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Effect of physical and crystallographic properties on diffusion mechanism of copper and titanium sheets joined via explosion welding

Mehmet Serkan Yıldırım[1], Gözde Altuntaş[2]*, Onur Altuntaş[3], Yakup Kaya[4]

[1]*Department of Mechanical and Metal Technologies, Vocational School of Technical Sciences, Gazi University, Turkey*
[2]*Department of Metallurgical and Materials Engineering, Faculty of Technology, Gazi University, Turkey*
[3]*Department of Warfare Weapons and Tools, Alparslan Defense Sciences and National Security Institute, National Defense University, Turkey*
[4]*Department of Manufacturing Engineering, Faculty of Technology, Karabük University, Turkey*

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Abstract

In this study, ASTM C11000 commercially pure copper and Grade 2 commercially pure titanium sheets were joined by explosive welding using two different explosive ratios (R = 2.5 and R = 3.5) to produce Cu/Ti layered composites. The effects of the explosive ratio on the interfacial morphology, crystallographic characteristics, dislocation density, electrical conductivity, and thermal behavior of the composites were investigated. Microstructural and elemental analyses were performed using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS), while crystallographic characterization was conducted using X-ray diffraction (XRD). Differential scanning calorimetry (DSC) analyses were performed at heating rates of 5, 10, and 15 °C min^{-1}, and the apparent activation energies associated with the selected interfacial thermal event were calculated using the Kissinger method. Increasing the explosive ratio from R = 2.5 to R = 3.5 transformed the relatively flat Cu/Ti interface into a distinctly wavy morphology and resulted in the formation of island-like regions and a locally broadened interfacial interaction zone. The dislocation density increased from 1. × 10^{15} to 2.1 × 10^{15} m^{-2} with increasing explosive ratio. The composite produced at R = 2.5 exhibited approximately 25 % higher electrical conductivity than that produced at R = 3.5. The apparent activation energies were determined as 206 and 44 kJ mol^{-1} for R = 2.5 and R = 3.5, respectively. The lower apparent activation energy obtained at R = 3.5 indicates that the thermal process associated with the selected DSC peak occurs more readily at the highly deformed and defect-rich interface. These findings reveal a trade-off between interfacial deformation and electrical performance. R = 2.5 is more favorable when higher electrical conductivity and a relatively uniform interface are required, whereas R = 3.5 promotes a wavy interface and greater defect density at the expense of electrical conductivity. Therefore, the explosive ratio should be selected according to the required balance between interfacial morphology, electrical conductivity, and thermal response in Cu/Ti layered composites.

K e y w o r d s: explosive welding, Cu/Ti composite, crystallography, diffusion calculation, microstructure

1. Introduction

With developing technology, welded joints of the same parts are not preferred due to performance limitations. Instead, joints that combine the superior properties of the parts by welding different parts are more preferred in modern engineering applications [1]. One of the preferred welding methods for welding different materials is the explosion welding method [2]. Explosive welding method is a solid-state welding technique based on the controlled detonation of explosives on the metal surface, used to join similar or dissimilar metals [3].

As a result of the explosion, high pressure of up

*Corresponding author: gozdealtuntas@gazi.edu.tr

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Table 1. Chemical composition of copper and titanium alloys used in experimental studies (% by weight)

Alloying Element	Al	Zn	Si	Cu	C	O	H	N	Ti
Copper (ASTM C11000)	0.021	0.001	0.001	balance	–	–	–	–	–
Titanium (Grade 2)	–	–	–	–	0.10	0.25	0.015	0.03	balance

to 1–10 GPa is achieved [4]. In the explosion welding method, the base metal and the top metal, which are kept at a certain distance between them, collide obliquely at high speed with the effect of the explosion [3]. After this collision, a metallurgical bond occurs between the metals. Bonding interfaces obtained by explosive welding have a distinctive periodic wavy structure. The ability to join metals with superior physical and mechanical properties using the explosion welding technique makes this method more advantageous than other solid state welding methods [3]. For this reason, it is frequently used in the production of laminate and multilayer materials with high bond strength consisting of different metals [5, 6].

