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ELECTRON BEAM WELDING OF METALLIC MATERIALS AND ALLOYS

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Abstract
This report reveals results obtained via electron beam weldment between different metallic materials and alloys. Different process conditions were applied to achieve strong connection between these dissimilar materials. The provided X-ray diffraction (XRD) method was used to obtain the phase composition of the welded joints, scanning electron microscopy (SEM) was used for the study of the microstructure of the welds and energy-dispersive X-ray spectroscopy (EDX) was applied to investigate the chemical composition. The results will contribute to expand the understanding of electron beam interactions with materials and to the development of new engineering solutions with high added value.

Keywords: electron-beam welding, metals, alloys, microstructure; mechanical properties; process optimization.

INTRODUCTION

Producing durable welds between dissimilar materials is challenging because of differences in their physical and chemical properties. Their successful joining depends largely on metallurgical compatibility and the welding process used. Metallurgical compatibility is governed by the mutual solubility of the metals in both liquid and solid states and by the formation of intermetallic phases. This mutual solubility depends on the similarity of the metals' crystal lattices, differences in atomic radii, and the bonding energy between the elements [1, 2].

Electron-beam welding (EBW) enables effective joining of dissimilar materials and, for certain material combinations, is among the most widely used methods [3-5]. EBW features high energy density, accurate beam positioning and focusing, and a narrow heat-affected zone. Like all welding processes, it results in residual stresses, micro-deformations, and defects such as micro-cracks. Various studies have reviewed methods for welding dissimilar materials [6-

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8], with emphasis on EBW and its future development [9-11].

EBW offers several advantages over other methods for joining dissimilar materials. These include the formation of a homogeneous molten pool resulting from the high heating rate and the rapid attainment of the differing melting temperatures of the metals. In addition, the vacuum environment minimizes gas inclusion in the weld, leading to improved plastic properties. EBW also produces a narrow, deep weld, enabling the joining of dissimilar materials with substantial thicknesses [12-14]. Many methods and techniques were developed for joining of similar materials [15-21].

EXPOSITION

Materials and methods. The subjects of the investigation were the following combinations of welds between different materials: Cu-304L; Cu-Al6082T6; Ti-Ti6Al4V and Ti6Al4V-Al6082T6. The chemical composition of the metallic materials and alloys used are presented in Table 1.

Table 1. *The chemical composition of studied metals and alloys*

304L		Al 6082 T6		Ti6Al4V		Ti		Cu	
El.	wt, %	El.	wt, %	El.	wt, %	El.	wt, %	El.	wt, %
C	0.03	Si	1.3	Al	5.5	Ti	100	Cu	100
Mn	1.52	Mg	1.0	V	4.5				
Si	0.10	Mn	0.8	Fe	0.3				
P	0.03	Fe	0.2	Ti	Bal.				
Si	0.03	Cr	0.1						
Cr	17.70	Al	Bal.						
Ni	8.30								
N	0.10								
Fe	Bal.								

All the samples are prepared in form of plates with size of 100x50x8 *mm*. Subsequently, the welding side of each was grinded, polished and clean with acetone. Finally, the specimens were clamped before processing to prevent gaps.

The EBW process was performed using an Evobeam μEBW Cube 400 machine (Evobeam GmbH, Germany) – Figure 1. The main parameters of the machine are shown in Table 2.

Technological conditions of provided experiments. The technological parameters of provided EBW experiments are shown in Table 3.



Fig. 1. *Evobeam μEBW Cube 400 machine*

Table 2. *Main parameters of Evobeam μEBW Cube 400 machine*

Parameter	Value
Accelerating voltage U_a, kV	60
Beam current I_b, mA	100
Welding speed v_{max}, mm/s	80
Scanning frequency S_f, kHz	20
Working pressure P, mbar	5.10^{-3}

Table 3. *Technological conditions of EBW*

Sample	Cu/304L	Cu/Al6082T6	Ti/Ti6Al4V	Ti6Al4V/Al6082T6
Accelerating voltage U_a, kV	60	60	60	60
Beam current I_b, mA	60	50	35	35
Welding speed v_{max}, mm/s	5	15	10	10
Scanning frequency S_f, kHz	-	20	-	-
Offset, mm	0,3 toward Cu	0,4 toward Al	-	0,5 toward Al
Beam oscillation	-	circle 0,1mm	-	-

Evaluation technique. The phase analysis was conducted by a Bruker D8 Advance X-ray diffractometer. The method applied was "Coupled Two Theta" in the range from 40° to 120° using Co Kα radiation with a wavelength of 1.78897 *Å* and line focus orientation. The X-ray generator current was 40 *mA* and the used voltage was 35 *kV*. Other characteristics of the test were a 0.05° step size and 0.25 *s* step time.

