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Investigation on the Effects of Explosive Welding Parameters on the Mechanical Properties and Electrical Conductivity of Al-Cu Bimetal

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Abstract

The joints of dissimilar materials are widely used in industrial applications due to their technical and beneficial advantages. The dissimilar combination of aluminum and copper is generally difficult for fusion welding. This is because of formation of undesired intermetallic phases which reduces electrical conductivity in the joint interfaces. Therefore, in order to restrict these limitations solid states welding methods such as explosive welding have been suggested. Hence, in this research the effect of explosive welding parameters on microstructure, mechanical and electrical properties were investigated. Stand-off distance and thickness of explosive material were taken as the variable parameters which were affect the microstructure, mechanical and electrical properties. After conducting the Explosive welding process, Microstructural investigations using Optical and Scanning Electron Microscope which is equipped with Energy Dispersive Spectroscopy was performed. Also, for investigation of mechanical properties, hardness test was done. The results of microscopic investigations demonstrated that with increasing the thickness of explosive material, the joint interface was transformed from linear to wavy appearance. Also, the results showed that the Al-Cu interface had a higher hardness in comparison to the hardness of Al and Cu. Evaluations showed that forming the CuAl and CuAl2 intermetallic phases in the joint interface are the reason for increasing the hardness. Electrical resistance values of 0/3, 0/55, 0/38 and 0/40 mS/cm were obtained for Al-1050, Cu, Al-Cu joint interface of A and B samples.

Keywords: Explosive Welding, Aluminum 1050, Pure Cu, Hardness, Electrical Conductivity.

1. Introduction

Explosive welding is a method that welds two or more plates with high pressures coming from the explosion. In this method, the welded surfaces that are spaced apart at a certain distance approach each other at a high-speed and collide with each other. Due to the high impact pressure, a high-speed jet is formed by the two connecting surfaces which creates clean joints at the welded interface and removes the surface contaminants. The formation of this jet is one of the essential conditions for the proper bonding in explosive welding. This important welding process is a non- fusion one and extensively used in industrial applications for the joining of homogeneous and heterogeneous metals in two or more layers. Due to lack of heating during this process, the welding performed using this method lacks many disadvantages of the parts bonded using fusion welding, hot rolling or hot forging processes. This method is mostly applicable for similar and dissimilar materials that utilize the detonation force to form a metallic bond by electron sharing among two elements. Using this welding technique in different industries including shipbuilding, aircraft and aerospace industries, cladding of sheets and production of multilayer tanks have attracted many researchers' attention [1-4]. The welding of different metals is important due to the numerous applications that they provide. For example, an aluminum clad copper plate is 50% lighter and has conductivity equal to that of a copper alloy [5-8]. According to literatures, during the collision, a high-velocity jet is produced to remove away the impurities on the metal surfaces. The flyer plate collides with the base plate resulting in bonding at the interface of metals. The metal plates are joined at an internal point under the influence of very high pressure and cause considerable local plastic deformation at the interface in which metallurgical bonding occurs in nature. These joints are even stronger than the parent metals [9-12]. While the bonding of materials such as aluminum, titanium, copper and stainless steel with the conventional joining methods is difficult, they can be easily welded with explosive welding [13]. Gulenc proved that aluminum can be bonded to copper sheet by explosive welding [1]. Loureiro et al.[3] investigated the influence of the explosive ratio and type of sensitizer on the quality of explosive welds between copper and aluminum alloy plates. Formation of intermediate phases such as CuAl, $CuAl_2$, Cu_9Al_4, and Cu_3Al_2 was noticed in the interface. Acarer [5] investigated the

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microstructure, electrical, corrosion, and mechanical properties of plate-shaped aluminum-copper couple produced using the explosive welding method, and concluded that the Al-Cu bimetal had an acceptable joint resistance. Hoseini Athar et al. [8] calculated the weldability criteria for aluminum–copper joints and established a relationship between the microstructure and properties of the joint.

2. Materials and Methods

To understand the effect of explosive welding parameters on the microstructure and mechanical properties of Al-Cu (bimetal), the specimens of these two materials were cut into the dimensions of 15×15×3 mm3 (Al-1050) and 15×15×4 mm3 (for Cu). The chemical composition of Al-1050 and pure copper samples were represented in Table. 1. and Table. 2., respectively. In this study, a parallel arrangement was selected for the experimental set-up of explosive welding in which Al-1050 was used as a flyer plate and pure copper was employed as a constant plate. Also, AMATOL 5-95 which contains 5 wt.% of Ammonium nitrate and 95wt.% of TNT, was used as explosive material. The detonation velocity was equal to 256 m/s. Among all the parameters which can affect the properties of the final samples, the standoff distance and explosive ratio parameters were taken as variable factors. In Table. 3. different values of standoff distance and thickness of explosive has been shown.