Titanium (Ti) and its alloys are frequently used in automobile, aerospace biomedical engineering and military industries due to their excellent corrosion resistance, high strength, light weight and high temperature creep resistance [7, 8]. Copper (Cu) is frequently used in sectors such as electronics and construction due to its good thermal and electrical conductivity [9, 10]. Due to these superior properties, copper and titanium sheets are welded and used in many different areas. Copper and titanium welded parts have practical uses as electrolytic cell materials, aerospace components and ship parts. In addition, pipes made of copper and titanium are used in all kinds of sea water pipelines and steam pipelines used in military ships and coastal power plants [11, 12]. The Ti/Cu explosive coating interface was examined with different microscope methods and its effects on its physical and mechanical properties were examined. The effect of interface morphology on the electromechanical properties of produced Ti/Cu coated composites has been investigated in detail [13, 14]. In a different study, the effect of Ti/Cu material produced by explosion welding on mechanical properties was examined [15]. At the same time, the effect of joining these two metals on structural properties was investigated by using different methods [16]. Recently, Chen et al. performed microstructure characterization by applying post-weld heat treatment [17].

In this study, unlike previous studies in the literature, the effects of different explosive velocities on electrical conductivity, structural properties and diffusion were investigated from the perspective of physical metallurgy.

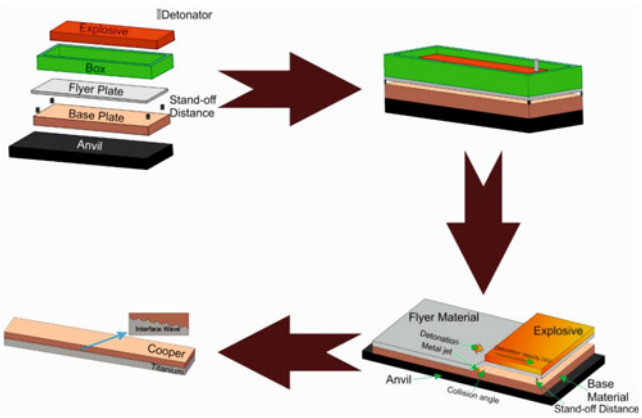


Fig. 1. Schematic representation of materials joined by explosion welding.

2. Materials and methods

In experimental studies, copper (ASTM C11000 series) and titanium (Grade 2) alloys, whose chemical composition is given in Table 1, were joined using the explosion welding method. In the welding process, $170 \times 120 \times 2\,\text{mm}^3$ copper plate was used as the base metal and $170 \times 120 \times 1.5\,\text{mm}^3$ titanium plate was used as the coating metal. Parallel plate geometry with an interspace distance of 1.5 mm was chosen for all explosion welding processes.

Elbar-5 was used as an explosive in explosive welding processes. In experimental studies, two different explosive rates (R = explosive weight/top plate weight) were determined. 350 g of explosive with an explosive rate of $R = 2.5$ and 490 g of explosive with an explosive rate of $R = 3.5$ were used. In experimental studies, samples were coded as R2.5 and R3.5, respectively. The produced Cu-Ti composite sheets were cut and made ready by the wire erosion method for both microstructural-crystallographic characterizations and thermal analysis and electrical conduction measurements. Figure 1 shows the schematic representation of the joining process.

Elemental mapping analyzes were carried out by examining the joint interfaces of the samples, which underwent traditional metallographic processing steps, with a Hitachi SU8700 branded SEM (scanning electron microscope) device. For diffusion calculations, analyzes were carried out with a Hitachi 7020 DSC device at heating rates of 10, 20, and 30 °C min^{-1}.

