam. This method as well as a laser beam welding brings several benefits. Among the benefits of electron beam welding (EBW) belong high energy density (about 10^7 W·cm^{-2}), presence of vacuum, precise control and high welding speeds. The high energy density is required for welding by the keyhole mode resulting in deep and narrow welds with limited deformation. The fusion and heat affected zone are usually narrower than in other fusion welding technologies. High welding speeds leads to small interaction zone which promote high thermal gradients. Thermal gradients are useful for the local phase content optimization. The mixing and diffusion phenomena can be reduced. Furthermore, the differences in thermophysical properties of welded materials can be reduced by offsetting the beam toward one of the BMs. The resulting strength of joint is related to the thickness of IMC layer formed at the weld interface [2, 3].

Nevertheless, publications about EBW of aluminum to titanium are limited. For this reason, the weldability of aluminum alloy AA6061 and titanium alloy Ti6Al4V is studied in this paper. The main objective is minimized dilution of BMs by offsetting the electron beam to the aluminum or titanium side. The interfaces between aluminum and titanium alloys are analyzed in more details.

2. EXPERIMENTAL MATERIALS AND PROCEDURES

Aluminum alloy AA6061-T651 and titanium alloy Ti6Al4V were selected as BMs for this experiment. The BMs were delivered in form of sheets with thickness 8 and 8.5 mm. Chemical composition of used alloys is presented in **Table 1**. The structure of heat treated aluminum alloy contained α-Al solid solution, hardening β phases (Mg_2Si) and Q phases (Al-Mg-Si-Cu-Fe-Mn)). Titanium alloy was in mill annealed condition with structure formed by equiaxed grains of α phase and small amount of β phase.

Table 1 Chemical composition of base metals (wt.%)

	Ti	Al	V	Fe	Si	Mg	Cu	Mn
Ti6Al4V	Bal.	6.46	4.11	0.21	-	-	-	-
AA6061	0.01	Bal.	-	0.45	0.72	1.11	0.24	0.14

Table 2 Parameters of electron beam welding

Sample	Accelerating voltage (kV)	Beam current (mA)	Welding speed (mm·s^{-1})	Frequency (Hz)	Spot (mm)	Offset (mm)
A	120	20	15	500	Ø 0.2	0
B	80	30	15	500	Ø 0.25	0.3 (Ti)
C	80	30	15	500	Ø 0.25	0.3 (Al)
D	120	20	15	500	Ø 0.2	0.4 (Al)
E	120	20	15	500	Ø 0.2	0.5 (Al)
F	120	20	15	500	Ø 0.2	0.5 (Al)

The EBW was carried out using the universal chamber machine K26 (EBG 60-150; Pro-Beam company, Germany). The parameters of the dissimilar welds are given in **Table 2**. The term *spot* used in **Table 2** describes the dimensions and shape of electron beam scanning patterns. Each sample was welded with electron beam focused on the sample surface. The samples were welded without preheating except the sample F. Sample F was welded with preheating on 400 °C by defocused electron beam (beam current 1.3 mA; 5 minutes). Samples B and C were made with lower accelerating voltage in order to reduce the evaporation of alloying elements which released mainly from the aluminum alloy. The remaining samples were made with a higher accelerating voltage and a lower beam current. This setting provided the same level of energy (2.4 kW) and a lower divergence of electron beam.

The samples were ground, polished and etched in Kroll's reagent (2 ml of hydrofluoric acid, 8 ml of nitric acid and 92 ml of distilled water) for metallographic analysis. Microstructure analysis was performed by light microscopes Olympus GX-51 and Zeiss Axio Observer Z1m. Further studies of microstructure and chemical composition were performed by scanning electron microscope Zeiss Ultra Plus equipped by energy-dispersive X-ray spectroscopy (EDS) detector Oxford. Leco LM 274AT device was used for microhardness measurements (HV0.1) across the weld joint.

