Investigation of ECAR Routes on Mechanical Properties of Explosive-Welded Al-Cu Bimetal

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Abstract
Equal channel angular rolling (ECAR) is a severe plastic deformation method that covered plastic deformation of sheets. In this study, effects of ECAR route shave been investigated on the mechanical and microstructure properties of explosive-welded Al-Cu bimetal. At first, the explosive welding process has been performed to prepare the Al-Cu bimetals. Then, to relieve the stress and preparing of samples for ECAR process, the annealing process of the samples was done. Finally, the ECAR process was performed on the samples in two routes A and C. Results showed that yield and tensile strengths and micro hardness of ECARed samples significantly increased with increasing the number of passes, whereas their ductility decreased. The yield strength of bimetals has been increased from 80 MPa to 100 MPa and 130 MPa at the routes A and C, respectively. Also, with increasing the number of ECAR passes, the grain size of the ECARed bimetals decreased to about 2µm.

Keywords
ECAR, Explosive Welding, Mechanical Property

1. Introduction

Explosive welded Bimetals are used in different industries such as aerospace and food industries. These new materials have superior properties such as corrosion and wear resistance with proper mechanical and metallurgical properties. The explosive welding is used as an excellent alternative for joining similar and dissimilar metals and alloys at solid state [1]. Although, other techniques can be used to weld dissimilar metals [2, 3] but explosive welding process can bond materials such as aluminum, titanium, copper and stainless steel [4]. This process can join wide variety of both similar and dissimilar metals [5, 6]. High strength of bonding and interface is one of the main advantages of the explosive welding process. In this method, the impact causes work-hardening [7].

In recent years, severe plastic deformation (SPD) processes have been widely used due to strength enhancement of metals. In the SPD processes, grain sizes of materials catch up ultrafine grained (UFG). Materials with an average grain size in sub micrometer range are defined in literature as the UFG materials. One of the SPD methods which used for billets is equal channel angular press (ECAP) process. However, it is reported in earlier studies that ECAP is usually a discontinuous process and not applicable to deformation of sheets or strips [8, 9].So, equal channel angular rolling method is an applicable method to deform sheet samples [10, 11]. The ECA Red samples provide advanced material properties as high strength, suitable ductility and good corrosion resistance [12]. Figure 1 presents a schematic of the ECAR process.

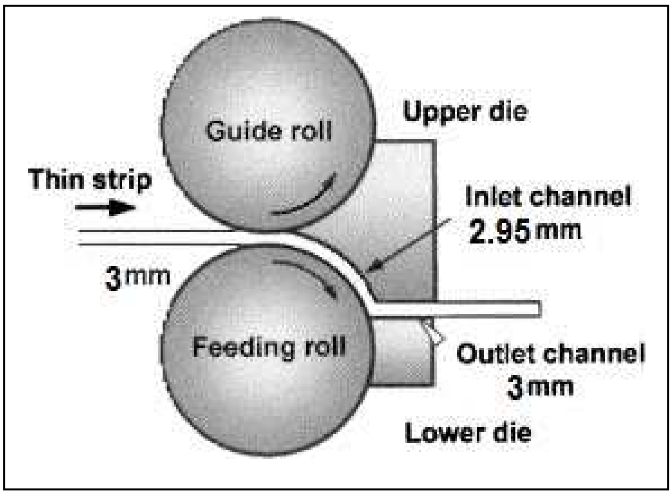


Figure1. A schematic illustration of ECAR equipment

Already several researches have been reported on ECAR process. Han [13] considered pre-ECAR and post-ECAR effects on microstructure and mechanical properties of aluminum alloy 7050. Chang et al. [14] investigated the ECAR process on the AZ31 alloy. They found that flexibility of ECARed samples increases by performing the process at room temperature. Kvackajet al. [15] studied mechanical and metallurgical properties of OFHC copper during the ECAR process. Habibi and Ketabchi [16] considered increasing strength and capacity of electrical conducting in micro structure of copper alloy, using ECAR process. Hassani et al. [17] achieved nano grain size in AZ31 through the ECAR process.
To the best of authors' knowledge, investigation of ECAR routes in the explosive-welded multi layers is not reported so far. Therefore, in this study, the effects of ECAR routes (routes A and C) have been investigated in the explosive-welded Al-Cu bimetal and their mechanical and metallurgical properties were evaluated.