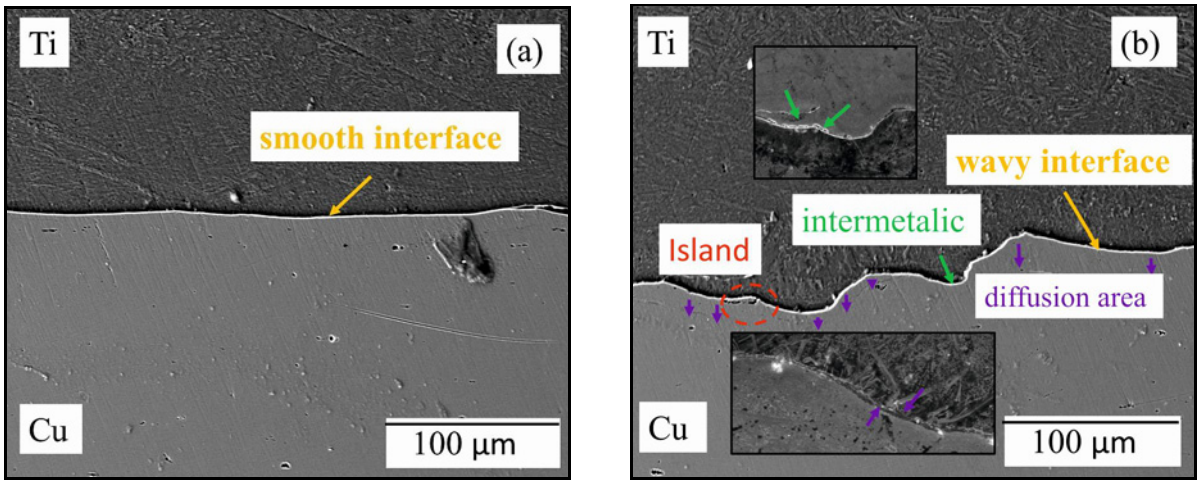


Fig. 2. SEM microstructure images of the samples (a) R2.5 and (b) R3.5.

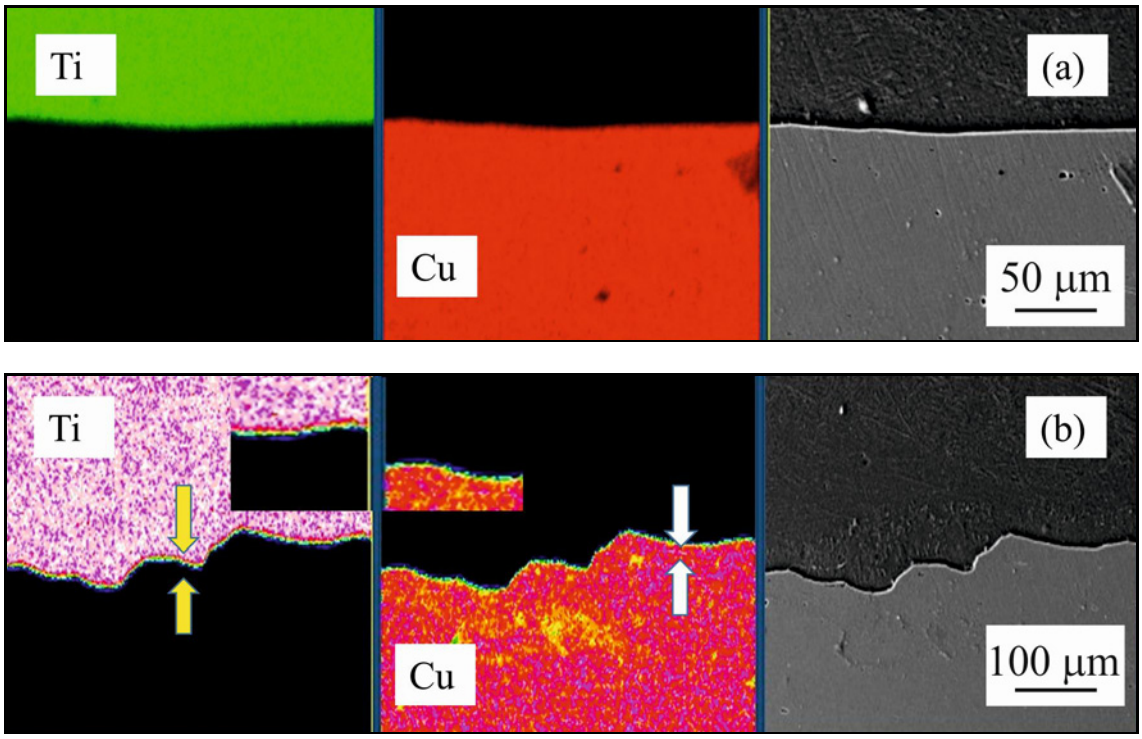


Fig. 3. EDS elemental mapping profiles illustrating spatial element distribution and interfacial diffusion in (a) R2.5 and (b) R3.5 samples.