3. RESULTS AND DISCUSSION

In the case of significant dilution of BMs, the several individual areas were distinguished during the macroscopic evaluation of dissimilar Ti/Al welds. These were the five areas: aluminum base metal (Al-BM); aluminum weld metal (Al-WM); titanium base metal (Ti-BM); titanium heat affected zone (Ti-HAZ) and bulk of titanium intermetallic phases (Ti-IMC). This was typical for samples A, B and C (**Figure 1**) where the settings of diameter and offset of the electron beam were inadequate to reduce the dilution of BMs. Tomaschuk [2] used high energy of the laser beam and high welding speed to reduce the interaction time between liquid phases during welding of 2 mm thick Ti/Al sheets. Vice versa, the formation of bulk Ti-IMC was still observed in the upper part of welds during welding of thick sheets by high welding speed and high electron beam energy. The pores and cracks were presented in the bulk of Ti-IMC due to rapid solidification. The pores originated from entrapped vapors of alloying elements [9]. When the dilution of BMs was limited (sample D, E and F), only three individual areas were observed in the dissimilar welds: Ti-BM; Al-WM and Al-BM. This has been achieved by shifting of electron beam more than 0.3 mm into the aluminum alloy. Under these conditions, the melting occured predominantly in the aluminum alloy (**Figure 2**). The cracks in Al-WM arising at solidification of weld metal were observed in the upper half of weld.

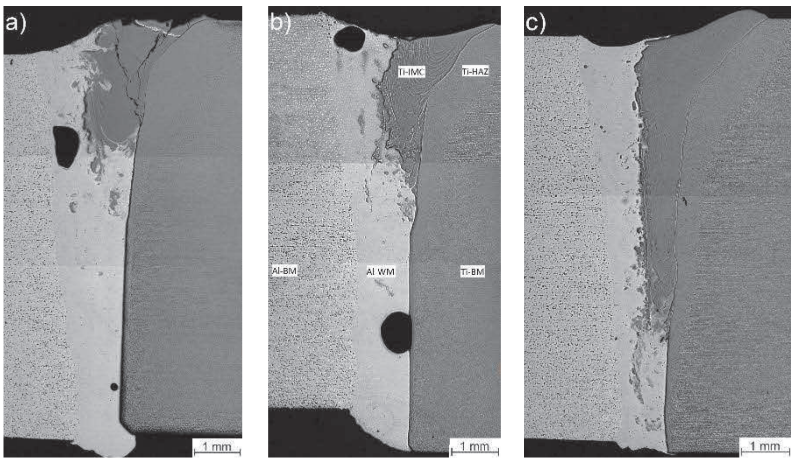

Figure 1 Macrostructure of dissimilar Ti/Al welds: a) sample B; b) sample A; c) sample C

The resulting microstructures of welds depend on the values of the beam offset. A limited portion of Ti alloy was heated and melted when the beam offset was less than 0.3 mm (to the Al alloy). Titanium alloy had the same microstructure as in the Ti/Ti welds [10]. This microstructure contained the mixture of martensitic structure and portion of non-transformed β-phase (**Figure 3a**). The formation of bulk IMC phases at the Ti/Al interface depend on the size of dilution of Ti and Al alloys (**Figure 3b**). The chemical composition of IMC phases gained from EDS spot analysis is shown in **Table 3**. The amount of hard, brittle and prone to cracking Ti_3Al phase (no. 2) increased with higher portion of melted Ti-BM. The smaller amount of melted Ti-BM led to formation of TiAl phase (no. 1). This phase grew from Ti-rich phases at Ti/Al interface into

Al-WM. $TiAl_3$ phase (no. 3) was presented in the form of clusters and needles in Al-WM. $TiAl_3$ phase (no. 3) was observed in form of clusters and needles. The needles of $TiAl_3$ grew from Ti/Al interface into Al-WM after solidification of Ti alloy due to diffusion process. Higher proportion of IMC phases degraded mechanical properties of resulting weld joints [1, 8]. Thin IMC layer was formed due to diffusion process at Ti/Al interface when the electron beam offset was set more than 0.4 mm into Al-BM. In this case, titanium atoms diffused from Ti-BM into Al-WM during heating and subsequently these atoms reacted with molten Al to form TiAl compounds [1, 4]. Creation of layer was suppressed by beam offset more by 0.4 mm (sample E and F). These joints contained small interdendritic cracks in Al-WM typical for weld metal of aluminum alloys. Reducing the cooling rate by preheating to eliminate interdendritic cracks was not successful (**Figure 3d**). Microstructure of Al-WM (**Figure 3e**) was created by α-Al solid solution. The interdendritic areas were enriched by alloying elements, due to the segregation process.