2. Materials and Methods

In this study, the parallel arrangement was used for experimental group of explosive welding. The structure of the composite was once manufactured by explosive welding. The explosive used in this study was a powder type, AMATOL, of detonation velocity 2500 m/s (it is the speed at which the detonation wave travels through the explosive) and density 800kg/m^3. The thickness of the explosive was equal to 14mm.
To study the effect of ECAR routes on the explosive-welded bimetal samples, at first the explosive welding process has performed on layers of Al and Cu. The chemical compositions of used alloys were determined by chemical analysis and have been presented in Table 1 and 2:

Table1. Chemical composition of Al-1100 alloy (wt%)

Si	Fe	Mn	Co	Cr	Ni	Zn	Ti	Pb	Sn	V	Al
0.09	0.18	0.02	0.01	0.02	0.01	0.03	0.01	0.01	0.01	0.01	Base

Table2. Chemical composition of Cu alloy (wt%)

Zn	Pb	Sn	P	Mn	Fe	Ni	Si	Cr	Co	Cu
<0.01	<0.01	<0.01	<0.02	0.01	0.01	<0.05	0.01	<0.002	0.02	Base

Experiments were carried out on an ECAR setup by two-high rolling mill with work-rolls dimensions equal to105 mm in diameter, a die with 3 mm in channel, an oblique angle 115°and a curvature angle 0°. To conduct the bimetal in the die, distance between the work-roll has been set to 2.97 mm. Figure 2 shows a view of the ECAR setup.

Figure2. A photograph of the ECAR setup

The annealed bimetals (at 350°C for 2 h followed by furnace cooling to room temperature) with a dimension of 400 (L)×30(W)×3(t) mm^{3}were prepared for the ECAR Process.

Then, the ECAR process has performed on the bimetal samples at two routes A and C during 8 passes for each route at room temperature. As to ECAR route, feeding direction was unchanged between adjacent 2 passes of ECAR usually referred to route A. If feeding direction changed between 2 passes of ECAR, then it would be referred to route C.

To conduct the metallographic studies and hardness tests, the specimens were cut from the samples in explosion and ECAR direction. For better grounding and polishing operations, the specimens were mounted first, and then grounded by emery papers of grade number 120 to 3000. Finally, these specimens were polished by using diamond paste of 1.0 micron grain size.

To study the strength of the ECARed samples, the biaxial tensile test has performed based on ASTM-E8 [18] with a constant strain rate of $2\times10^{-3}s^{-1}$.

Also, to evaluate the impact of the ECAR routes and numbers of passes on the properties of the ECARed bimetals, the Vickers micro-hardness test based on ASTM E384-11 [19] was carried out using a 200g loads.

3. Results and discussion

Figure 3 presents an image taken by the optical microscope from the interface of explosive-welded Al-Cu bimetal.