Table. 1. Chemical composition of Al-1050 alloy (wt %).

Cu	Fe	Mn	Mg	Si	Zn	Ti	Al
0.04	0.42	0.05	0.05	0.21	0.07	0.04	Bal.

Table. 2. Chemical composition of pure copper (wt %).

Al	Fe	O	Si	Cu
0.040	0.030	< 0.006	0.003	Bal.

Table. 3. Values of stand-off distance and thickness of explosives.

Explosive welding variables	Sample A	Sample B
Stand-off distance (Cm)	1.5	2
Thickness of explosives(Cm)	1.42	1.90

For the microstructural investigations, samples were mounted and then ground by emery papers of grade numbers 400-2500. Microstructural examinations were conducted using an optical microscope and a scanning electron microscope (SEM), Meiji-ML7000, Seron technology AIS2300C, equipped with an energy dispersive X-ray spectrometer (EDS). The acceleration voltage was 25 Kv, the filament current 23-30 µA, and the working distance was around 20-25 mm. Microhardness values were measured under 100 g load and according to ASTM E92 standard. All tests have been done in the transverse cross-section of the samples. The electrical conductivity tests were performed by an Instek device and according to ASTM B 193-87 standard. The Eq. 1. stated below was used to calculate resistivity [10].

$$\rho = RS/L \qquad \text{(Eq. 1.)}$$

Where "R" is resistance, "L" is the distance of potential probes, and "S" is the contact area, and Eq. 2. was used to calculate G, conductivity.

$$G = L/(RS) \qquad \text{(Eq. 2.)}$$

In order to analyze the *shear* strength of the copper-aluminum connection, two specimens were cut, with one of which being along the welding direction, while the other being vertical to the connecting line. This test was performed according to DIN 50162.

3. Results and Discussion

In Fig. 1(a.b), OM images of A and B samples have been presented, respectively.

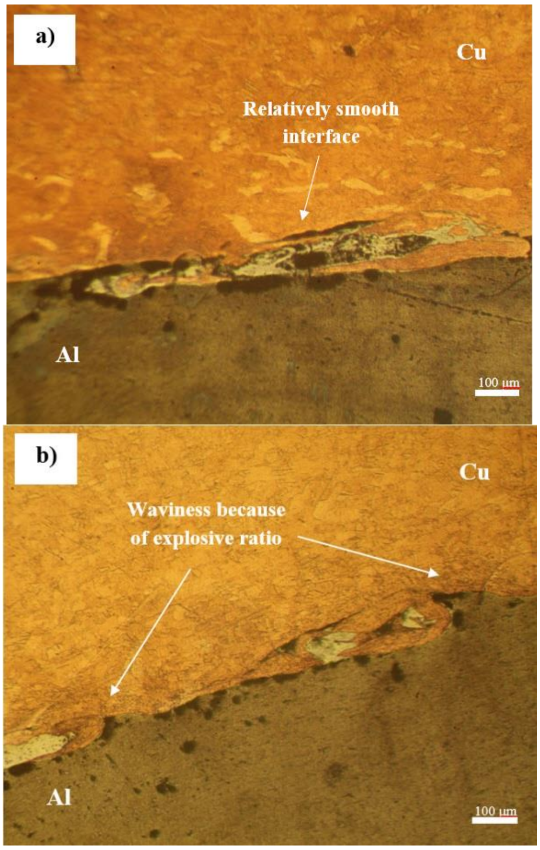
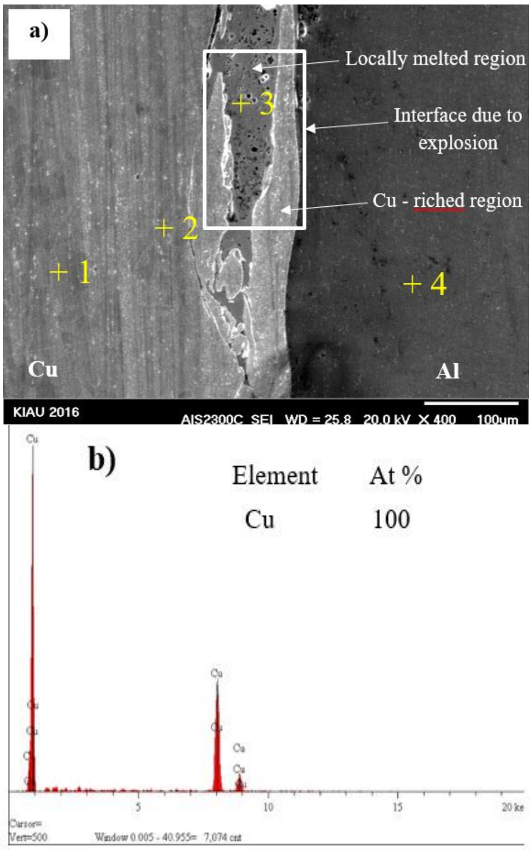


