The Effect of Annealing Heat Treatment on the Bond of Explosive-welded Copper/Steel after the ECAR Process

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Abstract
Equal channel angular rolling (ECAR) process is one of the severe plastic deformation (SPD) methods that have been used to make ultra-fine grain (UFG) materials with improving the mechanical properties of samples. After performing the process at several paths, a large strain is applied to the material that can cause decreasing the grain size and improving the mechanical and physical properties of the metal. In this paper, the effects of annealing thermal treatment at various temperatures and times on the weld bond of bimetal explosive welded stainless steel-copper sheet during the equal channel angular rolling process have been investigated. For this purpose, after performing the ECAR process and thermal treatment on bimetal sheet, hardness and welding interface were studied. The results showed that performing thermal treatment at different temperatures caused the formation of intermetallic compounds in the weld bond, which would change the hardness of this region. Also, increasing the annealing time increased the thickness of the weld bond.

Keywords
ECAR, Annealing, Explosive-welded Bimetal, Interface, Hardness

1. Introduction

Today, severe plastic deformation processes have been considered by the researchers to improve the mechanical properties of metal materials by cutting grain size. Processes such as high pressure torsion [1], cyclic extrusion compression [2], equal channel angular pressing [3], accumulative roll bonding [4], constrained groove pressing[5], etc. are the examples in this field.Equal channel angular rolling is one of the severe plastic deformation methods, in which the metal sheet experiences a great strain. In this process, continuous shear deformation is created without significant changes in sheet thickness. The advantages of this process can be considered as, being easy to handle, taking different routes to achieve a more uniformed structure dependent on applied uniform strain and being flexible for various lengths of different sheets [6-8].Lee et al. [9] examined the microstructure of the 1050 aluminum sheet with this process. In 2003, Nam et al. examined the microstructure of the 7050 aluminum sheet during ECAR process [10].In 2007, Cheng et al. dealt with the draw ability changes on the Az31 magnesium sheet at room temperature during this process and reported the positive effects [11].They also looked at the effects of the mold clearance on the expansion of Az31 crystalline forms of magnesium [12].In 2011, Habibi et al. studied pure nano grain copper with high strength and high electrical conductivity during ECAR [13].Also in 2011, Hasani et al. studied ECARed Az31 magnesium alloy to achieve nano grain magnesium alloy. In 2012, Azimi et al. examined the mechanical and micro structural properties of the Al1100 aluminum alloy during several passes of this process [15].The study of the residual stresses distribution in the thickness of aluminum sheet 5053 by layer removal technique and X-ray diffraction in 2012 was carried out by Mahmoodi et al. [16].In the year 2012, Kvackaj studied on TEM images from the OFHC copper structure after the ECAR process [17]. Mahmoodi et al. [18] investigated correlation between structural parameters and mechanical properties of Al5083 sheets processed by ECAR process. Honarpisheh et al. [19] studied the effect of ECAR process on the thermal conductivity of Aluminum alloy 3003. On the other hand, explosive welding sheets are recently used as new materials in various industries [20, 21]. Providing simultaneously several mechanical and physical properties is one of the benefits of these products. The study of secondary processes on these products is a new subject of interest by various researchers. These include extrusion [22], cold rolling [23-25] and incremental forming [26, 27]. In this paper, for the first time, the effects of thermal operation are investigated on the weld bond formed on ECARed Steel-Copper explosive welded bimetal. In fact, the attractiveness of the study on ECAR process is on explosive welding sheets, which is then subjected to thermal operation, in order to study changes in the weld band.

2. Materials and Methods of Research

The bimetal sheet used in this study consists of AISI 304L low-carbon stainless steel and Bahonar's commercial copper with a purity of 99.9%. The chemical composition of these two sheets obtained from quantum analysis is presented in Table 1.

Table1. Chemical composition of stainless steel and pure commercial copper elements obtained from the quantum test

Elements combination	N	Ni	Cr	S	P	Si	Mn	C
Low-carbon stainless steel AISI 304L	0-0.10	8.0-12.0	18.0-20.0	0-0.03	0-0.045	0-0.75	0-2.0	0-0.03
Pure commercial copper				0.004 Max			99.9.% Cu	

The thickness of primary sheet used in this study is 3 mm, which is produced by the explosive welding method. The thickness of each layer of steel and copper is 1.50 mm. The sheets are annealed for 3 hours at 300° C. Sheets with a width of 40 mm and length of 200 mm are cut and prepared to execute the ECAR process. The process is carried out by rolling machine with a diameter of 120 mm, equipped with two different thickness channels. The mold angle is 120° and the input channel thickness is 3 mm and the output channel thickness is 2.97 mm. High friction increases the driving force and facilitates feeding the sheet into the mold. In Figure 1, the device used in this study is visible. After performing the ECAR operation on copper-steel sheets in 4 passes, the annealing thermal treatment was performed at 3 different temperatures of 450, 550, and 650° C for 1 hour at 4 pass ECARed samples.

