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Effect of heat treatment on bonding interface in explosive welded copper/stainless steel

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ABSTRACT

In this investigation, explosive welding and heat treatment processes provided an effective method for manufacturing high-strength and high-ductility copper/ austenitic stainless steel couple. In order to improve diffusion in the interface of copper/stainless steel, first the tensile samples were provided from the welded part, then they were subjected to annealing at 300 °C (below recrystallization temperature) for 8–32 h with 8 h intervals and then samples were cooled in the furnace. Optical microscopy (OM), scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) were utilized to evaluate the possibility of diffusion in the joints. Moreover, in order to measure the hardness of the samples, microhardness test was performed. Microstructural evaluations showed that the stainless steel 304L had a wavy interface. Furthermore, the post heat treatment process resulted in great enhancement of diffusion. Microhardness measurements showed that the hardness of the sample near to the interface is greatly higher than other parts; this is due to plastic deformation and work hardening of copper and stainless steel 304L in these regions. The interface of samples with and without the post heat treatment was exhibited ductile and brittle fracture, respectively.

1. Introduction

The challenge of developing materials for advanced structural applications is gradually shifting from the optimization of novel bulk materials to the synthesis of compounds that contain metallurgical joints. This means that the design of modern metallic compounds must be built on a detailed microstructure-oriented understanding and property optimization of the underlying interfaces at the joints between dissimilar bulk metals [1,2].

Dissimilar joints to bind two discrete materials with completely various physical and mechanical features can be produced by either fusion or solid state welding [3]. General occupied dissimilar joining processes are roll bonding, pressure welding, friction welding, ultrasonic welding, diffusion bonding, laser forming and explosive welding [4].

Explosive welding is a welding method that welds two or more plates with each other with high pressure coming from explosion. Explosive welding, also known as explosive bonding, occurs as a result of an inclined crash between two metallic plates. In spite of the occurrence of heat during the explosion, a heat transfer is not observed from one plate to another due to the lack of time [5,6].

The bonding interface in explosive welding, presents three morphologies: wavy, straight and melted layer. These morphologies have received a lot of attention and discussions [4–9]. For technical purposes, these morphologies depend on the impact velocity and angle. The interface developed is related to two important phenomena that take place during bonding: rarefaction wave interaction and mechanical friction. The propagation of compressive and tension waves inside the material due to the impact and shock induced by the detonation, as well as their interaction, is responsible for the first phenomena. Sliding due to the acceleration of the flyer plate onto base plate, as well as the jet formation and its interaction with both flyer and base plates is responsible for the second one. These phenomena could introduce several metallurgical property changes [9].

The quality of the bonds strongly depends on careful control of the process parameters. These include material surface preparation, plate separation or stand-off distance, explosive load or explosive ratio, detonation energy and detonation velocity. The selection of parameters is based upon the mechanical properties, density and shear wave velocity of each component [6,10,11]. Considerable progress has been made to establish the optimum operational parameters which are required to produce an acceptable bond

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Table 1
The chemical composition of stainless steel 304L and copper.

Elements (wt.%)	Cr	Ni	Mn	C	Si	S	Al	Cu	Fe
AISI 304L (base plate)	18.91	8.44	1.79	0.015	0.483	0.03	–	0.043	Balanced
Copper (flyer plate)	0.03	0.03	–	–	–	–	0.155	Balanced	0.05

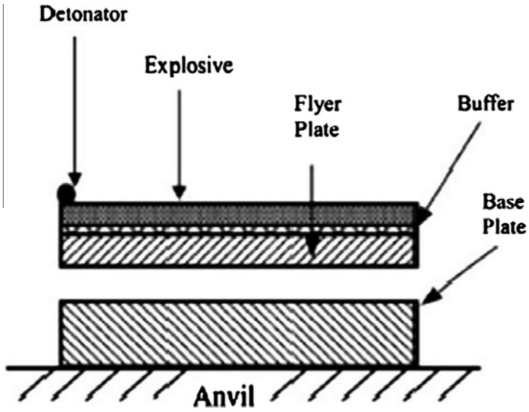


Fig. 1. Display of experimental set up of explosive welding process [6,7].