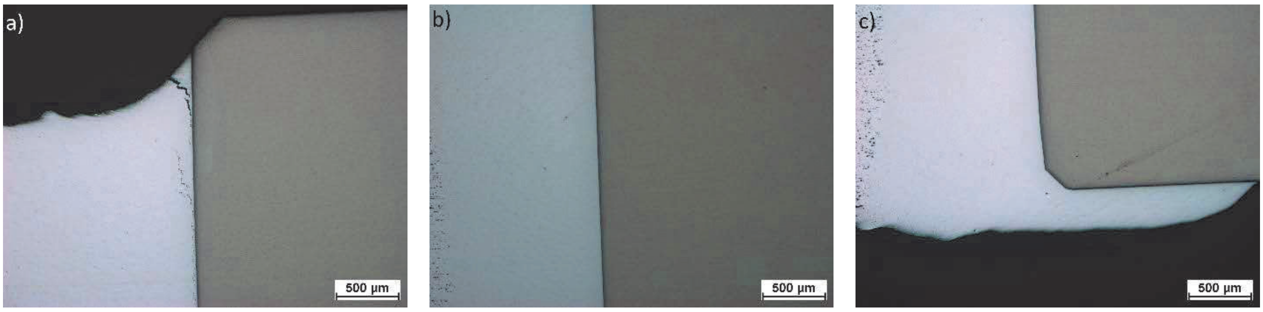

Figure 2 Macrostructure of dissimilar Ti/Al weld - sample $E^{400\ ^{\circ}C}$: a) weld top; b) weld center; c) weld root