Dislocation density calculations were determined by XRD analysis using the Bruker D8 Advance brand device. Electrical resistance measurements were analyzed on the samples at room temperature using the four-point probe method using a Keithley 2450 brand device. This method eliminates the effects of contact resistance between the sample and electrical contacts.

3. Results and Discussion

Figure 2 shows the cross-sectional SEM microstructures of the Cu/Ti composites produced at explosive ratios of (a) $R = 2.5$ and (b) $R = 3.5$. As shown in Fig. 2a, the Cu/Ti interface produced at $R = 2.5$ is relatively flat, smooth, and continuous. No pronounced island-like regions or interfacial reaction products were observed at this explosive ratio. In contrast, increasing the explosive ratio to $R = 3.5$ resulted in the formation of a distinctly wavy and locally indented interface, as shown in Fig. 2b. The higher explosive ratio may increase the collision velocity of the flyer plate and the impact pressure generated between the plates, thereby promoting severe plastic deformation and wave forma-

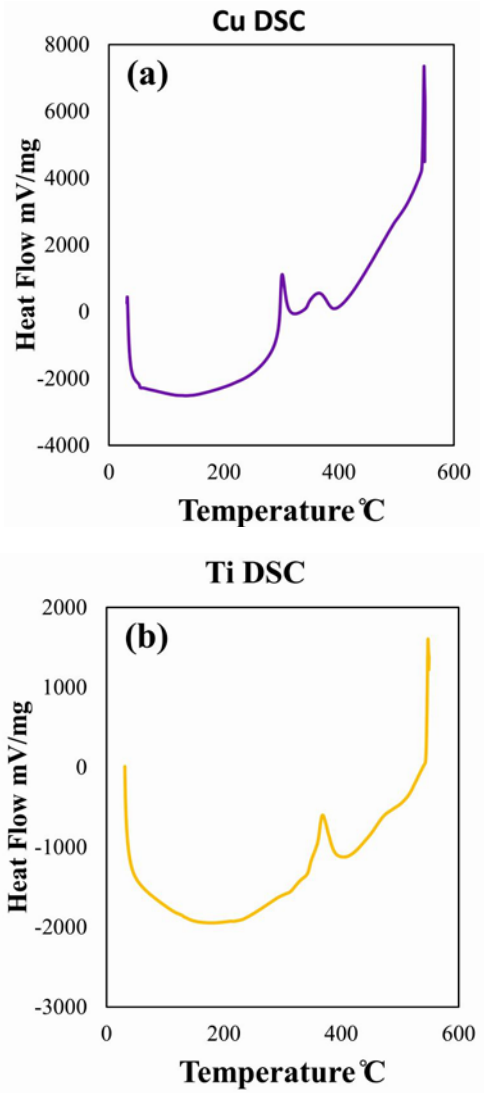


Fig. 4. DSC thermal spectra revealing characteristic phase transitions in (a) Cu and (b) Ti alloys.

