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# Effect of explosive ratio on explosive welding quality of copper to aluminium

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## Abstract

The goal of this research is to study the influence of the ratio of an explosive composed of 80% ANFO and 20% matrix on the quality of dissimilar explosive welds of Cu-DHP copper to aluminium alloy 5083-H11, in flat configuration. It is analysed the influence of four explosive ratios (1.4, 1.8, 2.3 and 2.6) on the microstructure and mechanical properties of welds. It was observed that the increase in the explosive ratio gives rise to an increase of the collision point velocity (Vc) and the impact velocity (Vp) and consequently reduces the thickness of the flying plate after welding as well as produces wavy interfaces of greater amplitude. Microstructural analysis showed the formation of hard and brittle intermetallic compounds in the interface region, more obvious in welds made with higher ratio of explosive.

*Keywords:* Explosive welding; explosive ratio; copper; aluminium; intermetallic phases.

## 1. Introduction

New applications in the areas of power generation, aerospace, automotive, defence, electronics, created the need for joining multifunctional materials and hybrid structures of dissimilar materials [1,2]. The aluminium-copper joining, for example, has increased its use in electronic applications, power transmission systems, heat exchangers, etc. The joining of these materials by fusion welding is considered not feasible due to mismatch of physical properties, especially the melting temperature, and the formation of brittle intermetallic phases in the weld [3]. Since the main thermodynamic variables for the formation of brittle intermetallic phases during the welding process are temperature, pressure and time, solid state welding processes are an alternative to fusion welding processes. Friction stir welding is a solid state process that, although promising in solving these problems because temperatures involved are lower than in fusion welding, causes also the formation of brittle intermetallic phases (CuAl, $CuAl_2$ and $Cu_9Al_4$) very detrimental to the mechanical properties of welds, as shown by one of the authors of the current study [4,5]. The restriction on the formation of brittle intermetallic phases in the weld can be achieved by reducing the temperature and time of interaction between the materials involved during the welding process. Explosive welding is considered a cold process because no external heat is provided; heat is generated by the almost instant impact between the plates together, showing the welds no heat affected zones, unlike fusion welds [6]. In this process a flying plate is accelerated due to the thrust promoted by the expansion of detonation gas, against a slightly spaced stationary plate, generating high pressure and causing

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considerable plastic deformation of plates and jetting of melted materials at the interface, resulting in a solid connection (Fig. 1).

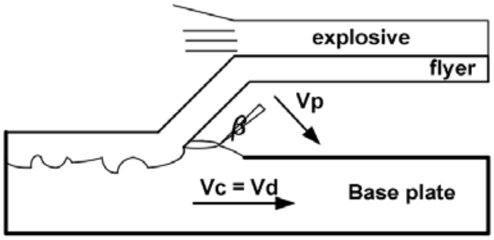


Fig. 1. Schematic representation of the explosive welding process. Vc - Collision point velocity, Vd - Detonation velocity, Vp - Impact velocity and β - Collision angle.

The detonation speed of the explosive controls the collision point velocity (Vc) of the plates along the interface, i.e., the welding speed.

The impact of the flying plate on the base plate promotes the formation of waves at the weld interface, but there is no consensus about their formation mechanism [7,8]. Quality of the joints is strongly dependent on process parameters such as type of explosive and explosive ratio, thickness and material type of plates to be welded and standoff distance [8,9].

## 2. Experimental Procedure

Dissimilar welds were made by explosive welding in flat configuration using a flying plate of copper Cu-DHP with 200x90x1 mm and as base plate the aluminium alloy 5083-H111 with 185x72x30 mm size. Before welding, plates were cleaned and abraded so as to remove impurities and imperfections from surfaces. An explosive consisting of a mixture of 80% ANFO (94% ammonium nitrate and 6% fuel oil) and 20% matrix (aqueous solution of ammonium nitrate) was used in different proportions controlled by the explosive ratio (1.4, 1.8, 2.3 and 2.6). The explosive ratio is given by the ratio between the mass of explosive and the mass of flyer plate under the explosive. Welds were referenced by letters SE, then the thickness of the flying plate and the height of the explosive used; SE1_20 means the explosive welding performed with a flying plate of 1 mm thick and 20 mm high of explosive. The SE1_20 and SE1_30 welds were made on a sand base while SE1_15 and SE1_25 on a steel base.