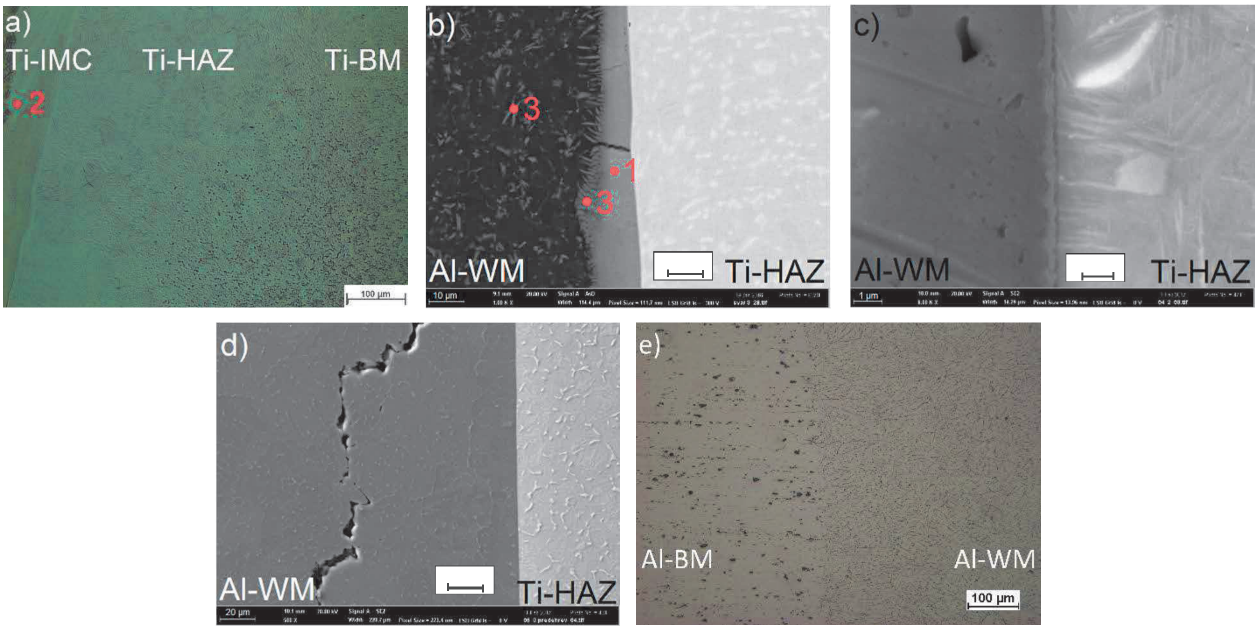

Figure 3 Microstructures of dissimilar Ti/Al welds - a) Ti-HAZ (sample A); b) Al/Ti interface (sample C); c) Al/Ti interface (sample D); d) Al/Ti interface (sample F) and e) Al-WM (sample D)

Table 3 Chemical composition of IMC phases (at.%)

No.	Ti	Al	V	Fe	Si	Mg	phase
1	38.0	60.2	1.6	-	0.2	-	TiAl
2	70.5	26.2	3.0	0.2	0.1	-	Ti_3Al
3	10.4	87.6	0.4	0.1	1.0	0.5	$TiAl_3$

Figure 4 presents results of EDS analysis across the weld joints. It is evident that concentration of Al in Al-WM was at same level like in Al-BM. Significant dilution of BMs occurred only in the case of set an inappropriate beam offset. These conditions led to formation of bulk IMC phases. When the beam offset was set more than 0.3 mm the dilution of BMs was reduced. Under these conditions concentration of presented elements (including alloying elements) were also at the same level as in BMs.

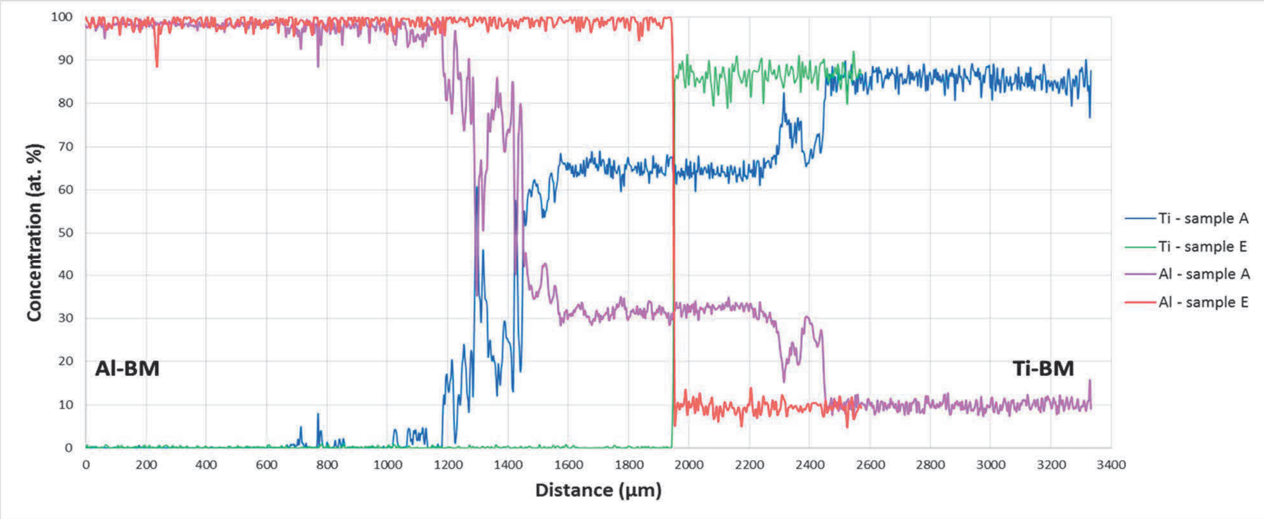

Figure 4 Results of EDS analysis across Al/Ti weld

The development of HV0.1 microhardness across dissimilar weld samples can be seen in **Figure 5**. In the case of formation bulk IMC phases the sharp change of microhardness profile was observed. This change indicated decrease of mechanical properties of weld joints. Increase in microhardness at Ti/Al interface was caused by presence of Ti_3Al and TiAl phases and depended on the amount of these phases. Maximal hardness arisen up to 600-700 HV0.1, which indicated low tensile strength of these welds [2, 6]. Microhardness in Ti-HAZ followed microstructure changed typically for homogeneous Ti welds. In Al-WM was not observed drops in hardness, conversely hardness was comparable to Al-BM.