Secondary-electrons scanning electron microscopy (SEM) on an EVO MA10 Carl Zeiss instrument was used to study the microstructure of the welded specimens. The accelerating voltage was 20 *kV*.

The chemical elements distribution in the fusion zone was analyzed by energy-dispersive X-ray spectroscopy (EDX) on a spot and on a line.

RESULTS AND DISCUSSION

Cu/304L(SS)

Joints of copper and stainless steel, Figure 2, combine the very good thermal and electrical conductivity of copper with the significant strength, wear resistance, and corrosion resistance of steel. Copper and stainless-steel joints are used in heat transfer devices, nuclear devices, energy sources, shipbuilding, aircraft, space, and other industries [1, 22].

The joining of these metals has many problems related to their different physical and chemical properties, including their melting points, thermal expansion coefficients, thermal conductivities, and so on [23-25]. The welding without a beam offset and with a beam offset towards either welded material to a distance of 0,3 *mm* is reported [13]. The phase composition of the considered specimens consisted of a double-phase structure of face-centered cubic (fcc) and body-centered cubic (bcc) phases. The sample welded without offset reveal the highest yield strength and tensile strength values [1].

The authors of [26] reported on the electron-beam welding of Cu with three austenitic stainless steels - 304-L, 304, and 316-L - under various technological welding conditions. These conditions were optimized to achieve full penetration. The results revealed heterogeneous microstructures in all cases, attributed to poor material mixing caused by the high cooling rate.

In the studies [1, 4, 27, 28], the microstructures of electron-beam welded specimens of Cu and 304L SS were investigated. In the studies [1, 13] the influence of beam power was obtained upon mechanical parameters of joints.

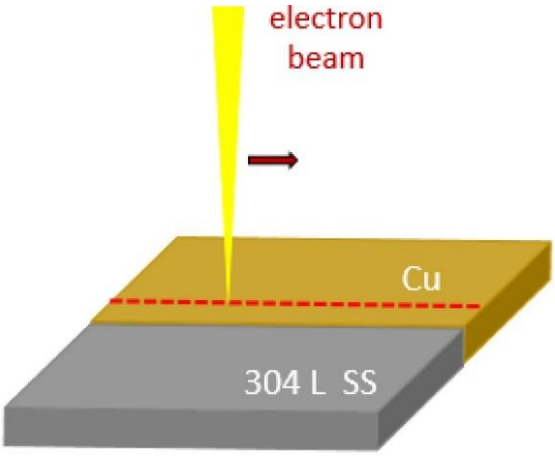


Fig. 2. *Schematic of the experimental design for EBW of copper and stainless steel 304L [1]*

The X-ray diffraction (XRD) analysis of the welded joints is shown in Figure 3. The two materials have the same crystal structure, with the phase composition of the face-centered cubic (fcc)(γ-iron) dominating those of the body-centered cubic (bcc) phases (α-iron). It is well known that the cooling rate during the electron beam welding process is quite high and the solidifying molten material is not in equilibrium. In this case, non-equilibrium solidification is the dominant process, leading to the preservation of metastable phases, which is the mechanism of formation of the bcc structure [29].

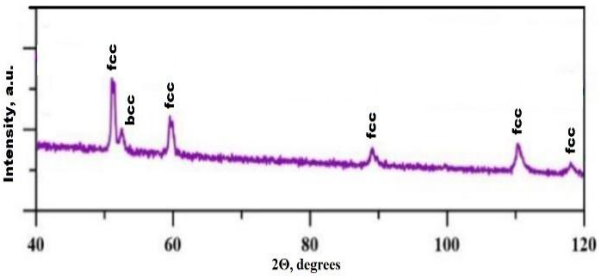


Fig. 3. *X-ray diffraction patterns of the welded joints in Cu/304L [1]*

The SEM images of the cross-section of the welded samples are shown in Figure 4. Two clearly demarcated zones with weak penetration of the opposing element into the base are observed. This means that the copper has not been completely dissolved into the steel matrix in the fusion zone (FZ).