Fig. 1. OM images of a) sample A, b) sample B.

Based on Fig. 1.b, the joint interface in sample B is roughened, while this region is almost smooth in sample A (Fig. 1.a). In Fig. 1(a.b), these regions are indicated with white arrows. Considering the thickness of explosive materials (1.42 cm and 1.90 cm) used for these samples, it is found that the reason of this difference between these two interfaces is because of more explosive material used for sample B. As it is mentioned, the joint interface of sample A is almost smooth, and that is because the stand-off and the explosive ratio were suitable. Due to the increase of standoff distance and explosive force in sample B, the velocity of the Flyer Plate has increased and severe plastic deformation has occurred in the interface of bonding. By the increase of the collision's velocity, collision pressure has been increased and dynamic angle of collision and impact kinetic energy in the collision point has been increased as well [7,8,10] which led to the formation of a wavy interface in sample B.

In Fig. 2.a, SEM photograph of the welded bond of Al-Cu in sample A is shown. In this figure, a part of locally melted regions is also indicated.

At the initiation of the explosive welding process, the collision of two plates causes the forming of the locally plastic area at the interface. Because of the high velocity of impact between two materials, jetting phenomenon forms in both the flyer and base plates leading to the formation of a strong bond at the Al-Cu joint interface.



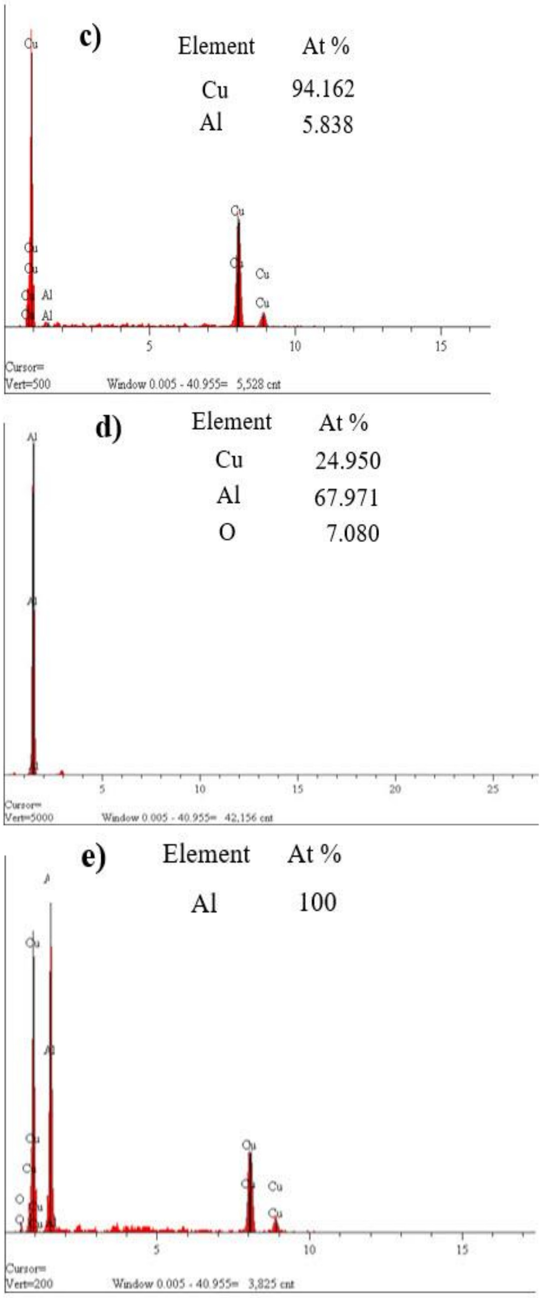


Fig. 2. a) SEM image provided from sample A interface and EDS analysis for sample A, b) point 1, c) point 2, d) point 3, and e) point 4.