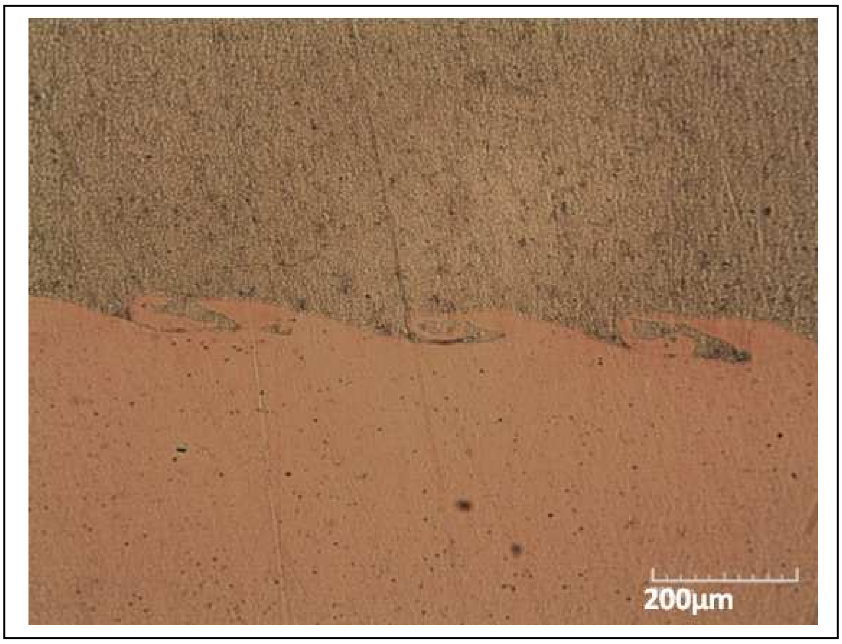
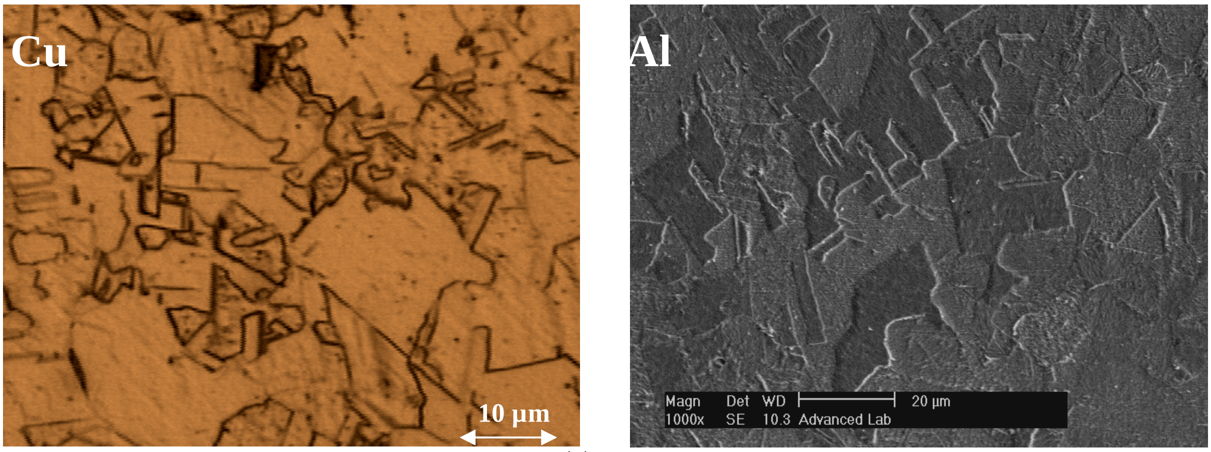


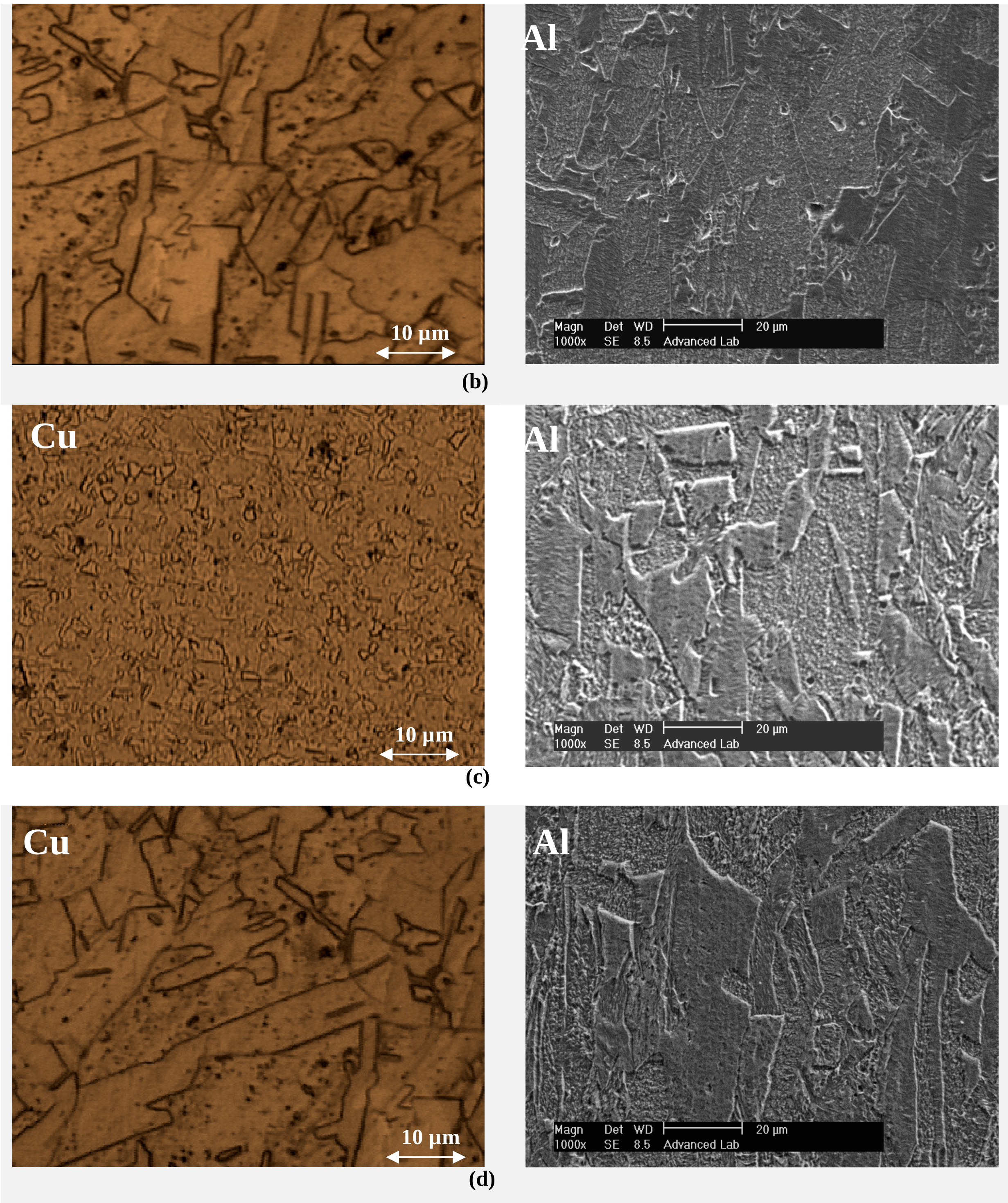
Figure3. Cross-section optical image of Al/Cu interface

