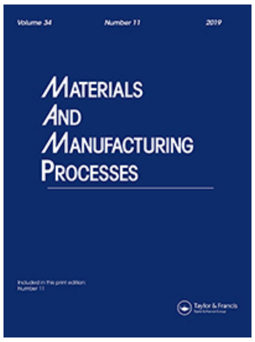

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Friction stir welding and explosive welding of aluminum/copper: process analysis

G.H.S.F.L. Carvalho[a], I. Galvão[a,b], R. Mendes[c], R.M. Leal[a,d], and A. Loureiro[a]

[a]CEMMPRE, Department of Mechanical Engineering, University of Coimbra, Coimbra, Portugal; [b]ISEL, Department of Mechanical Engineering, Polytechnic Institute of Lisbon, Lisboa, Portugal; [c]ADAI, LEDAP, Department of Mechanical Engineering, University of Coimbra, Coimbra, Portugal; [d]ESAD.CR, Polytechnic Institute of Leiria, Caldas da Rainha, Portugal

ABSTRACT

The 6082 aluminum alloy was welded to copper-DHP by friction stir welding and explosive welding. The effect of each welding process on the microstructural evolution, the intermetallic phases distribution, and the mechanical behavior of both types of welds was analyzed and compared. The microstructural changes proved to be much more expressive in friction stir welding due to the larger area under plastic deformation, the stirring and mixing of the alloys, the longer time under high temperature, and the longer interaction times between the base materials during welding. As explosive welding process is much faster, it avoids extensive microstructural changes and significant interaction of the materials, reducing the intermetallic volumes and their distribution along the interface. The friction stir welds presented Cu-rich intermetallics while the explosive welds presented Al-rich intermetallics. For alloys that can easily form brittle intermetallic phases, excessive interaction during the welding process leads to a very poor mechanical behavior of the joints.

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Friction; stir; welding; explosive; manufacturing; processes; intermetallics; microstructure; aluminum; copper

Introduction

The joining of dissimilar materials is an important research area, especially with the design requirements becoming more complex. Copper and aluminum are two of the most used metals because of their physical and mechanical properties. Although the combination of these metals is very strategic for many industries, the significant differences in the physical properties of these metals hinder their welding by conventional fusion processes. Friction stir welding (FSW) and explosive welding (EXW) solid-state processes have been regarded as very promising techniques for this combination. Nevertheless, there are still gaps of knowledge in both processes that need to be filled.

Since the development of FSW, the study of Al-Cu joining has notably increased.[1] Murr et al.[2] performed one of the first researches addressing Al-Cu welding microstructure. The difficulty in achieving welds with an excellent surface finish, sound structures and good mechanical properties has been reported over the years.[3] The formation of extensive intermetallic layers is the most referenced concern in literature.[4] These phases, besides being very brittle, also affect the material flow and weld morphology.[5] Many researches have been conducted to study suitable welding parameters[6] and the development of non-conventional FSW strategies.[7] However, the intermetallic formation and the high incidence of surface and internal defects remain a problem in Al-Cu FSW.[1]

The Al-Cu joining by EXW has been studied for more than a decade. Berski et al.[8] and Kaya[9] reported the production of consistent welds of aluminum and copper, but both studies did not analyze the phenomena affecting the intermetallic distribution after welding. Paul et al.[10] conducted a relevant work broadening the microstructural analysis by EBSD and TEM/EDX. More recently, Loureiro et al.[11] investigated the influence of different welding parameters on the quality of Al-Cu welds, while Carvalho et al.[12,13] studied process characteristics, addressing features about the interface morphology and wave formation by changing the flyer and baseplate position. The use of interlayers in Al-Cu joints was also studied.[14]

The two processes have some differences, such as the most commonly used welding configuration. While FSW uses mostly the butt joint, the most common configuration in EXW is the flat overlapping joint. However, other designs have already been tested for both processes, such as lap joints in FSW[4] and cylindrical configuration in EXW.[15] Consequently, the type of joint used will directly affect the suitable applications for which each process is indicated. Despite this, the two processes also present some similarities such as the suitability for joining difficult alloy combinations, with very different properties.

The presence of a high temperature, pressure and plastic deformation in Al-Cu solid-state joining makes the formation of intermetallic compounds almost inevitable. Mehta and Badheka[4] have claimed that FSW joints usually present the CuAl, Cu_9Al_4 and $CuAl_2$ intermetallic phases. In EXW, Paul et al.[10] also found the same three equilibrium phases. Intermetallic compounds in the Al-Cu system are often reported to be brittle and harmful to the mechanical properties.