In Figs. 2(b.e), EDS analysis of sample A are shown. It is seen that at the left (Fig. 2.b) and right side (Fig. 2.e) of the welded region copper and aluminum are exist, respectively. EDS analysis of point 2 (Fig. 2.c), shows that the matrix is enriched with Cu and a little amount of dissolved Al.

EDS analysis taken from the locally melted region (Fig. 2.d) shows that this region has consisted of Al and Cu elements, which came from the base and the flyer plates. Atomic percentage related to point 3 demonstrates that $CuAl_2$ intermetallic phase has been formed in the joint interface. According to Al-Cu phase diagram, a lot of intermetallic phases could be formed based on the chemical composition of welded components [3, 5].

In the explosive welding process, intermetallic compounds of welded materials are formed because of jetting formation and getting trapped between waviness of interface which along with increasing in adiabatic temperature near to interface resulted in the formation of locally melted regions. Because of jetting phenomena, the chemical composition of the melted regions is a mixture of the base and flyer plates. In Fig. 3., SEM images from the interfaces of samples A and B are shown. From Fig. 3., it can be seen that due to higher crash pressure of the upper plate to the base plate in sample B microcracks formed in some areas of the joint interface. In general, it is not possible to use explosive materials with highly explosive rates because of their severe pressure impact leading to tensile stress and severe dynamic transformation of flyer plate causing the fracture of the joint interface or even flyer plate [14]. Thus, according to the results obtained from previous studies [15], it can be concluded that the speed of the upper plate (in the case of sample B) was maximum, and consequently, the impact pressure was too high. On the other hand, in the case of sample A, no crack was found in the Al-Cu interface which indicated that the flyer plate welded to the base plate with sufficient crash velocity.

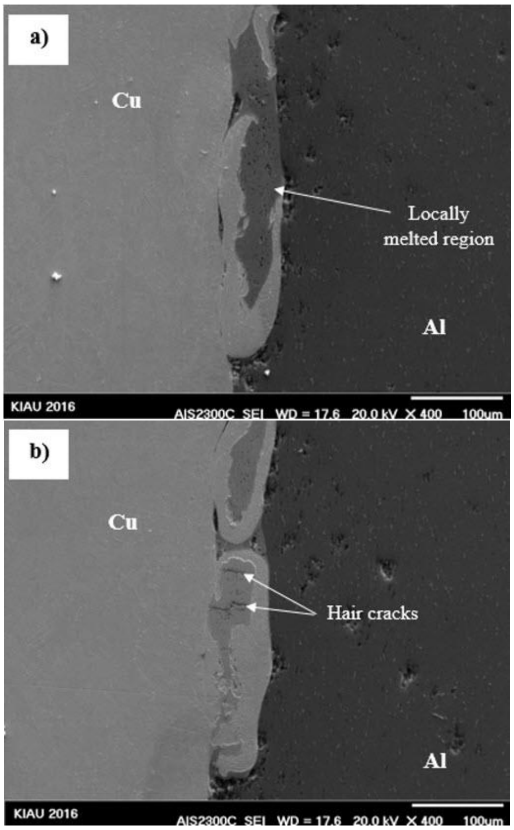


Fig. 3. SEM images provided from the interface of (a) sample A, and (b) Sample B.

In Fig. 4., the results of EDS analysis from sample B have been shown.