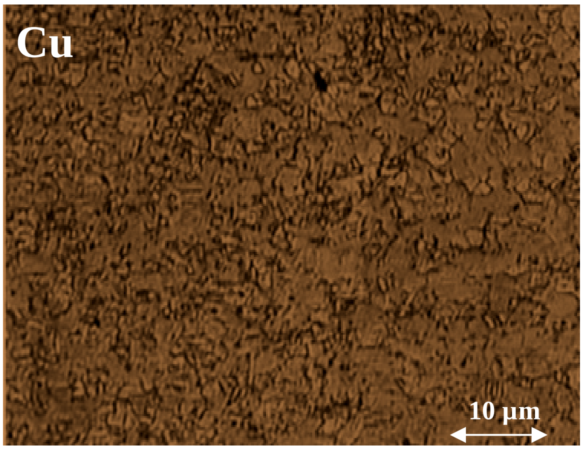
As can be seen, the interface has a wavy form. This is because of a high plastic deformation during the explosive welding process. Also, increasing in explosive loading could increase the impact energy of flyer plate which causes transition from straight to wavy form [20]. Botros et al. [21] have completely explained the wavy interface and the mechanism of its formation in high velocity impact welding.

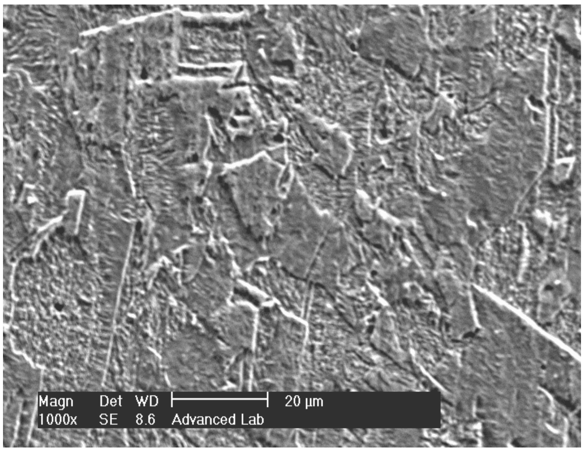
Figure 4 shows the image taken by the optical microscope from the Al-Cu bimetals.



(a)


Al
10 µm
Magn Det WD 20 µm
1000x SE 8.5 Advanced Lab
(b)
Cu
Al
10 µm
Magn Det WD 20 µm
1000x SE 8.5 Advanced Lab
(c)
Cu
Al
10 µm
Magn Det WD 20 µm
1000x SE 8.5 Advanced Lab
(d)





(e)

Figure4. Optical image of Al-Cu bimetals (a) As-received (b) 2passes under route A(c) 8 passes under route A(d) 2 passes under route C (e) 8 passes under route C

It should be noted that in the ECAR process, a few elongation in the grains in the A routes can be created rather than route C. Rotation of the specimen around the longitude direction by 180˚after each pass results in a uniform distribution of plastic strain [22].