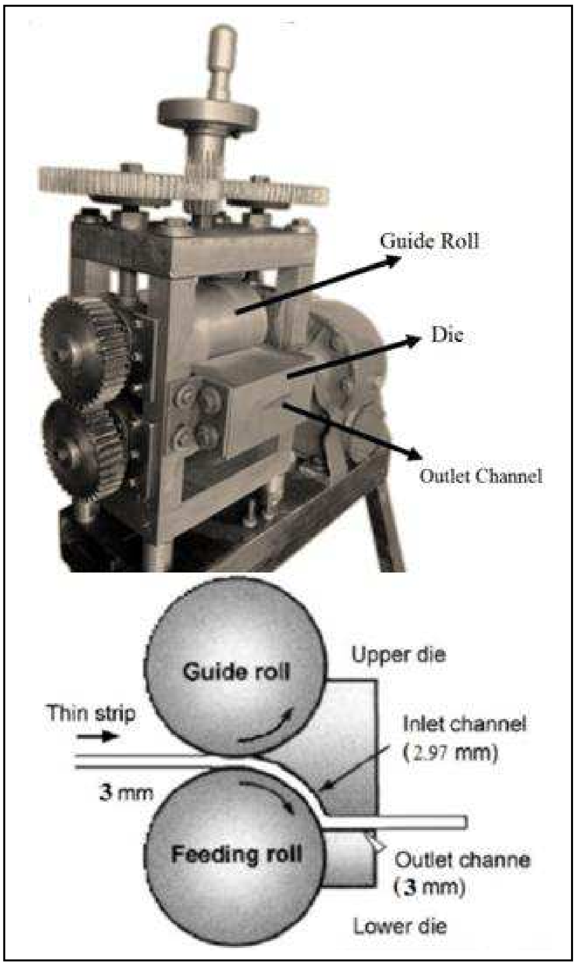


Figure1. The used device in this study, along with a schematic of the ECAR process

3. Results and Discussion

Figure 2 indicates the hardness variations for three bonding zones of copper- stainless steel based on the number of passes during ECAR process. The tendency of all the graphs is incremental, which is an evidence of the effect ECAR on increasing of hardness.

It can also be found that the highest hardness for the steel region is 262, the weld bond 143, and for the copper region 135 Wickers. Since pass 4 gives us the biggest hardness rate for all areas, the piece is annealed in this pass to analyze the effect of this thermal operation. In this regard, the diagram of Figure 3 is obtained after annealing treatment at various maximum temperatures, which shows that it is possible to control the hardness of the sheet by changing the annealing temperature. Mostly, it can be seen from the chart that it is possible to achieve to a lower hardness of 60 HV for steel area and to 100 HV for copper area by annealing treatment.