Measurement of detonation velocity (Vd) was based on the record of time of explosion propagation, using ionization probes, in a digital oscilloscope *LeCroy WaveJet 352*. Specimens for metallographic study were removed parallel to welding direction, ground and polished according to conventional procedures. Etching of copper was done using a mixture of 5 mL of $H_2O_2$ and 50 mL of $NH_4OH$. It was not possible to etch the aluminium alloy although several chemical reagents have been used. The hardness measurements were taken on a line transverse to the copper-aluminium bonding interface with a load of 200 gf for 15 seconds. In the case of intermetallic compounds, it was used a load of 50 gf due to their small size. The analysis of the intermetallic compounds was carried out through an electronic scanning microscope (SEM) provided with energy dispersive X-ray spectroscopy (EDS) *Philips XL30 SE*.

## 3. Results

The increase in the explosive ratio promotes increased detonation velocity (Vd), impact velocity (Vp) and small increase in collision angle (β), as shown in Table 1. Detonation velocity was measured, as mentioned above, while the other variables were computed according to the procedure described in Ribeiro *et al.* [10].

Table 1. Detonation results.

| | SE1_15 | SE1_20 | SE1_25 | SE1_30 |
|---|---|---|---|---|
| R | 1.4 | 1.8 | 2.3 | 2.6 |
| Vc (m/s) | 1712 | 1854 | 2013 | 2149 |
| Vp (m/s) | 660 | 755 | 830 | 885 |
| β (º) | 22.2 | 23.5 | 23.8 | 23.8 |

R - Explosive ratio, Vc - Collision point velocity, Vd - Detonation velocity and β - Collision angle.

Based on experimental conditions used, a weldability window was constructed, which defines the set of parameters from the domain providing welds with good quality; based on the calculated values, it was inserted in this area the point corresponding to each weld, as illustrated in Fig. 2. Looking at the figure, it is found that welding with the lowest ratio of explosive (SE1_15) is outside the weldability window to the left of the left edge which delimits the formation of waves in the weld interface. The SE_20 and SE_25 welds are within the weldability window and SE_30 welding is on the upper limit which delimits the possible formation of excessive molten zones.

According to this weldability window, it is expected that the weld SE_1_15 presents a flat interface without any wave, while the weld SE_1_30 should provide broad melted zones.

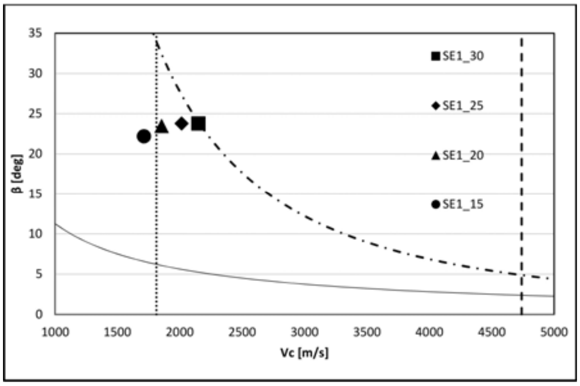
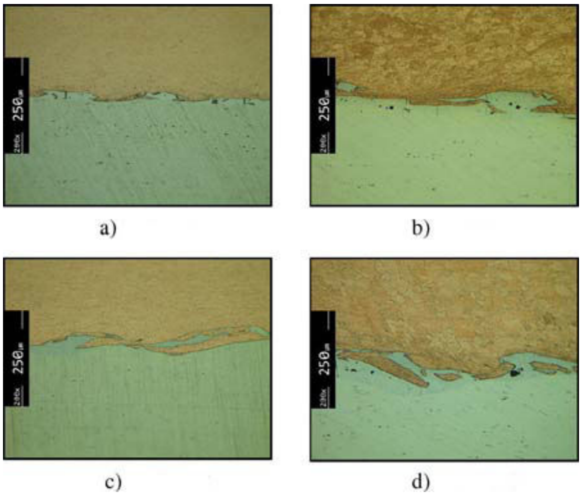


Fig. 2. Weldability window.