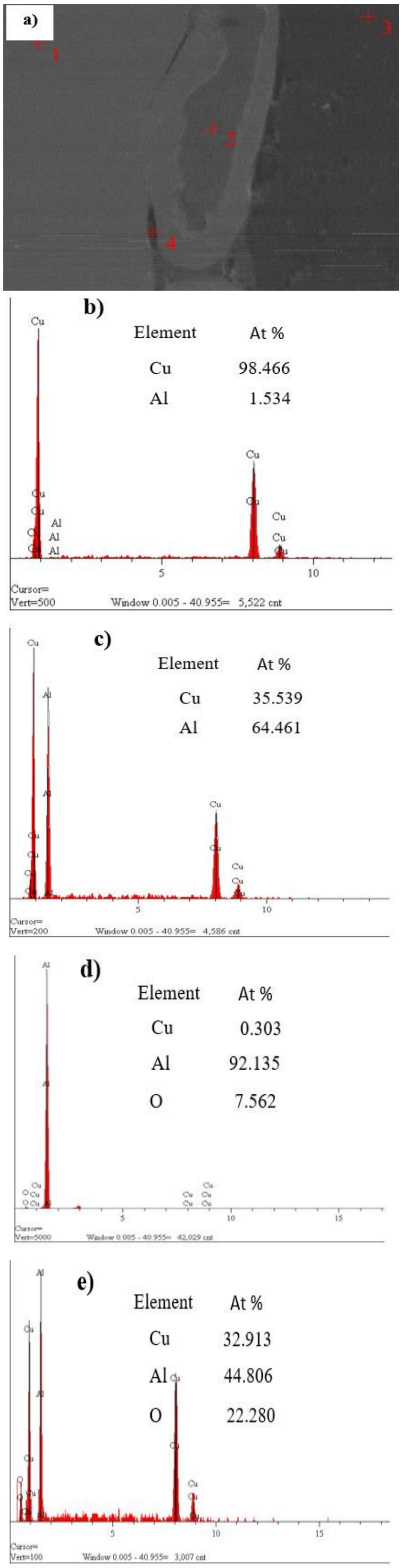


Fig. 4. a) SEM image provided from sample B interface, and EDS analysis taken from b) point 1, c) point 2, d) point 3, and e) point 4.

According to EDS analysis of point 2 in the joint interface, the atomic percentage of Al and Cu were determined to be 64.46 % and 35.54 %, respectively. According to Al-Cu phase diagram, it is concluded that this melted region is probably CuAl2 phase.

The microhardness results of samples A and B are shown in Fig. 5. According to Fig. 5.a, it is found that the joint interface has a higher hardness value in comparison to Al and Cu base plate. Also, the results indicated that as moving away from the interface, hardness values are decreased. That is because the amount of transformation due to explosive welding is reduced, with getting distance from the joint. In Fig. 5.b variations of microhardness values as a function of distance for sample B are indicated. As it is mentioned for sample A, with moving away from Al-Cu interface, the microhardness value is decreased significantly. The results showed that because of cold work caused by the collision of base and flyer plates, the hardness of Al-Cu bimetal is higher than the hardness of Al and Cu plates individually. Also, it is found that the hardness of regions near to the joint interface is lower than the joint interface itself. According to previous studies and the present study, releasing the kinetic energy in joint interface lead to increasing in temperature and consequently, annealing of this regions occurred and as a result the hardness will reduce [10].

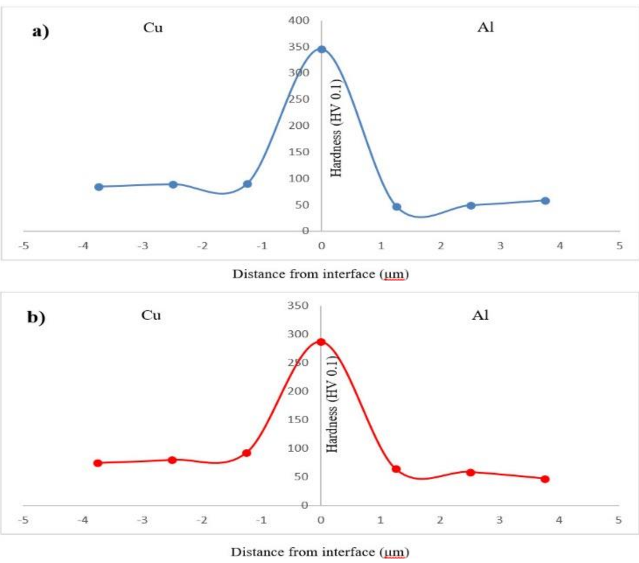


Fig. 5. Variation of hardness as a function of distance from the interface a) sample A, b) sample B.

Table. 4. illustrates the electrical resistance and conductivity of the Al-Cu bimetal, by Eq. 1 and 2. The results are in good agreement to those stated in the literature confirm that the Al-Cu bimetal had an average electrical conductivity, in comparison to original aluminum and copper materials that form the joint [16-18]. As concluded from the microstructural results, intermetallic phases may form during production using the explosive welding method, and these phases may reduce the conductivity. Cheng et al. [19] and Abbasi et al. [20] reported that the conductivity decreased as the thickness of intermetallic compounds increased. On the other hand, based on Acarer studies [5], when CuAl2 intermetallic phase is formed in small quantities and different regions, no adverse effect on the electrical conductivity of the Al-Cu bimetal is observed.