Grain size of each ECARed bimetal was measured in this study. Figure 5 shows the grain size of bimetal layers.

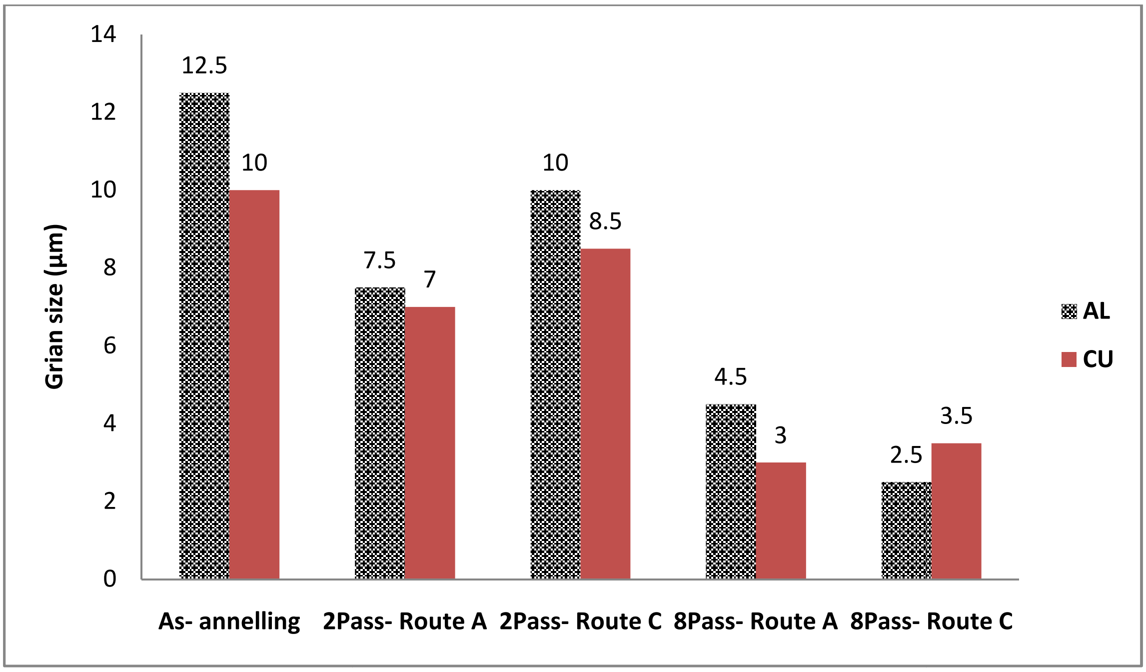


Figure5. Variation of grain size with number of ECAR passes

As it can be observed, the grain size in the annealed bimetals (before the ECAR process) is equal to 10µm and 12.5µm for the Cu and Al layers, respectively. The grain size of annealed material reduces after one pass. After the eighth pass of ECAR process, the grain size is about 4.5 and 3 µm for the Al and Cu layers, respectively for route A and 2.5 and 3.5 µm for the Al and Cu layers, respectively for route C.

The stress-strain behaviors of Al-Cu bimetals (2 and 8 passes in the routes A and C) are shown in Figure 6 obtained by tensile test.