[6]. It was reported in the literature that in explosive welding, a hard and brittle intermetallic is formed during the welding and this intermetallic affects the bonding quality with a negative manner [12].

The microstructural characteristics and mechanical properties of the explosively welded various metals and their alloys have been studied by several investigators. Recent applications of explosively welded copper/stainless steel in corrosion environment prompted the present investigation. Although, there are articles about copper/stainless steel produced by explosive welding technique in literature [9,12,13], there are no report about the effect of post heat treatment on bonding interfaces in explosively welded copper/stainless steel 304L. Therefore, the goal of this study is to investigate the effect of post heat treatment on the bonding interface properties to derive optimized conditions of explosively welded copper/stainless steel 304L.

2. Experimental procedure

The chemical compositions of the copper and austenitic stainless steel 304L are given in Table 1. The parallel preparation was used for experimental set up for explosive welding as schematically revealed in Fig. 1. Due to the mechanical and corrosion properties of stainless steel, this metal was chosen as base plate while, copper was obtained as overlay plate (flyer plate) for to their high application in the vessel industry [13]. Copper and stainless steel plates were designed with dimensions of $420 \times 520 \times 1\ \text{mm}^3$ and $400 \times 500 \times 1\ \text{mm}^3$, respectively. The amatol (TNT 10% and ammonium nitrate 90%) was chosen as explosive material. The initial gap between two metal plates was chosen to be about 3 mm. The matching surfaces were carefully cleaned by polishing and degreaser. After welding, the tensile samples were prepared according to ASTM: E8/E8M-11 (Fig. 2) and post heat treatment process was performed at 300 °C, to avoid formation of $Cr_{23}C_6$ in stainless steel (below recrystallization temperature of both metals) from 8 h to 32 h with 8 h intervals. After the heat treatment the samples were cooled in the furnace. The tensile tests were conducted at ambient temperature on a Hounsfield H50KS testing machine at an initial strain rate of 10 mm/min.

Samples for metallographic observations were cut as parallel to the explosion direction from the explosively welded plates and these were mounted in bakelite. Then, these samples were polished using 80–4000 grit water-proof SiC paper. Finally, the polishing was finished on a cloth using diamond paste of 3 μm and then the plates etched in etchant of 33 cc HCl, 33 cc HNO_3 and 34 cc H_2O. A Nikon EPIPHOT 300 optical microscopy (OM) was used for the microscopic examination of the etched samples. For investigation of the fracture surfaces, the scanning electron microscopy examinations were carried out on samples using Seron AIS-2100. Also, for investigation of diffused layer, the energy dispersive spectroscopy (EDS) analysis was performed. Microhardness testing was carried out on a Leitz Wetzlar using a 100 g load. For each sample, three different measurements were taken in the distance of 50, 100, 200, 400 and 600 μm from the interface and the average values are reported.

3. Results and discussion

3.1. Microstructural observation

Fig. 3 and 4 demonstrated the OM figures of copper/stainless steel joints before and after the heat treatment at different times, respectively. These figures indicated that bonding at the copper/stainless steel interface had wavy morphology. In other words, after explosive welding process, both copper and stainless steel had wavy welding interface. Total interface area increased as a result of wavy interface. Straight and wavy interfaces can be formed between explosively welded materials and wavy interface is