CONTACT Ivan Galvão ivan.galvao@dem.uc.pt; igalvao@dem.isel.ipl.pt CEMMPRE, Department of Mechanical Engineering, University of Coimbra, Rua Luís Reis Santos, Coimbra 3030-788, Portugal

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Although relevant advances have been achieved for Al-Cu joining by FSW and EXW, the published works are essentially single process researches. It is rare to find an analysis combining these two solid-state welding technologies, such as FSW and EXW, identifying and comparing the main phenomena occurring during each process. The aim of this work is to analyze and compare the effect of each welding process on the microstructural evolution, the intermetallic phases distribution, and the mechanical behavior of copper and aluminum dissimilar joints.

Materials and methods

Two series of copper (Cu-DHP) and aluminum (AA6082) welds were manufactured by FSW and EXW. The FSW joints (FSWJ) were performed with 3 mm-thick plates in a butt weld configuration. The copper plate was located at the advancing side of the joint because the reverse positioning of the plates would promote improper welding conditions.[5] An H13 steel tool, with a 16 mm-diameter shoulder (7°conical) and an M5x0.8 cylindrical pin was used. The FSW process parameters are displayed in Table 1 and were selected based on previous works on dissimilar Al-Cu FSW.[5] No tool offset or any other non-conventional FSW strategy was used, thus enabling a more direct comparison between the phenomena from both welding processes.

The explosive joints (EXWJ) were produced in a partially overlapped configuration to obtain specimens that were comparable with the FSW butt joints (load transfer applications). The aluminum plate was 3 mm-thick and was positioned as the baseplate, while the copper plate was 1 mm-thick and was positioned as the flyer plate (parallel to each other) with 1.35 mm of stand-off distance. The use of a flyer plate with a lower thickness was due to the high density of the copper compared to aluminum. A 3 mm-thick flyer plate would significantly increase the energy transmitted by the collision at the interface.[16] Preliminary tests showed that when welding low strength baseplates with a much lower density than the flyer plate, the use of flyers with a similar/greater thickness may have a deleterious effect on the welding conditions. Also, the weldability is increased using copper as flyer and aluminum as the baseplate.[13] The explosive mixture was composed of an ammonium nitrate-based emulsion and expanded polystyrene spheres (EPS), previously characterized by Mendes et al.[17]

The EXW process parameters are presented in Table 1 and were chosen according to previous studies on Cu-Al[11,12] dissimilar welding. The impact velocity and the collision angle (β) were estimated using the Gurney equation for a one-dimensional problem in parallel configuration.[18] The explosive ratio (R), which is the ratio of the mass of the explosive to the mass of the flyer, was computed according to Carvalho et al.[12], who considered only the plate section beneath the explosive.

Metallographic analyses were performed by optical microscopy and scanning electron microscopy (SEM) with the use of energy-dispersive X-ray spectroscopy (EDS) to analyze the chemical composition. The aluminum microstructure was revealed using Weck's reagent, while a combination of 50 ml H_2O + 50 ml HNO_3 + 1ml HF was used to reveal the copper microstructure. Microhardness measurements were performed along the section of the welds ($HV_{0.2}$) as well as in localized mixing regions ($HV_{0.025}$).

The weld mechanical behavior was assessed by surface bending testing (FSW joints) and tensile/shear testing (EXW joints). The tensile/shear tests were performed with a testing speed of 5 $mm.min^{-1}$, and the local strain fields were acquired over the surface of the tested specimens by digital image correlation (DIC), using the GOM Aramis 5M system. The tensile/shear specimens were manufactured according to Loureiro et al.[11], in which the aluminum 3 mm-thick plate was machined to 1 mm to match the thickness of the copper plate. The fracture surfaces of the bending and the tensile/shear-tested specimens were analyzed by SEM and EDS.

Table 1. Welding parameters for the FSW and EXW joints.

FSWJ	Axial load	Traverse velocity	Rotational velocity	Tilt angle
	6 kN	50 $mm.min^{-1}$	1000 $rev.min^{-1}$	3°
EXWJ	R	Collision point velocity	Impact velocity	β angle
	2.15	2121 $m.s^{-1}$	642 $m.s^{-1}$	17°

Results and discussion

Microstructural evolution

The Al-Cu welding by FSW and EXW resulted in consistent joints, i.e. the alloys were joined without after-welding failure or separation of the plates. A macrograph of the transverse cross-section of the FSWJ is presented in Fig. 1(a). The mixture of both alloys is clear in the center of the image, occurring throughout the thickness of the plates and encompassing a width of about 5 mm. Figure 1(b) shows a macrograph of the longitudinal cross-section of the EXWJ. The main difference between both processes is the absence of an expressive mixture of the alloys in EXW. While there is an intense stirring of the alloys in FSW, with the formation of large and complex interaction structures (Fig. 1(c)), the deformation and mixing of the alloys only occurred in a very small region of the EXWJ (Fig. 1(d)). The lower interaction of the materials in this process results from EXW being a very short-cycle process in which only a highly localized region is affected by the impact.