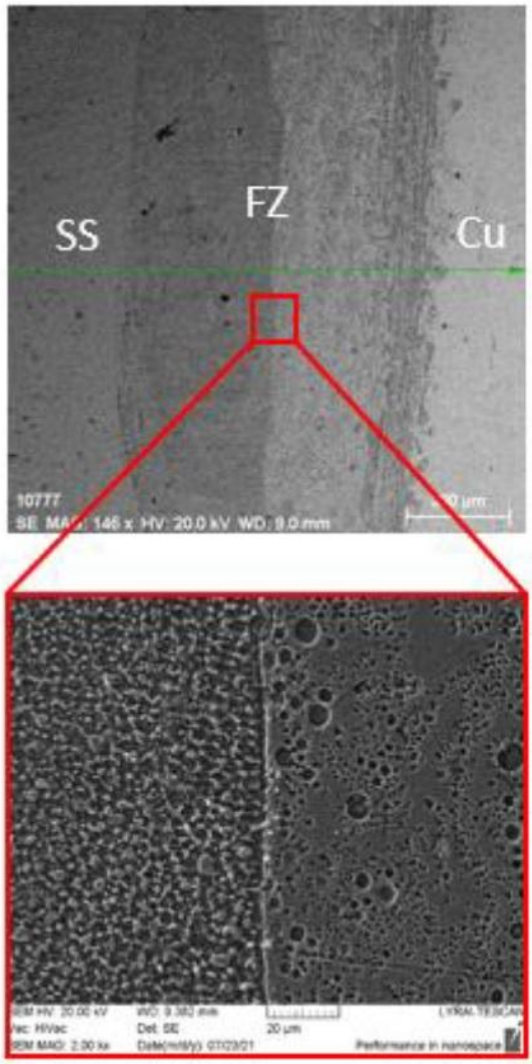


Fig. 4. *SEM images of fusion zone in Cu/304L [1]*

Cu/Al6082T6

The effect of electron beam offset toward the aluminum plate during the electron-beam welding of copper and the Al6082-T6 alloy were investigated [4, 30, 31, 32, 33]. Their results demonstrated that a sound welded joint was successfully formed in this material system.

Electron beam offset and beam oscillation techniques were employed during the fabrication of the copper–aluminum alloy specimen, as illustrated in Figure 5. The electron beam was offset toward the aluminum alloy side in increments of 0,4 mm, while a circular beam oscillation with a radius of 0,1 mm was applied.

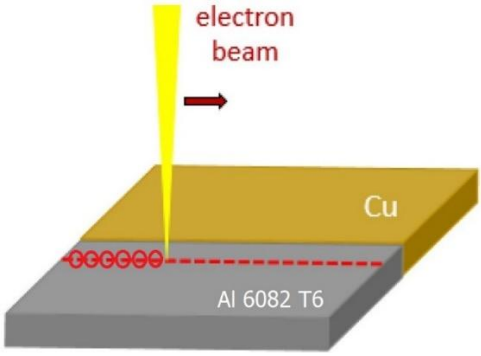


Fig. 5. *Schematic of the experimental design for EBW of Cu/Al6082T6 [31]*

Figure 6 presents the XRD patterns of the welded specimen. The fusion zone is primarily composed of the $CuAl_2$ intermetallic phase, which exhibits a body-centered tetragonal crystal structure. Additionally, diffraction peaks corresponding to aluminum and copper with face-centered cubic structures are also detected.

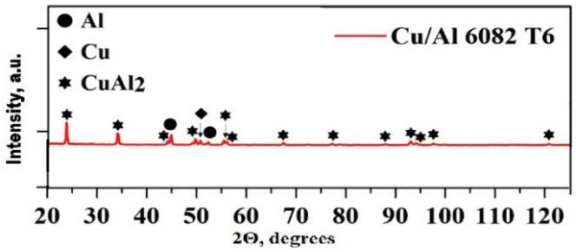


Fig. 6. *X-ray diffraction patterns of the welded joints in Cu/Al6082T6 [31]*

The fusion zone of the specimen consists of three different phases: an aluminum matrix, an intermetallic phase in the form of $CuAl_2$, and a region of pure copper adjacent to the copper plate, as evidenced by the SEM micrograph shown in Figure 7.