The metallographic analysis shows that the welding operation promotes the formation of irregular waves in the welding interface, as shown in Fig. 3, but very different from those that occur for example in welding of stainless steel to carbon steel [8].



a) b) c) d)

Fig. 3. Morphology of the interface welding.

Because of that randomness of the interface, it was not possible to evaluate the average wavelength in the various welds. In the weld carried out with the lowest ratio of explosive, SE1_15 (Fig. 3), it can be seen that the interface is already wavy, unlike to what is predicted by the weldability window, because the reference point is on the left of the window (Fig. 2). Fig. 3 also shows that, increasing the explosive ratio, the amplitude of the pseudo waves increases also appearing copper islands within the aluminium, see Fig. 3 d). This suggests that the impact is so strong that leads to copper pieces are torn off and placed into aluminium. A more detailed analysis shows that there are in the interface of welds small regions of few microns size and clear blue colour, inside of which there are voids and cracks as well. The presence of voids reveals that these regions had melted and, on cooling, gave rise to voids and brittle phases, because they display cracks. These regions exist in all welds, although they are more easily visible in welds made with a higher ratio of explosive. The analysis of these regions, using scanning electron microscope provided with EDS, has shown that they were not homogeneous and consist essentially of intermetallic compounds.

Fig. 4 illustrates the morphology of one of these zones from weld SE_1_25 and the points where it has been done semi-quantitative analysis. It can be seen in the image that the area near the interface has two regions with different colour, one close the copper with the marking 1 and the other by the aluminium with marking 2.

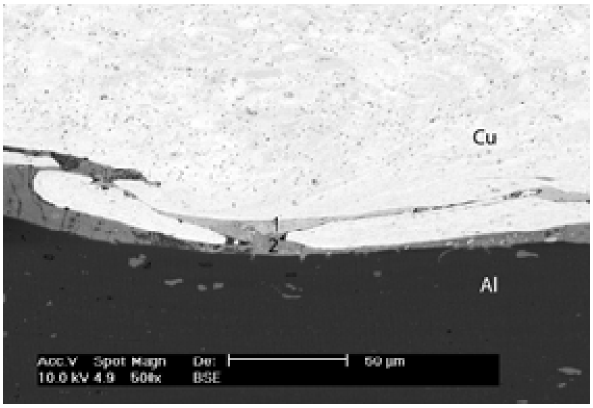
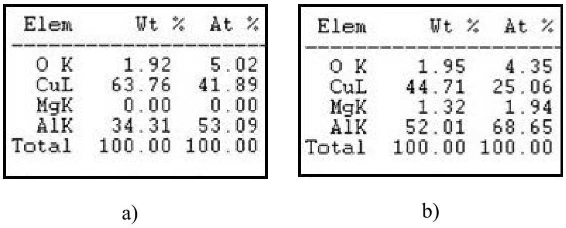


Fig. 4. Image SEM - sample SE1_25.

The chemical composition of the phase in the area 1, shown in Fig. 5 a), is close atomic composition of the intermetallic compound CuAl, according to Al-Cu phase diagram and also Hyoung-Joon *et al.* [11]. The chemical composition of zone 2, shown in Fig. 5 b), suggests that the phase present is near the intermetallic compound $CuAl_2$, according to Al-Cu phase diagram and [11].



| Elem | Wt % | At % |
|---|---|---|
| O K | 1.92 | 5.02 |
| CuL | 63.76 | 41.89 |
| MgK | 0.00 | 0.00 |
| AlK | 34.31 | 53.09 |
| Total | 100.00 | 100.00 |

a)

| Elem | Wt % | At % |
|---|---|---|
| O K | 1.95 | 4.35 |
| CuL | 44.71 | 25.06 |
| MgK | 1.32 | 1.94 |
| AlK | 52.01 | 68.65 |
| Total | 100.00 | 100.00 |

b)

Fig. 5. Energy Dispersive X-ray spectroscopy of phases on interface of sample SE_1_25: Zone 1 (a) and Zone 2 (b).