Figure 2 shows the microstructural evolution after FSW, from the unaffected materials to the nugget. Microstructural changes encompassing a width of about 20 mm were found, which is slightly larger than the diameter of the shoulder (16 mm) (Fig. 2(a)). These changes were found to be more significant on the aluminum side of the joint. From Fig. 2(c), which shows the partially-recrystallized TMAZ, it can be observed that the aluminum alloy presented an expressive grain refinement from this region until the nugget (Fig. 2(d,e)) compared to the unaffected material (Fig. 2(b)). The grain was gradually refined as it approached the nugget, where the tool pin performed. Inside the nugget, the grain is also much smaller than the original. In turn, the copper presented a more localized grain refinement (Fig. 2(f)) in the nugget and some grain growth in the HAZ (Fig. 2(g,h)) compared to the original material (Fig. 2(i)).

In EXW, this level of microstructural change does not occur, and the final microstructure is very similar to the microstructure before welding. Figure 3 shows the microstructure of the weld interface. Deformed grains with some

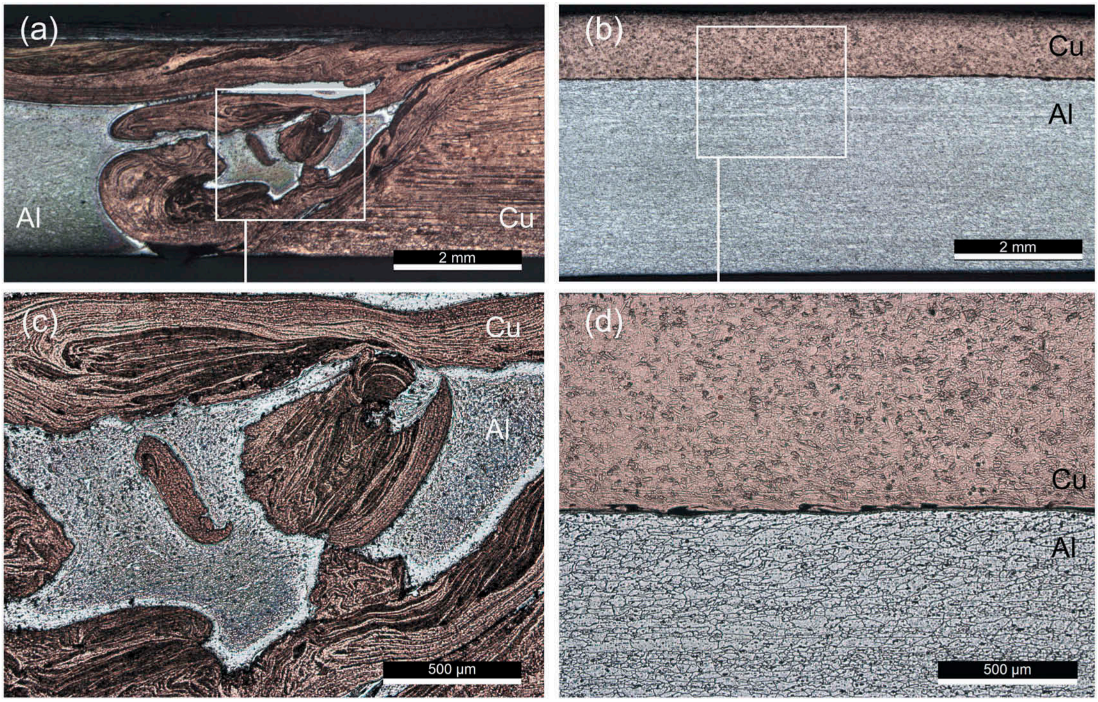

Figure 1. Macrograph of the cross-section of the (a) FSWJ and (b) EXWJ, and the transition region of the (c) FSWJ and (d) EXWJ.