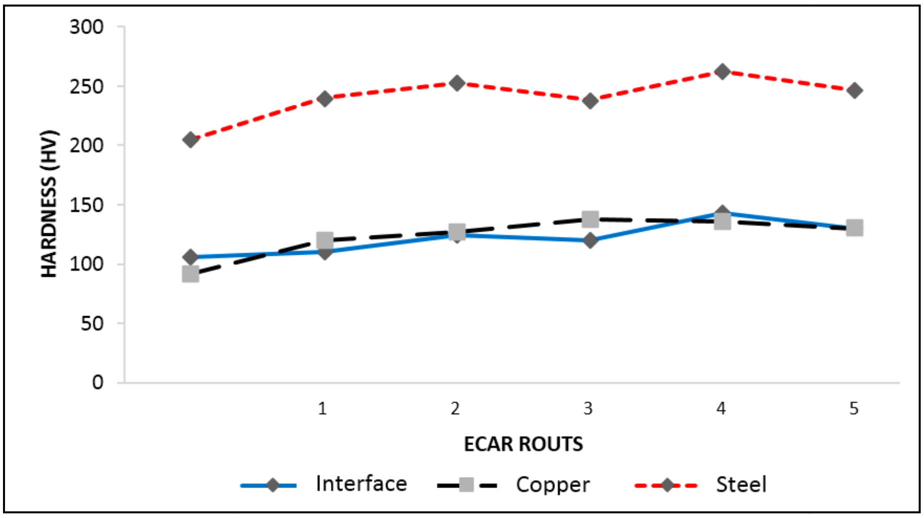


Figure2. The hardness of the two-layer sheet in various passes

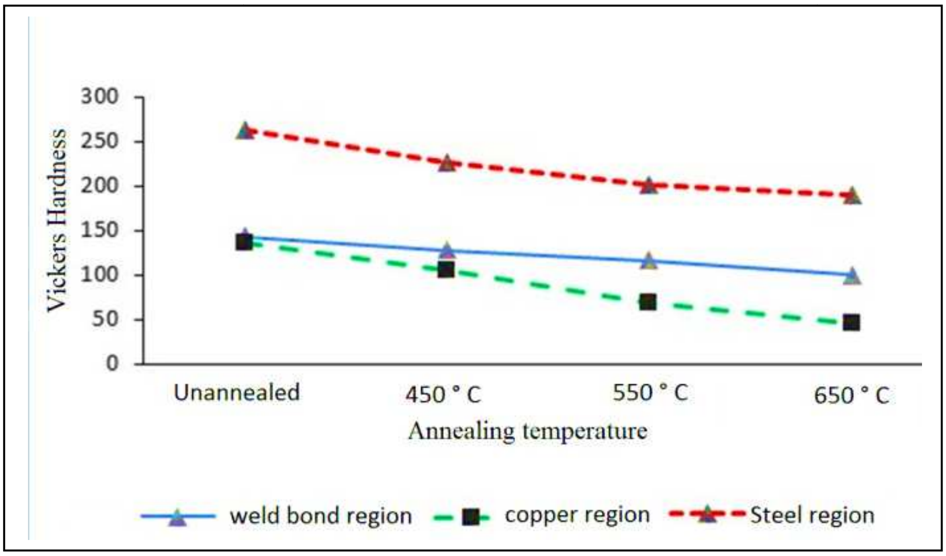
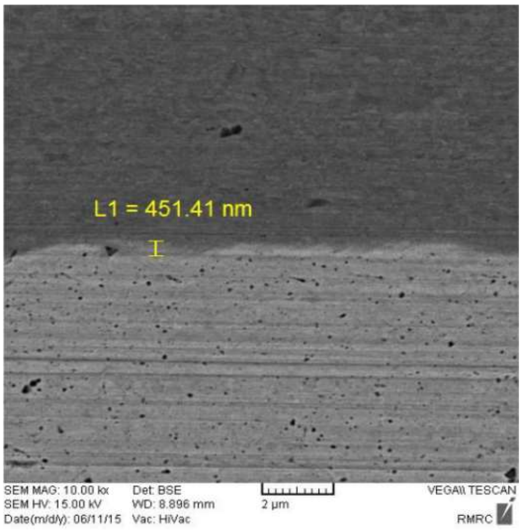


Figure3. The hardness of the two-layer sheet in different regions and annealing temperatures

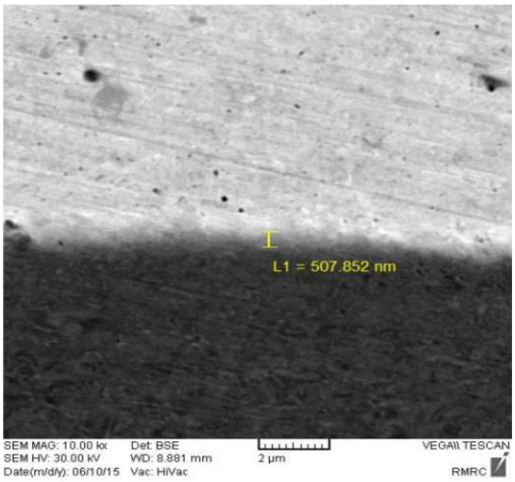
Annealing, in addition to its hardening effect, can affect the width of the joint between two steel and copper metals, which can be checked through SEM images. Figure 4 shows that thermal treatment increases the weld band width and improves the interference between two stainless steel metals and finally increases the strength of the weld region.

Figure 4a presents that the thickness of interface is equal to 451 nm in non-thermal operation. According to Figures 4b and 4c, the interface thicknesses are equal to 508 and 677 nm in annealing conditions of 450°C with a duration of 1 and 3 hours, respectively.