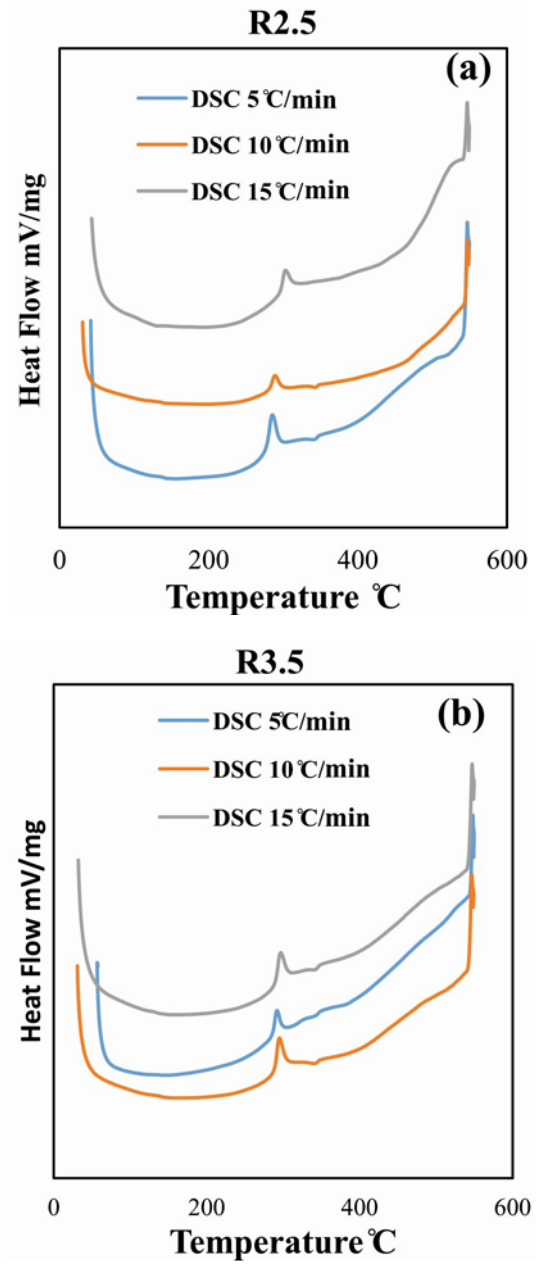


Fig. 5. DSC graphs at three different heating rates taken from the interfaces of the samples after explosion welding.

tion at the bonding interface [18, 19]. Island-like regions and a locally broadened interfacial interaction zone were also observed at $R = 3.5$. These features indicate that increasing the explosive ratio intensifies interfacial deformation and material interaction during explosive welding. The chemical characteristics of the interfacial regions were further evaluated by EDS analysis.

Elemental mapping images obtained as a result of EDS analysis of R2.5 and R3.5 samples are presented in Fig. 3. In Fig. 3a, the diffusion effect cannot be distinguished at the interface. In Fig. 3b, a linear fluctuation in which blue and green colors are more dominant stands out as diffusion occurs at the interface. As it is known, the process, also known as explosive bonding with explosion welding, occurs with an inclined collision between two metal plates. Although heat is generated during the explosion, no heat transfer is observed from one plate to another due to lack of time [20–22]. The situation obtained without heat transfer is the blue-green wavy image formed at the interface due to diffusion, as seen in Fig. 3b.

Figure 4 shows the DSC curves of Cu and Ti. The DSC curve of Cu exhibits two clearly distinguishable exothermic peaks, which are attributed to the gradual oxidation of Cu and the formation of Cu_2O [23]. For Ti, an exothermic peak was observed at approximately 375 ℃ and was attributed to titanium oxidation [24].

Figure 5 presents the DSC curves obtained from

the interfacial regions of the samples produced at explosive ratios of $R = 2.5$ and $R = 3.5$ at three different heating rates (5, 10, and 15 °C min^{-1}). For both samples, the characteristic DSC peaks shifted toward higher temperatures with increasing heating rate. At lower heating rates, the samples remain within a given temperature range for a longer period, allowing the thermally activated process to occur at a lower temperature. Conversely, at higher heating rates, the shorter reaction time and thermal lag cause the characteristic peaks to shift toward higher temperatures [25, 26]. The slope was obtained with the DSC graphs obtained at different heating rates and the activation energy at the interface after the explosion welding was calculated. Activation energie calculated with the Kissinger equation were calculated as 206 kJ mol^{-1} in the sample produced using an explosive ratio of $R = 2.5$. In the sample produced using an explosive ratio of $R = 3.5$, this value was calculated as 44 kJ mol^{-1}. Generally a lower activation energy indicates easier diffusion. This situation is stated in the Arrhenius equation in Eqs. (1) and (2) [27]:

$$D = D_0 \exp\left(-\frac{E_a}{RT}\right), \tag{1}$$

$$k = A \exp\left(-\frac{E_a}{RT}\right), \tag{2}$$

where D is diffusion coefficient, D_0 is diffusion constant, E_a is activation energy, R gas constant (8.314 J mol^{-1} K^{-1}), T is temperature (°K), k is reaction rate, and A is the pre-exponential (frequency) factor.

The Kissinger equation is given in Eq. (3) [28]:

$$\ln\left(\frac{\beta}{T_p^2}\right) = -\frac{E_a}{RT_p} + C, \tag{3}$$

where β is the heating rate, T_p is the absolute peak temperature obtained from the DSC curve, and C is a constant.

The slope graphs obtained for activation energies with the Kissinger equation are shown in Fig. 6. The results obtained show that as the explosive rate increases ($R = 3.5$), the activation energy decreases and diffusion will be easier. This situation proves the information given as a result of the calculations made as stated in the literature [20, 21].