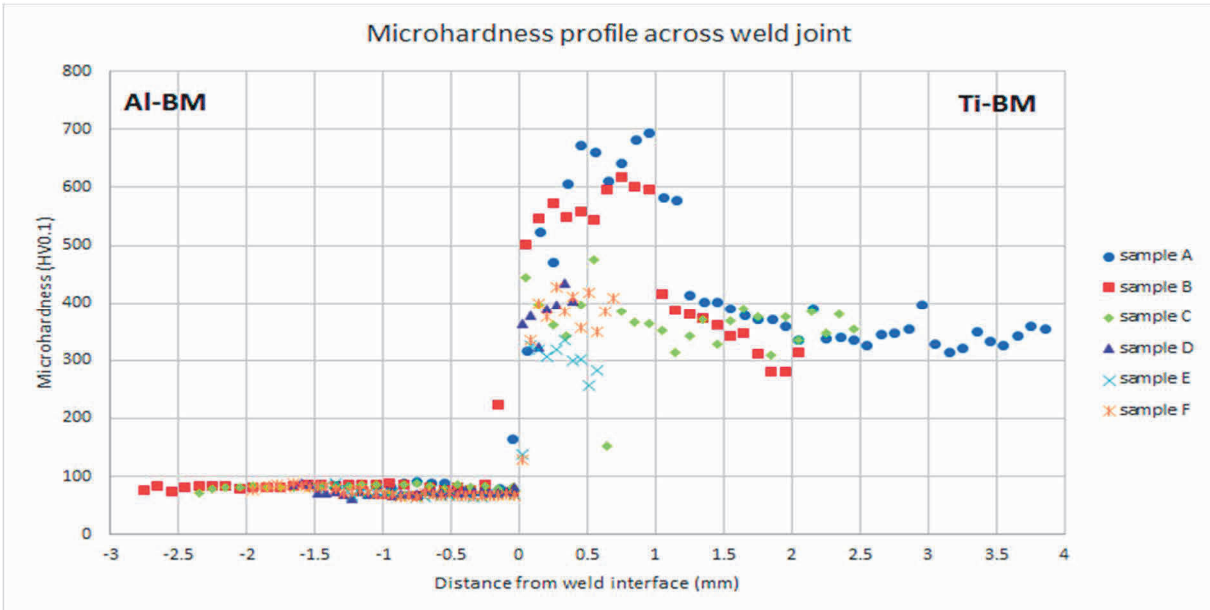

Figure 5 Microhardness profile across dissimilar welds

4. CONCLUSION

In this paper the electron beam welding process was used for joining of Ti6Al4V titanium alloy and AA6061-T651 aluminum alloy.

- By appropriate settings of electron beam offset could be controlled type and amount of emerging IMC phases in dissimilar Ti/Al weld joints. It depends whether the beam energy is used to melt one or both BMs.
- Beam offset below 0.3 mm to Al side lead to significant dilution of BM and subsequent formation of bulk IMC phases. IMC bulk contains especially hard and brittle Ti_3Al and TiAl phases which are sensitive to the cracking under high cooling rates.
- At offset 0.4 mm to Al slide only aluminum alloy was melted. But the formation of thin IMC layer was occurred due to the diffusion processes between solid titanium and liquid aluminum.
- The beam offset greater than 0.4 mm to Al side lead only to aluminum alloy melting. The formation of IMC phases was completely suppressed. The conditions of solidification lead to the formation of small interdendritic cracks inside Al-WM.

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