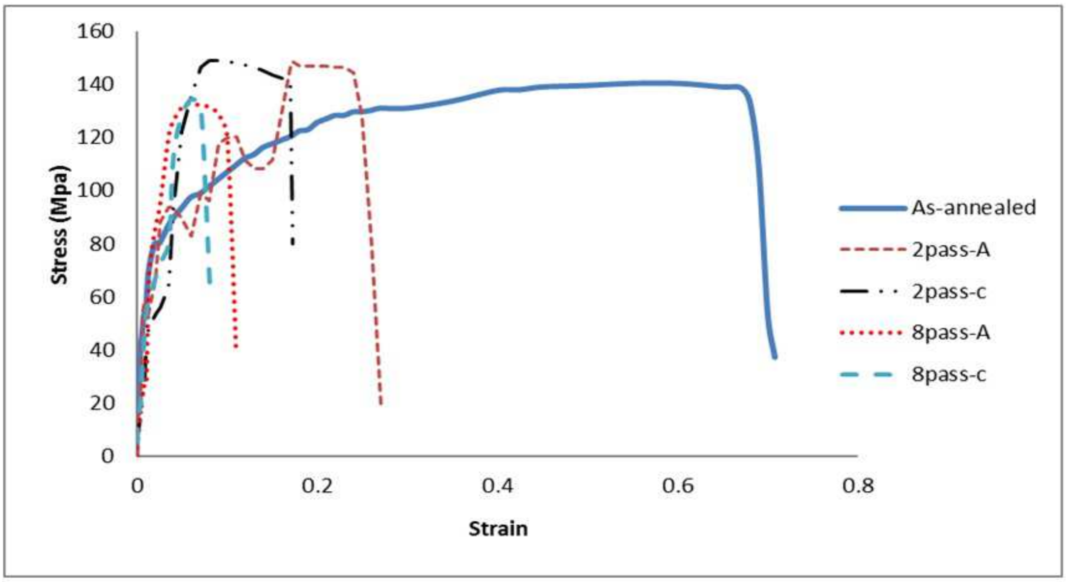


Figure6. Stress–strain behaviors of ECARed bimetals

As it can be observed, after the ECAR process, stress–strain curves show higher strength and lower elongation. Also, in the second and eighth passes in the route C, the tensile strength is more than the route A. The intense increasing of tensile strength after the first pass was observed in this study. Other studies in the literatures have reported same phenomenon at their studies [13, 15, 17].The strain hardening and dislocation strengthening play main role in the strength increase. Two strengthening models of ECARed samples can be explained. According to the first one, plastic flow in a nano crystalline material is considered to be controlled by the stress required to attain dislocation loops (from Frank-Read sources) in a set of larger grains with the critical semicircle configuration [23]. Based on the second model, two strengthening mechanism can be contributed to the strengthening during large deformation of materials [24]. The first is the dislocation strengthening due to the presence of incidental dislocation boundaries and the second is the grain boundary strengthening via Hall–Petch relationship due to the formation of geometrically necessary boundaries arising from the difference in slip system operating in neighboring slip systems or local strain difference within each grain.

It is necessary to mention that performing the eighth pass of the ECAR process does not change the strength and elongation of samples significantly. Figure 7 presents variation of the yield and tensile strength as a function of ECAR pass number in routes A and C.

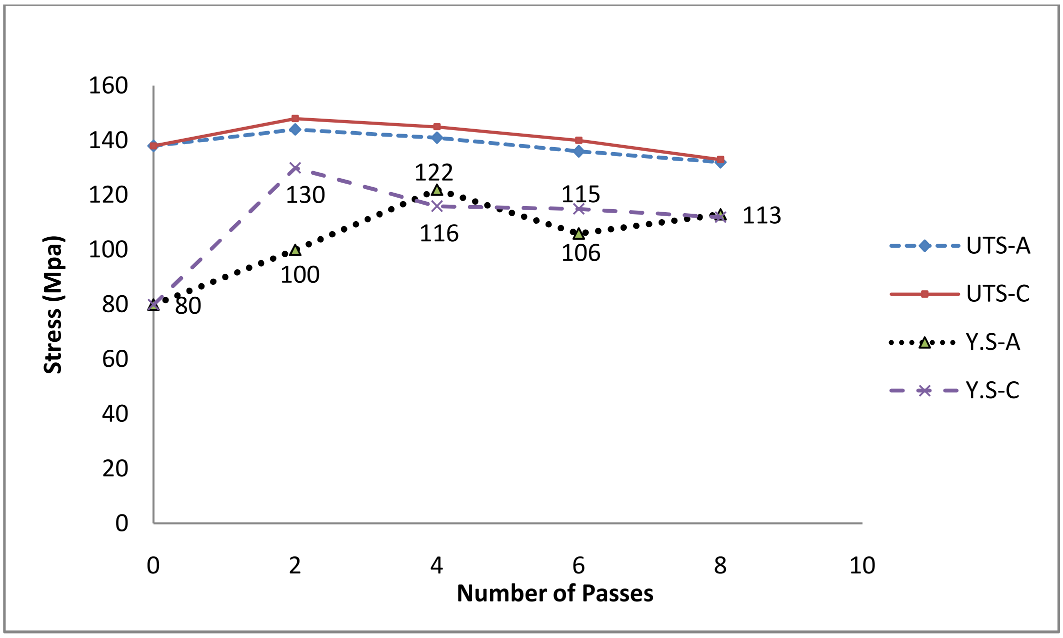


Figure7. Variation of the yield and tensile strength as a function of ECAR pass number in routes A and C

As it can be observed, the yield strength led to the largest value in the fourth pass in the route A and in the second pass in the route C. Also, the yield and tensile strength in the route Care higher than the route A. Rotation of the specimen around the longitude direction by 180˚after each pass results in a uniform distribution of plastic strain.