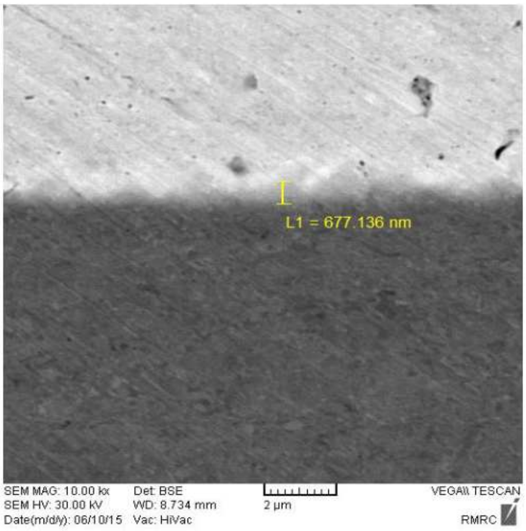
It is obvious that by increasing the two factors of temperature and time, the penetration of the joint increases. This leads to an increase in the thickness of the weld band at the joint [28]. In fact, with increasing thermal treatment time, the activated penetration mechanism and the thickness of the intermetallic layer are significantly increased, and in some parts the intermetallic layer consists of several layers of different compounds, which will cause the sample to become brittle.



(a)



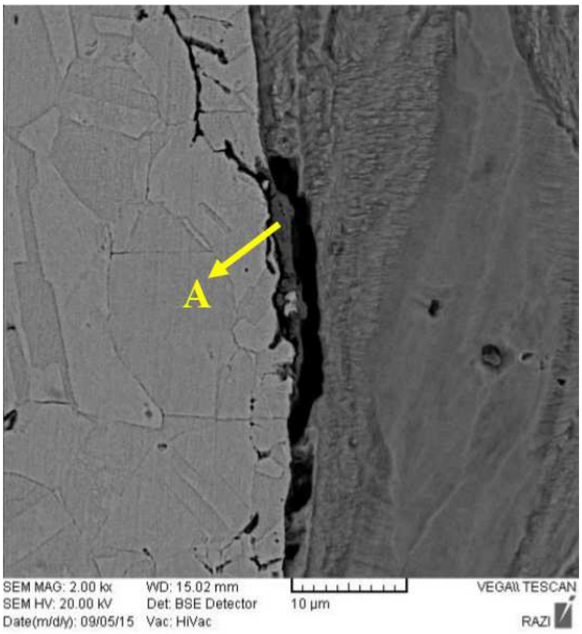
(b)



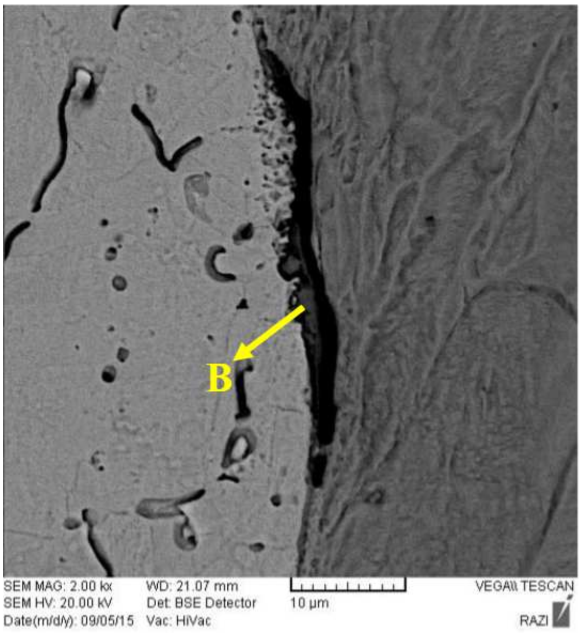
(C)

Figure4. Weld width thickness after heat treatment (a) without annealing (b) annealing at 450 ° C for 1 hour; (c) annealing at 450 ° C for 3 hours

The SEM images of the interface area at two annealing temperatures 550° C and 650° C for one hour have been shown in Figure 5.



(a)



(b)

Figure5. SEM images of the interface area (a) Annealed at 550 ° C (b) Annealed at 650 ° C for one hour

As shown in Figure 5, with increasing annealing temperature, the weld band thickness is increased. In Figure 5, the formation of new phases is observed in a limited area of the interface area. This middle phase is one of the characteristics of explosive welding and, of course, the thermal treatment performed on it, caused by the induction of local heat and high shear stress at the interconnection zone [28]. In order to investigate the effects of thermal treatment in different situations on weld bond, EDS analysis was used. Figure 6 shows the EDS analysis of the point A shown in Figure 5.