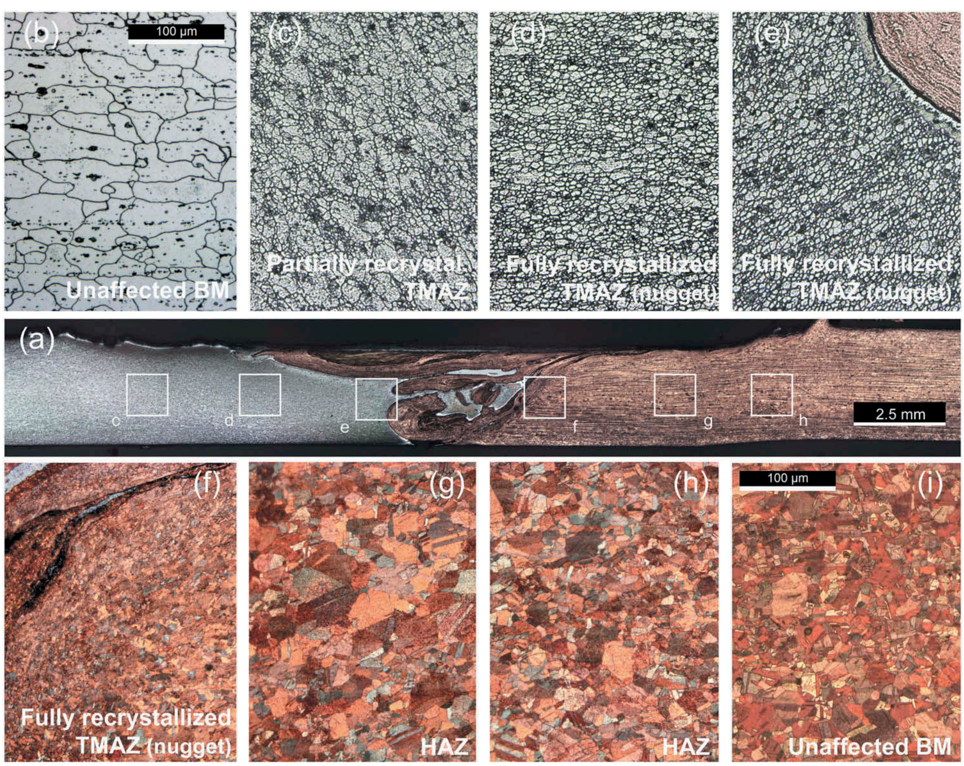

Figure 2. Macrograph of the FSW joint (a) and its microstructural evolution. Aluminum side: (b) unaffected BM, (c) partially-recrystallized TMAZ, (d) and (e) fully-recrystallized TMAZ. Copper side: (f) fully-recrystallized TMAZ, (g) and (h) HAZ, (i) unaffected BM.

elongation (arrows in Fig. 3) are present for about 0.5 mm from the weld interface. Although some areas with localized recrystallization are possible[10], the microstructure is usually very similar to the unaffected material away from the interface (Fig. 1(d)). The dark region on the interface is a transition region which, due to its different chemical composition, experienced a much stronger etching than both alloys.

To understand the microstructural differences between these processes, it is important to analyze their specific characteristics. Although both processes share some similarities,

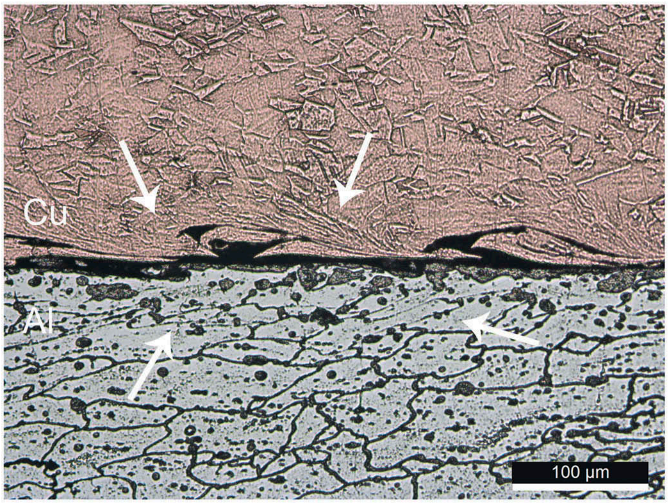

Figure 3. Microstructure of the EXW joint at the interface. The arrows point to deformation found on the interface.

one of the most significant differences is the velocity at which each process occurs. The FSW was conducted with a welding velocity (traverse velocity) of 50 mm.min^{-1} (8.33x10^{-4} m.s^{-1}) while the welding velocity (collision point velocity) was 2121 m.s^{-1} in EXW. This leads to welding times per unit length (the reciprocal of the velocity) with considerably different orders of magnitude. Effectively, the welding time per millimeter of weld is 1.2 seconds in FSW, while it is only 4.7×10^{-7} seconds in EXW (2.5 million times less). Thus, the welding velocity interferes with the thermal cycle and will profoundly affect the post weld microstructure.