Figure 8 shows the variation of hardness as a function of the number of ECAR passes in the routes A and C.

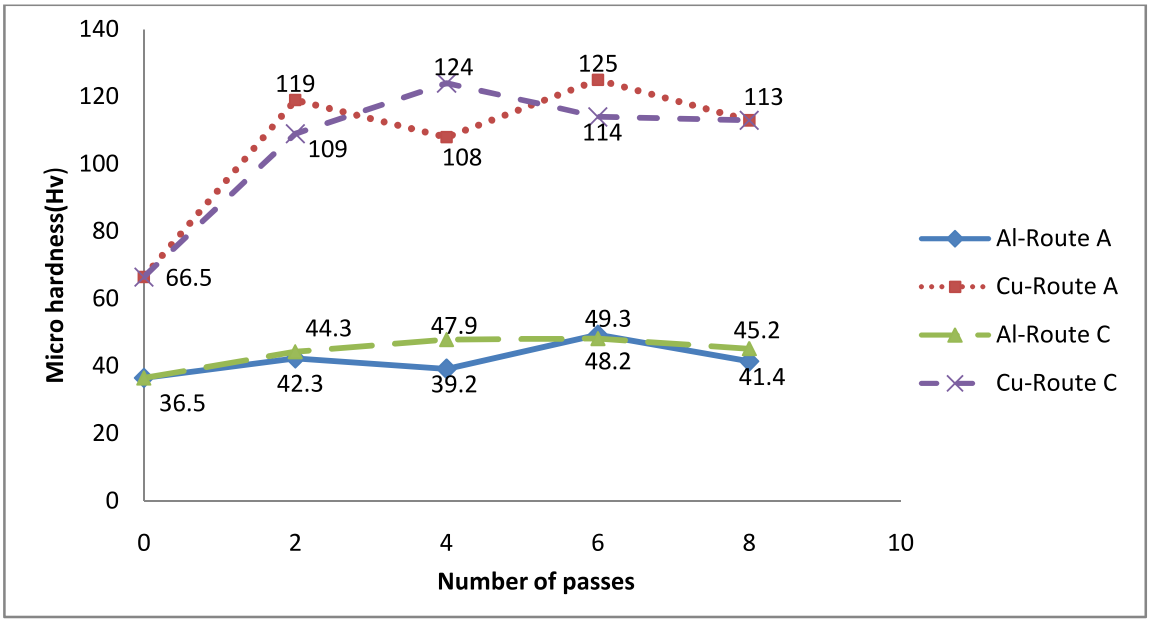


Figure8. Variation of hardness as a function of the number of ECAR passes in the routes A and C

As it can be observed, after the 2 passes of the ECAR process, The micro hardness increases up to~119 and 109 Hv from ~66.5 Hv in the Cu layer and up to ~44.3 and 42.3 Hv from ~36.5 Hv in the Al layer in the routes A and C, respectively.
The rapid increase of micro hardness at the first pass seems to be attributed to strain hardening as a result of sub grain boundaries formation rather than grain refinement [18]. The significant changes of the micro hardness do not observe at the following passes. However, the rate of micro hardness enhancement is saturated in the next passes. This phenomenon could also happen in other SPD processes [15]. The strengthening in next passes could be attributed to the rapid increase of the dislocation density followed by dislocations rearrangement to sub grains (cells) and grain refinement [25].

4. Conclusions

In this study, investigation of equal channel angular rolling routes on mechanical properties of explosive-welded Al-Cu bimetal has been performed. Results show that the yield and tensile strength in the route C are higher than route A and the yield strength led to the largest value in the fourth pass in the route A and in the second pass in the route C. The research indicates that performing the eighth pass of the ECAR process does not change the strength and elongation of samples significantly. Also, the significant changes of the micro hardness do not observe at the following passes.

5. References

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