Figure 7 shows the XRD graphs and dislocation densities of the materials combined using different explosive ratios. It is seen that the Cu and Ti peaks have higher intensity due to the higher explosive rate in the sample produced using $R = 3.5$ explosive rate. At the same time, it was calculated that the dislocation density was approximately 50 % higher compared to the sample produced using an explosive rate of $R = 2.5$.

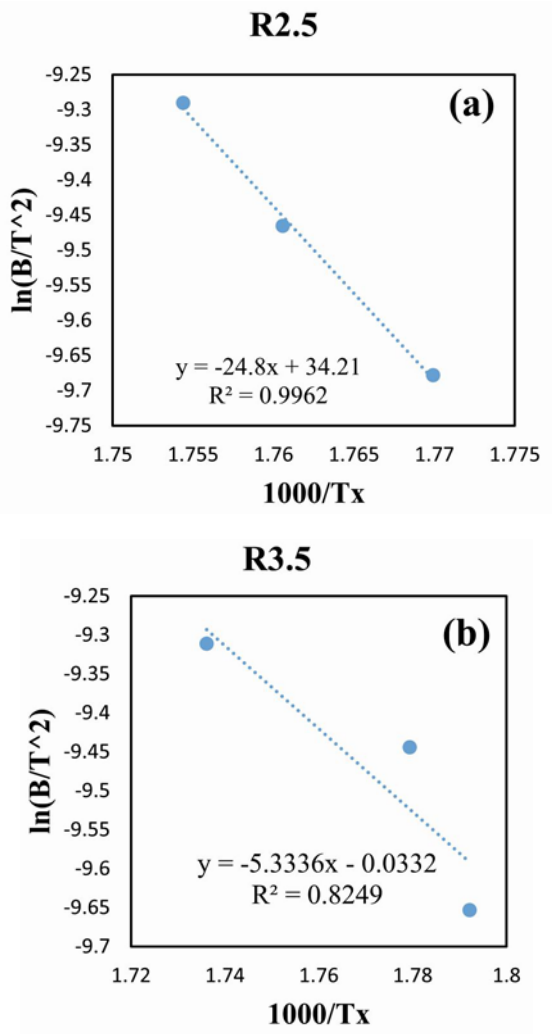


Fig. 6. Slope graphs of the samples obtained for the Kissinger equation: (a) R2.5 and (b) R3.5.

The appropriate combination of low resistivity and high strength is needed for coatings used in electrotechnical applications. Copper-titanium composites are one of the industrially suitable bilayer materials used in this field. Copper-titanium is widely used because it has good conductivity [13]. It has been determined that the Ti element reinforced in the Cu/Ti composite produced by spark plasma sintering technique increases the electrical resistance of the Cu alloy (compared to pure Cu) [29]. In particular, it was stated that the addition of Ti up to approximately 4.0 % by weight increased the resistance of Cu [30].

After this change in dislocation density, the electrical conductivity of the samples was measured and the relationship between them was investigated. Figure 8 shows the electrical conductivity graphs of the samples. Electrical conductivity values are calculated as % IACS. Measurement results showed that the electrical conductivity of the sample with a low explosive rate

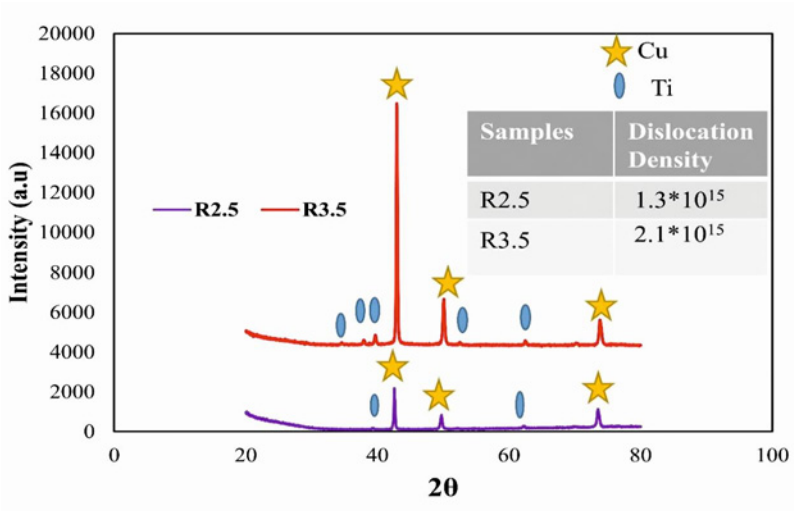


Fig. 7. Effect of explosive ratio on crystal lattice distortion: Integrated xrd patterns and dislocation density evolution.