The thermal cycle experienced by the joint and the properties/behavior of each alloy during the welding conditions play a major role on the final microstructure of the weld. FSW is a thermomechanical process, in which the material experiences the effects of heat and severe plastic deformation. The deformation of grains increases the stored energy in the metal. Increasing the temperature, that energy is released with the growth of a new set of strain-free grains (recrystallization), which grow at the expense of the original deformed grains.[19] The thermal cycle of FSW allowed the recrystallization and grain refinement of the aluminum (Fig. 2(c–e)) and the copper alloys (Fig. 2(f)) in the nugget. The recrystallized grain size is inversely proportional to the amount of deformation.[19] That said, the small grains found for both alloys show that the amount of deformation was high. Also, considering that copper has a significantly higher thermal conductivity than aluminum, the heat of the joint is directed preferentially to the copper, favoring its grain growth in HAZ (Fig. 2(g,h)). As reported by Xue et al.[20], some coarser grains are expected to be found in the heat affected zone due to the high temperatures experienced.

Intermetallics distribution

The combination of aluminum and copper alloys is known to form intermetallic phases easily. In fact, FSW and EXW, despite not promoting bulk melting, deal with pressure, high temperature, strong deformation and an intimate contact between the alloys. These characteristics increase the possibility of intermetallic formation. In EXW the impact between the materials generates heat that conducts to extremely high temperature peaks (even some melting), but in very small localized spots. On the other hand, FSW deals with lower temperatures[1], but for much longer times.

Regarding FSW, the intermetallic formation is usually reported to be related to solid-state diffusion[21], where the intense plastic deformation and alloy mixing reduce the time required to form the phases. Although there is no consensus about the phenomenon that causes the formation of intermetallic phases in EXW[10], the presence of molten zones significantly influences the formation of these phases. That said, it may result in different intermetallic distributions throughout the FSW and EXW joints. In agreement with this, Fig. 4(a,b)) show the complex microstructure (unetched) at a mixing region from the FSWJ, in which at least three different regions can be detected by three distinct colors (excluding the alloys): dark grey, light grey and yellowish (regions A, B and C in Fig. 4(a), respectively). In turn, the mixture of the alloys is more uniform in EXW (Fig. 4(c)).

Microhardness measurements were conducted in different zones for both weld series. All the values obtained were much higher than those relative to the unaffected alloys. From many measurements conducted in both joints, the FSW series presented values between 184 and 649 $HV_{0.025}$ and the EXW series presented hardness values ranging from 184 to 609 $HV_{0.025}$. Figure 4(b) shows some hardness measurements in a mixing region of the FSW joints. Figure 4(c) shows some of the typical microhardness measurements for the EXW joints.

Region H1 in Fig. 4(b), region H2 in Fig. 4(c) (zones with the highest hardness values), and regions 1, 2 and 3 in Fig. 5, which shows SEM micrographs of the mixing structures of both weld series, were analyzed by EDS. These results are shown in Table 2. Although lamellar microstructures were formed in the mixing zones of the FSWJ (Fig. 5(a)) and uniform mixing structures were formed at the interface of the EXWJ (Fig. 5(b)), all the analyzed regions presented a composition with the participation of both alloys. The nature of the mixed composition and the high hardness values suggest that all these regions are composed of intermetallic compounds. Table 2 shows that the lamellar regions in the FSWJ presented a variation in composition, but all the analyzed zones were rich in copper. In turn, the intermetallic layer in EXW presented a more constant composition, which was rich in aluminum.

Guo et al.[22] showed that Al-rich phases ($CuAl_2$) are the first ones to be formed and Cu-rich phases start to form with increments in the interaction time between the alloys in diffusion-bonded Cu/Al laminates. These results are in agreement with previous studies regarding the sequence of the Al-Cu phases formation.[23] Even considering the difference between these and the current research, these theoretical bases prove that the time of interaction under high temperature significantly affects the final microstructure of the FSWJ, enabling the formation of both Al and Cu-rich phases. Unlike FSW, the formation of intermetallics in EXW occurs mainly in molten regions which, due to the low melting point of the aluminum, are rich in aluminum. In addition, the EXW process is farther from equilibrium and metastable intermetallic phases usually form.[10] Therefore, based on the