Table. 4. Electrical conductivity and resistance of Al-1050, Cu and Al-Cu joint interface.

Sample	Electrical resistance (Ω.cm)	Electrical conductivity (mS/cm)
Al-1050	27.3	0.3
Cu	14.6	0.55
Sample A (joint interface)	22.5	0.38
Sample B (joint interface)	23.3	0.40

Table. 5. The results of shear tests performed on A and B samples parallel and vertical to welding direction.

Sample	Max. force along the welding direction (N)	Shear strength along the welding direction (MPa)	Max. force vertical to the welding direction (N)	Shear strength vertical to the welding direction (MPa)
A	10986	98.5	11440	103.6
B	10986	95.4	11440	103.5

To understand the role of the thickness of explosive materials and stand-off distance on the shear strength of Al-Cu explosive welded joints, shear tests were performed parallel and vertical to the welding direction of A (Fig. 6 (a,b)) and B (Fig. 7. (a,b)) samples. The results are summarized in Table. 5. Sample B presented the Al-Cu part in Fig. 7. of the drawn curves for the prepared samples in the cross-sectional and longitudinal directions of the connection. Measurements resulting from the shear strength test show that the shear resistance for B1 and B2 specimens are 95.4 and 103.5 Mpa, respectively. It can also be observed that in this case that cut specimen in the longitudinal and parallel to the welding direction of A2 manifests the most shear strength, similar to the obtained information for A1 and A2 specimens. Based on the research projects conducted by Accra, the cutting strength of the copper-aluminum equals 140 Mpa, under the ideal conditions of the explosive welding process [5]. According to the past studies, it has been specified that in the connection resulting from the explosive welding of the two metals, the amount of the shear strength of the obtained connection is more equal to 60 Mpa than the amount of the shear resistance of the weakest piece in the formation of the connection, which has been observed to be Al 1050 [10]. As for the shear strength of the basic alloy in all the cases under study, the amount of the shear strength of the specimens is more than the amount of the shear resistance of the weaker metal that is aluminum.

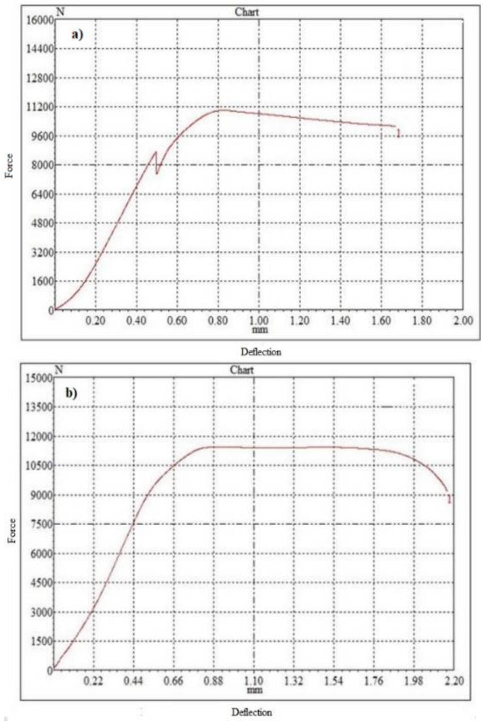


Fig. 6. Shear force-displacement curve for sample A, a) parallel connection, b) perpendicular to the direction of bonding.

Fig. 7. The force curves in terms of spacing for sample B, a) parallel connection, b) perpendicular to the direction of bonding.

4. Conclusion

1. The results of microscopic investigations demonstrated that with increasing the thickness of explosive material, the interface of the joint was transformed from linear to wavy appearance due to severe plastic deformation originated from high collision kinetic energy.
2. The results showed that the Al-Cu interface had higher hardness in comparison to the hardness of Al and Cu. Evaluations showed that forming the CuAl and $CuAl_2$ intermetallic phases in the joint interface are the reason for increasing the hardness.
3. SEM images provided from sample with Stand-off distance of 2 cm showed the presence of hair cracks at the joint interface that can affect the mechanical properties of the sample, thus it can be concluded that the suitable stand-off for joining the Al-1050 and pure Cu is 1.5 Cm.
4. Electrical resistance values of 0/3, 0/55, 0/38 and 0/40 mS/cm were obtained for Al-1050, Cu, Al-Cu joint interface of A and B samples.

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