Fig. 6 shows the hardness profiles of welds through the thickness of the welds, as well as the hardness of the base materials, these represented by a red solid line for copper and a red dotted line for aluminium. Copper has an average hardness of 91HV0.2 while aluminium alloy has 88HV0.2. The figure shows a significant increase in hardness, particularly at the interface between the two materials, with respect to their base materials in all welds made.

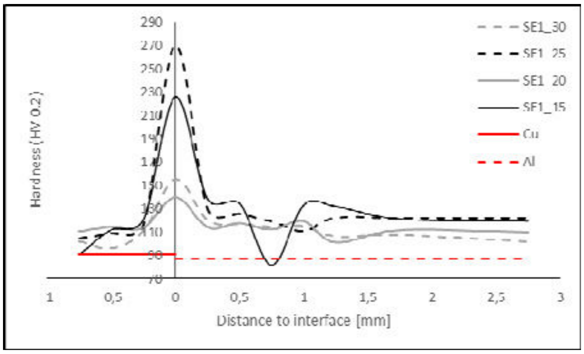


Fig. 6. Hardness profile.

This increase is due chiefly to plastic deformation imposed by the welding process. Note that the SE1_15 and SE1_25 welds tend to have higher hardness than the other welds because the supporting base of aluminium plates was of steel while in welds SE1_20 and SE1_30 was of sand, which reduced the stiffness of the set-up.

In the weld interfaces there are areas with higher hardness due to the presence of the intermetallic compounds mentioned above. The load used to measure hardness in those regions was of only 50 g due to their small size, of about few micrometres.

Fig. 7 illustrates the hardness printing produced on an intermetallic compound in the weld SE_1_30. The hardness measured in this intermetallic compound was of 618HV0.05. This hardness is close to the range (663-760 HV) given by Ouyang *et al.* [12] for intermetallic compound CuAl, precisely one of the phases mentioned above. In other intermetallic compounds were measured several hardness values, about 303 to 412 HV and others below 618 HV, which indicates the presence of $CuAl_2$, also detected above which, according to Ouyang *et al.* [12], has hardness in the range (486-557 HV) and also eutectic $\alpha$-Al/$CuAl_2$, in (257-385 HV) range, according to the same authors.

Such hard and brittle compounds result from a process of localized melting in a short time interval, as shown by the holes in Fig. 7. Cracks occur due to high residual stresses caused by rapid cooling and holes are formed during solidification, due to the change in volume between the liquid and the solidified material.

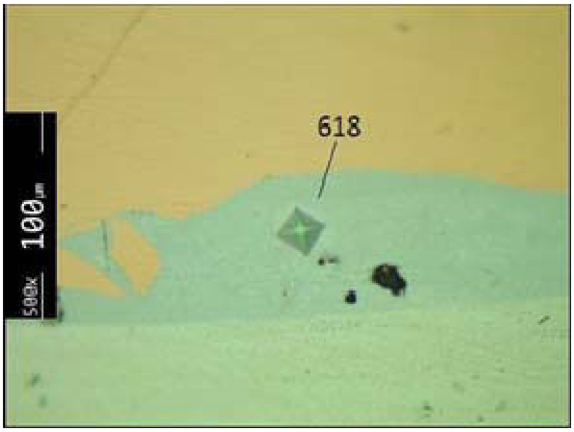


Fig. 7. Hardness measurement in an intermetallic compound of weld SE_1_30.

## 4. Conclusions

The experimental study in explosive welding of copper to an aluminium alloy AA6082-T6 allowed the following conclusions:

– The increase in the explosive ratio (R) leads to increased velocity of the collision point (Vc) and impact velocity (Vp) in all welds;

– The welds displayed interface morphology compatible with its location in weldability window;

– The amount of intermetallic compounds at the welding interface is superior for welds performed with higher explosive ratios, leading to an increase of voids and cracks in these areas;

– Intermetallic compounds found in the weld interface are mainly $CuAl_2$ and CuAl.

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