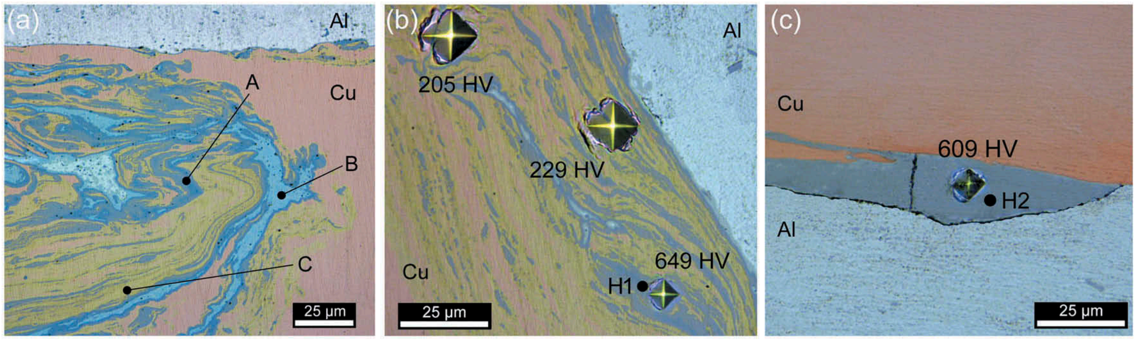

Figure 4. Lamellar pattern of the FSW joint (a) and microhardness measurements on the FSW (b) and EXW (c) joints. Regions H1 and H2 were also analyzed by EDS.

differences between both processes (velocity, interaction time, cooling rate) and considering that the formation of intermetallics in EXW occurs mainly in molten areas (Al-rich), the predominant intermetallic phases in EXW and FSW will be different.

Hardness analysis

Figure 6 presents the hardness profiles for the FSW and EXW joints, respectively. The FSW joint presents an increase in hardness in the nugget due to the intermetallic regions, and a decrease in hardness in the remaining region affected by the tool (Fig. 6(a)). The aluminum region 7–10 mm from the center is the region with the lowest hardness of the joint. In turn, the difference between the materials before and after welding is more uniform in EXW, with an increase in hardness throughout the section (Fig. 6(b)).

In FSW, the longer times the joint experiences high temperatures strongly affect the mechanical properties. The aluminum alloy has a very low recrystallization temperature[24] which causes the recovery stage (with a decrease in the dislocation density and consequent decrease in hardness) to initiate at lower temperatures. Also, the 6082 aluminum alloy easily reaches an over-aged condition at high temperatures.[25] Over-aged 6082 aluminum presents a lower strength due to the low density of the strengthening precipitates caused by their coalescence and/or dissolution, together with the inferior hardness of the solid solution because most of the magnesium and silicon from the matrix is precipitated as large Mg_2Si or silicon particles.[26] This results in an easier movement of the dislocations. For the copper alloy, it is known that the permanence at high temperatures causes a reduction in dislocation density and grain growth, leading to a loss of hardness.[27]

Table 2. Results of the EDS analyses conducted on the FSW and EXW joints.

Region	Al (at.%)	Cu (at.%)
H1 (FSW)	34.2	65.1
1 (FSW)	33.1	66.3
2 (FSW)	11.6	88.1
H2 (EXW)	65.1	34.0
3 (EXW)	62.8	36.1

In EXW, the impact leads to plastic deformation. Since the thermal cycle is extremely fast and the changes caused by the temperature are localized, the deformation is the main hardening mechanism acting. Therefore, the increase in hardness is proportional to the severity of the impact and the sensitivity of the alloy to work hardening. Materials in which work hardening is a significant strengthening mechanism usually present an expressive increase in hardness after impact. Age-hardened aluminum like the 6082 alloy is not very sensitive to work hardening, but, due to the severe deformation, the resulting hardness is greater than the unaffected material (Fig. 6(b)). Despite the increase in temperature in EXW, the process is extremely fast, and the temperature increase is almost fully concentrated at the interface. This avoids more severe effects regarding annealing.