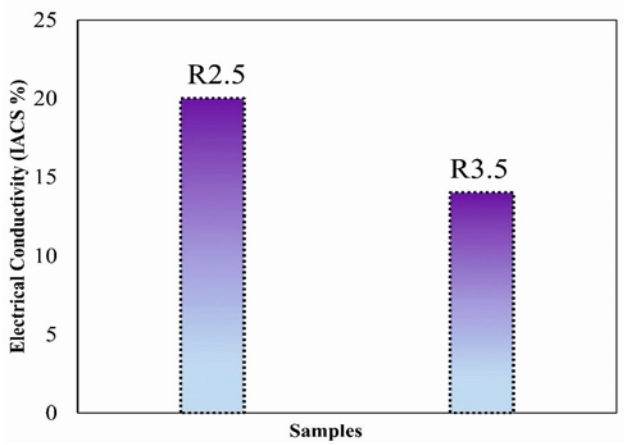


Fig. 8. Electrical conductivity measurements of samples.

($R = 2.5$) was 25 % better. This situation is related to the lower calculation of the dislocation density, which is one of the linear errors, as shown in Figure 7, compared to the joining using the $R = 3.5$ explosive rate. Dislocations, which are linear defects, cause scattering of electrons in the crystal structure. The decrease in electrical conductivity occurs by the expansion of the contact surface, microcracks, new interfaces, and strain hardening [31].

4. Conclusions

In this study, the effects of the explosive ratio on the interfacial morphology, crystallographic characteristics, electrical conductivity, and thermal behavior of explosively welded Cu/Ti composites were investigated. The main conclusions can be summarized as follows:

1. Increasing the explosive ratio from $R = 2.5$ to $R = 3.5$ transformed the relatively flat Cu/Ti interface into a distinctly wavy and locally indented morphology. Island-like regions and a locally broadened interfacial interaction zone were also observed at $R = 3.5$, indicating that the higher explosive ratio intensified plastic deformation and material interaction at the bonding interface.

2. The dislocation density increased from $1.3 \times 10^{15}\,\mathrm{m}^{-2}$ at $R = 2.5$ to $2.1 \times 10^{15}\,\mathrm{m}^{-2}$ at $R = 3.5$. This increase was attributed to the greater lattice distortion and severe plastic deformation generated by the higher explosive ratio.

3. Increasing the explosive ratio adversely affected the electrical conductivity. The composite produced at $R = 2.5$ exhibited approximately 25 % higher electrical conductivity than that produced at $R = 3.5$. The lower conductivity of the $R = 3.5$ sample was associated with its higher dislocation density, lattice distortion, and increased interfacial irregularity, which can enhance electron scattering.

4. Elemental mapping revealed the distributions of Cu and Ti across the bonding interface and indicated the presence of a local interfacial interaction zone, particularly in the $R = 3.5$ sample. However, additional phase analyses would be required to identify the specific reaction products formed within this region.

5. The apparent activation energies calculated using the Kissinger method were 206 and $44\,\mathrm{kJ\,mol}^{-1}$ for $R = 2.5$ and $R = 3.5$, respectively. The lower apparent activation energy obtained at $R = 3.5$ indicates that the thermal process associated with the selected DSC peak occurs more readily at the highly deformed and defect-rich interface.

6. From a practical perspective, the results demonstrate a trade-off between interfacial deformation and electrical performance. An explosive ratio of $R = 2.5$ is more favorable for applications requiring higher electrical conductivity and a relatively uniform interface.

In contrast, $R = 3.5$ produces a distinctly wavy interface, higher defect density, and lower apparent activation energy, but at the expense of electrical conductivity. Therefore, the explosive ratio should be selected according to the required balance between interfacial morphology, electrical conductivity, and thermal response in Cu/Ti layered composites.

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