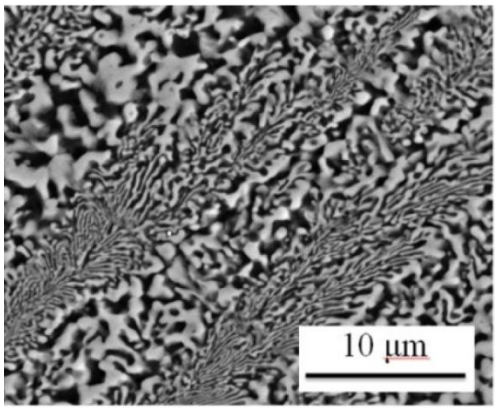


Fig. 7. *SEM images of fusion zone in Cu/Al6082T6 [31]*

Ti-Ti6Al4V

Titanium possesses exceptional corrosion resistance, exceeding that of stainless steel in many severe corrosive conditions, and shows excellent corrosion resistance and biocompatibility in the human body. Schematic of the experimental design for EBW of Ti/Ti6Al4V is shown in Figure 8.

Ti and the Ti6Al4V alloy exhibit distinct thermophysical properties due to the presence of alloying elements in the Ti64 microstructure. Although the two materials have comparable thermal and electrical properties, their mechanical properties differ significantly. Ti6Al4V demonstrates substantially higher yield strength, ultimate tensile strength, shear strength, and hardness than pure Ti [34].

Considering the pure Ti plate, its phase composition is in the form of a single-phase of α-titanium. In contrast, the structure of the titanium alloys is in the form of a double-phase of α+β. It is well known that β is the high-temperature modification of Ti [4].

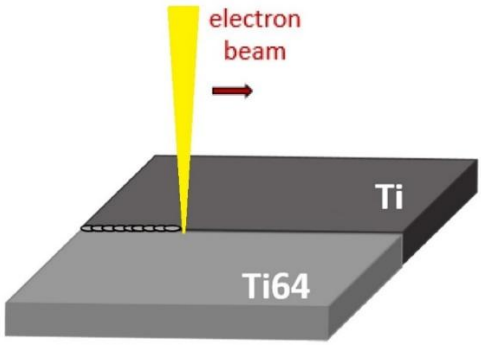


Fig. 8. *Schematic of the experimental design for EBW of Ti/Ti6Al4V [34]*

The higher beam power resulted in full penetration of the welding plates, leading to the formation of a symmetrical, rectangular-shaped weld pool.

XRD and SEM analyses indicated that a low fraction of the α -Ti phase was present in the weld joint – Figure 9. In the SEM image of the fusion zone, it is seen that there is no presence of the β-phase of Ti. The formed martensitic structure in the weld seam is clearly visible, Figure 10.

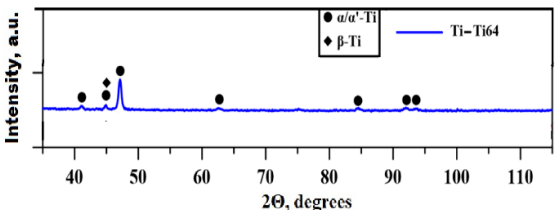


Fig. 9. *X-ray diffraction patterns of the welded joints in Ti/Ti6Al4V [34]*

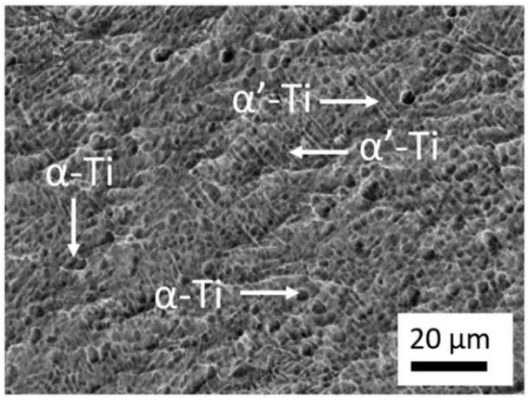


Fig. 10. *SEM images of fusion zone in Ti/Ti6Al4V [34]*

Ti6Al4V/Al6082T6

Titanium and aluminum are low-density materials.