When welding alloys in which the mechanical properties can be profoundly affected by thermal cycles, the welding process should be considered so that the materials are not subjected to conditions that lead to the deterioration of the mechanical properties. Post-weld heat treatments may be used to recover the mechanical properties of the aluminum.[26] However, raising the temperature in regions of mixture could cause the formation of thicker intermetallic compounds.[28]

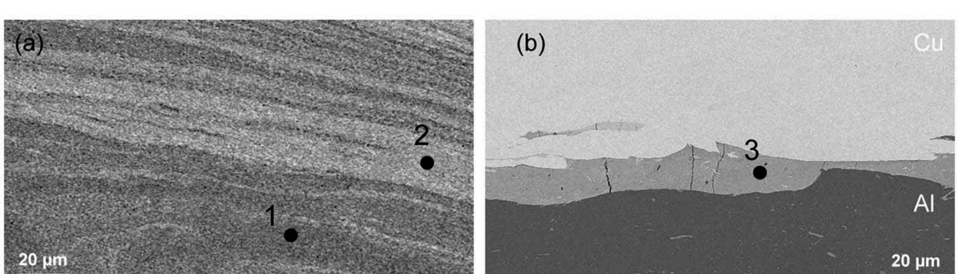

Figure 5. Locations analyzed by EDS: (a) FSWJ and (b) EXWJ.

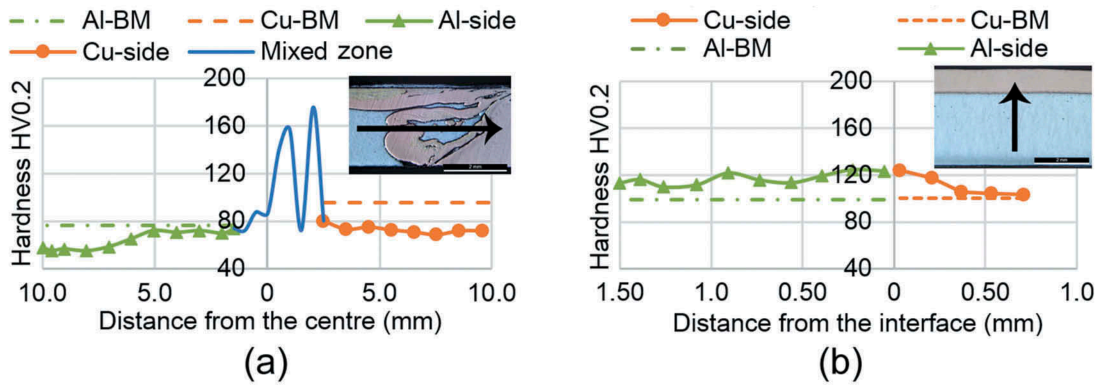

Figure 6. Hardness profiles: (a) FSWJ and (b) EXWJ.

Ductility and mechanical strength

In order to characterize the mechanical behavior of the welds, tensile specimens were produced. However, the FSW specimens failed during machining. So, the mechanical behavior of the FSW joints, and especially their ductility, was characterized by bending testing (Fig. 7).

As shown in Fig. 7(a), the FSWJ presented a very low ductility with the fracture occurring at the beginning of the test (very low bending angle/deformation), in the fully-recrystallized TMAZ. Regarding the morphology of the fracture surface of these welds, heterogeneity was noticed. Although localized dimples were observed, corresponding to the ductile fracture of Al and Cu layers, as well as some cleavage regions, most of the surface was found to present a morphology indicative of a brittle intergranular fracture (Fig. 7(b)). The material experiencing intergranular fracture presents a sub-micron grain size (Fig. 7(c)) and a mixed Al-Cu composition (Fig. 7(d,e)). The Cu-richer chemical composition of this material agrees-well with the predominant intermetallic composition identified in the fully-recrystallized TMAZ. The brittle fracture of the FSWJ matches the brittleness of the Al-Cu intermetallic phases. These results show that the strong interaction of the materials during FSW, and consequently, the formation of a large intermetallic volume, were deleterious to the mechanical behavior of the welds.

Figure 8 shows the tensile/shear force-elongation curves, the strain distribution map acquired at the maximum load by DIC, and the fracture surface by SEM for the EXWJ. It can be observed that the specimens fractured at the copper side, away from the interface, with a maximum force of about 2.6 kN (Fig. 8(a)). In agreement with this, dimples were observed at the fracture surface of these welds, indicating a ductile fracture (Fig. 8(b)). In fact, unlike the FSWJ, the EXWJ presented good ductility and a very good mechanical behavior, which is related to the much smaller intermetallic volume formed in these welds compared to the FSWJ.