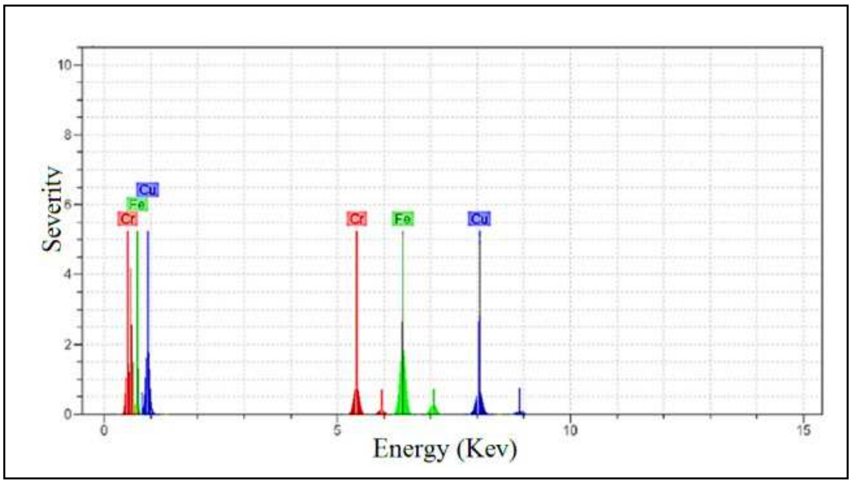


Figure6. The EDS analysis of the point A

The results of the EDS test indicate the presence of iron, copper and chromium in the joint. Therefore, the formation of the intermetallic compound in this section is obvious. Regarding the distribution of the elements, Fe_2Cu is one of the intermetallic compounds created on the interface. Of course, due to the wavy shape of the interface area, the ratios obtained in different parts of the interface will change. Figure 7 shows the EDS analysis of point B shown in Figure 5.

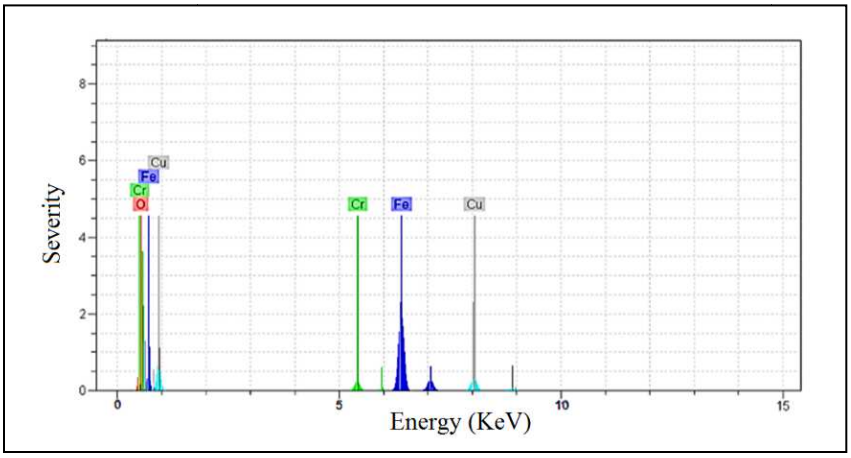


Figure7.The EDS analysis for point B shown in Figure 5

According to the results of the EDS analysis, annealing temperature is observed at 650°C, which is a mixture of iron oxide intermetallic. These results reported decreasing of the hardness about 16% for the weld bond in comparison with annealing temperature of 550°C.

4. Conclusion

In this study, the effects of thermal treatment at different temperatures on the weld bond of ECA Red bimetal copper-steel metal sheet were studied. The summary of the achievements of this research are:

- After the annealing process, the hardness of the samples decreased in all three areas and the highest hardness rate was observed around the interface.
- Annealing treatment after ECAR process increased the penetration and thickness of the weld bond at the copper-steel interface.
- Increasing the heat treatment time at 450°C of annealing temperature from 1 to 3 hours increased the weld bond thickness by 50%.
- The EDS analysis of the weld bond at 550 and 650°C, respectively, confirmed the presence of intermetallic Fe_2Cu and FeO_2 compounds.

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