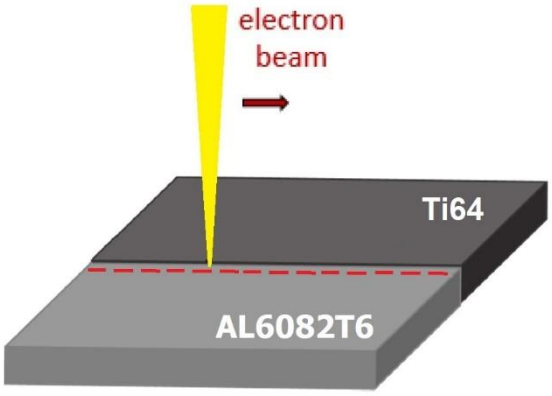


Fig. 11. *Schematic of the experimental design for EBW of Ti6Al4V/Al6082T6 [38]*

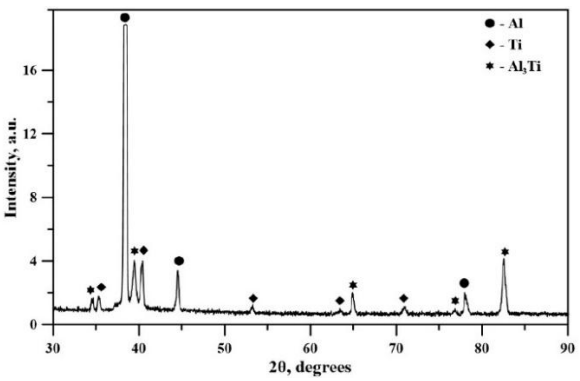


Fig. 12. *X-ray diffraction patterns of the welded joints in Ti6Al4V/Al6082T6 [38]*