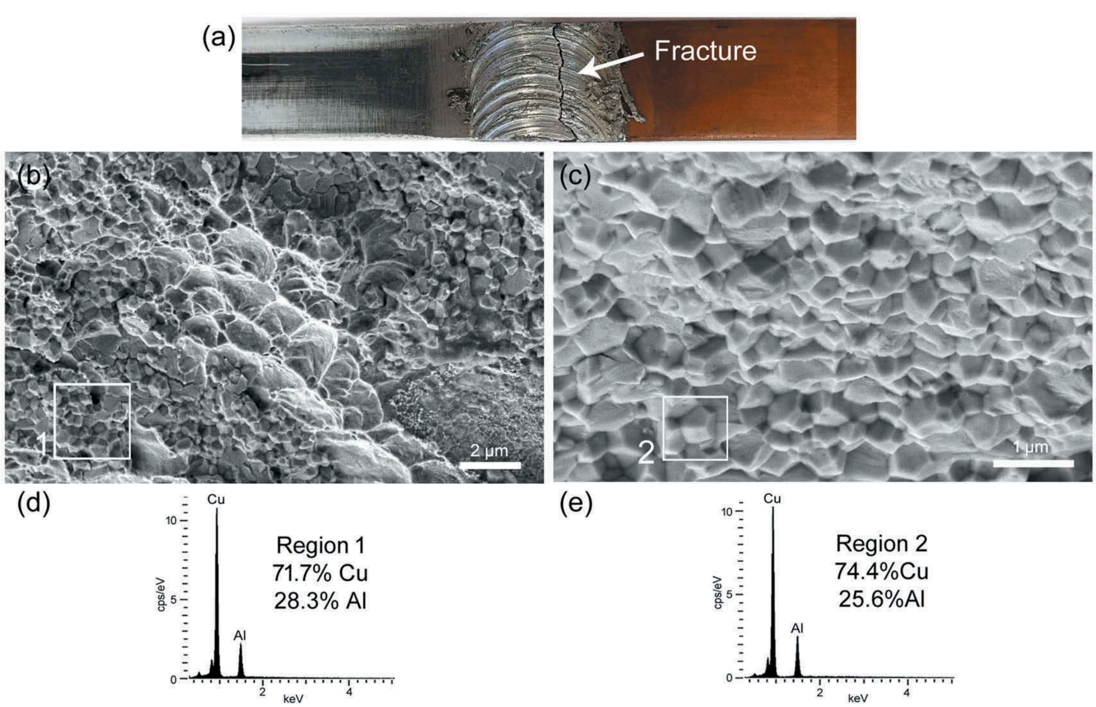

Figure 7. FSWJ bending results: (a) bended specimen; (b) SEM fractograph; (c) High magnification SEM fractograph; (d, e) EDS chemical composition (% at.) of regions 1 and 2.

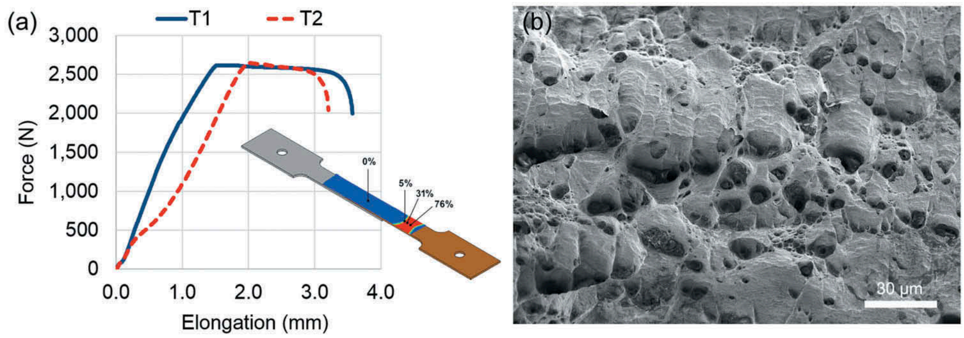

Figure 8. EXW tensile/shear testing results: (a) force-elongation curves and strain distribution map; (b) SEM fractograph.

Conclusions

Copper and aluminum alloys were welded by friction stir welding and explosive welding in order to compare the effects of the two solid-state welding processes. The following conclusions can be drawn:

- Both solid-state processes presented formation of intermetallic compounds. The chemical composition of the preferential intermetallic phases varied according to the welding process. Friction stir welding joints presented a larger amount of intermetallics distributed throughout the weld structure.
- The microstructural changes are much more significant in friction stir welding due to the larger area under plastic deformation, the stirring and mixing of the alloys, the longer time under high temperature, and especially, the longer interaction times between the alloys under high temperatures. As the explosive welding process is much faster, it avoids extensive microstructural changes and strong interaction of the materials, reducing the intermetallic volumes.
- The thermomechanical phenomena experienced by the materials during welding promote significant differences in the hardness and the mechanical behavior of the friction stir welds and the explosive welds. For alloys that can easily form brittle intermetallic phases, excessive materials interaction during the welding process leads to a very poor mechanical behavior of the joints.

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