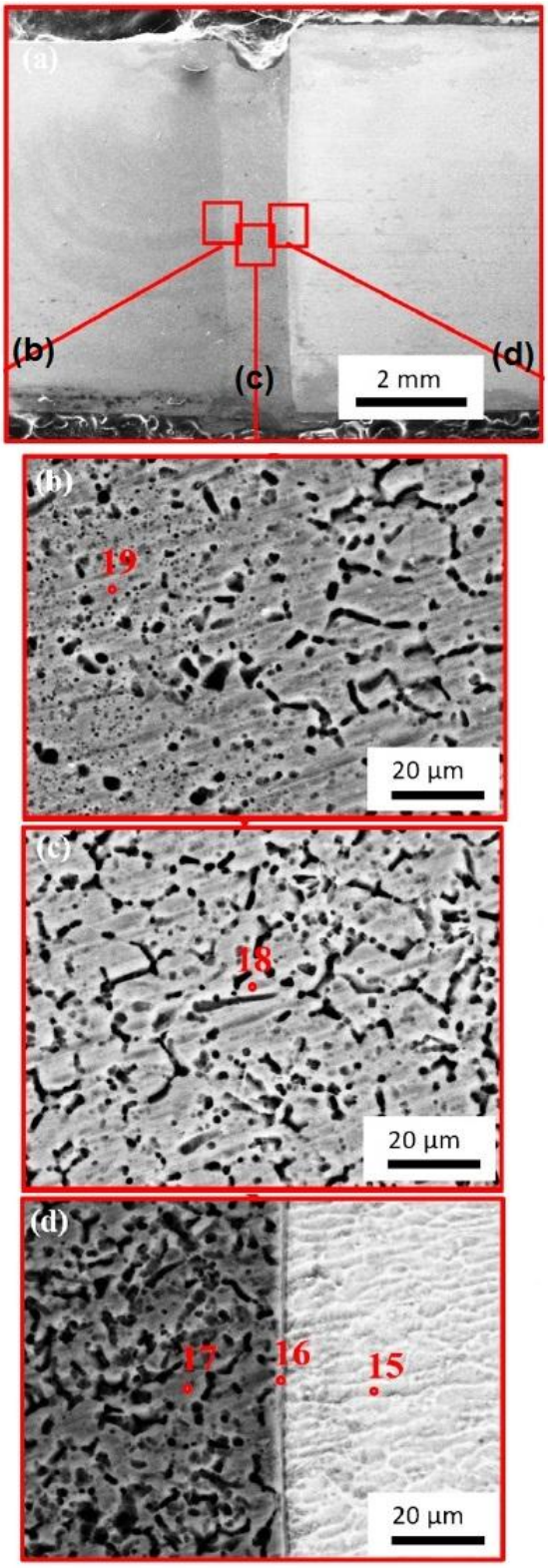


Fig. 13. *SEM images of fusion zone in Ti6Al4V/Al6082T6 [38]*

They are increasingly displacing steel in various structures, while titanium has strength comparable to that of steel. Weight reduction leads to energy and cost savings [35].

Schematic of the experimental design for EBW of Ti6Al4V/Al6082T6 is shown in Figure 11.

The joining of Ti- and Al-based alloys is considered difficult due to the different thermophysical and thermochemical properties of both kinds of materials [36, 37]. Welding of Ti and Al alloys leads to the formation of intermetallic structures, such as Ti_3Al, TiAl, and $TiAl_3$, in the welded seam that are characterized as very brittle, leading to fracturing the welded joint. This problem makes the joining of titanium- and aluminum-based materials challenging [38], Figure 12.

Figure 13 illustrates the electron beam weld obtained by shifting the electron beam toward the aluminum plate. This beam offset significantly accelerated the melting of the aluminum substrate, while resulting in limited melting of the Ti64 substrate. Consequently, the majority of the fusion zone (Figure 13c) and the heat-affected zone located closer to the aluminum specimen (Figure 13b) were predominantly composed of aluminum, with only a small amount of Ti64 introduced through the observed diffusion processes. A relatively small fusion zone was detected at the interface between the molten region and the Ti64 substrate.

CONCLUSION

In this paper, we demonstrated the possibilities for the fabrication of welded joints between dissimilar metals and alloys using electron beam technologies. Precisely selected technological conditions during the welding process led to obtaining strong and unbreakable welds. On the other hand, it contributes to the improvement of the mechanical characteristics (hardness, yield and, tensile strength) of the joints. These properties are very important for the implementation of dissimilar joints in various branches of modern industry.

Joints of copper and 304L stainless steel were successfully made via electron-beam welding without a beam offset and with a beam offset towards either welded material to a distance of 0,3 mm. The phase composition of the considered specimens is in the form of a double phase structure of face-centered cubic (fcc) and body-centered cubic (bcc) phases, with the amount of bcc being maximal in the weld formed without an offset. The specimen welded without an offset exhibits the highest values of yield strength and tensile strength.

Copper and 304L stainless steel specimens have been successfully welded using electron beam welding technology. A beam power of 1800 W is sufficient to weld 8 mm thick specimens in partial joint penetration weld. At a beam power of 2400 and 3000 W complete penetration weld has been formed at the same sample thickness. Higher values of the beam power lead together mechanical properties. In the sample welded with the highest power of 3000 W, the highest values of yield strength and tensile strength were measured - 93 MPa and 218 MPa, respectively.

The results of the current work indicate that electron beam welding is a very promising method for welding CP-Ti and Ti6Al4V, since a high precision of the joint can be achieved with a low number of internal stresses, a low number of defects, and satisfactory mechanical characteristics. The formed joints have moderately high plasticity and good mechanical characteristics, which makes them ideal for applications in specific industrial fields.

The present work reveals the effect of electron beam offset on the structure and microhardness of electron-beam-welded titanium and aluminum alloy specimens. Owing to the high input power of the electron beam, full penetration of the substrates was achieved in all cases, rather than the formation of a conventional keyhole-type weld. This outcome is advantageous, as it results in narrow and symmetrical heat-affected zones. However, applying an electron beam offset toward the Al6082-T6 alloy results in the formation of a welded joint composed predominantly of pure aluminum, with only a very narrow intermetallic layer. This characteristic can be

regarded as a significant advantage compared with the other two cases.

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