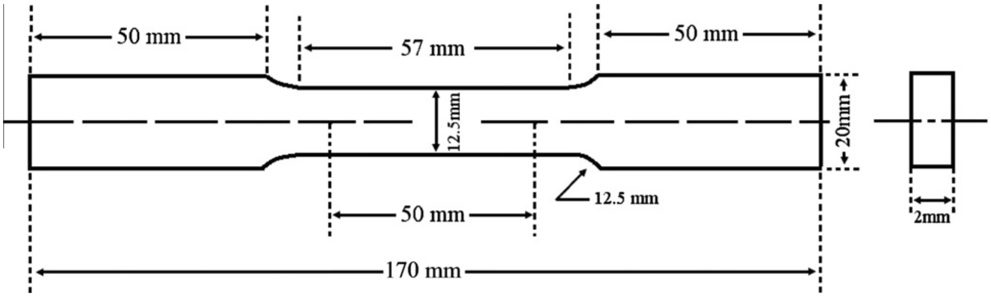


Fig. 2. Schematic representation of tensile test sample.

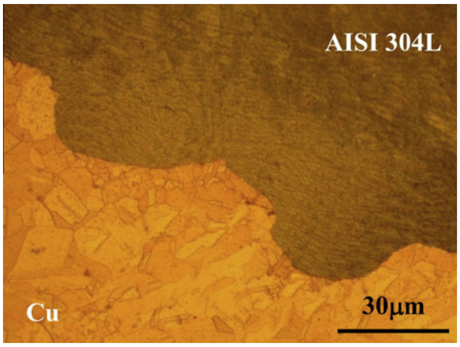
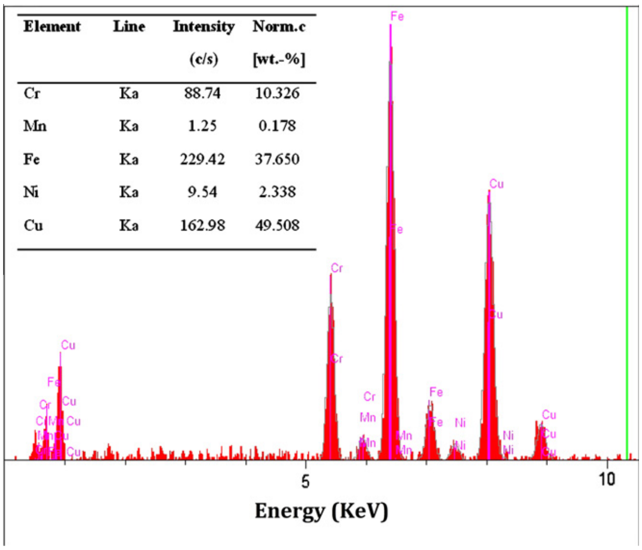


Fig. 3. The OM figure of copper/stainless steel joints before the heat treatment.

preferred due to better mechanical properties [9,13]. The interfaces were outlined by the characteristic sharp transition between two materials. Two types of bond are generally encountered at the both wavy and straight forms of explosive welded materials; these are metal/metal and metal/solidified melt [8]. In this study, copper/stainless steel had metal/metal transition type. Due to selection of welding parameters properly, there was no melting and intermetallic zone (Fig. 3). If high explosive ratio was used, ejection will be formed in between flyer and base plate after the explosion. This cause to melting area in interface and also possible oxidation and dirty surface will not be exported to outside [13]. Unlike some previous researches [9,14], in this work, there was no melting cavity or zone in the copper/stainless steel interface. The reason is that possibly due to the higher heat conductivity of copper. For this reason, it quickly distributed the formed heat into surrounding area during the explosion welding [13]. This result is consistent with the earlier works [12,13] investigated on the explosive welding of copper/stainless steel. In other hands, it was reported in the literature that in the explosive welding, a hard and brittle intermetallic is formed and this intermetallic affects the bonding quality and the mechanical properties with a negative manner [12]. Regarding to Fig. 3, it is clearly seen that no intermetallic layer was formed between the bonding layers and so, bonding quality was not affected by this layer.



Element	Line	Intensity (c/s)	Norm.c [wt.-%]
Cr	Ka	88.74	10.326
Mn	Ka	1.25	0.178
Fe	Ka	229.42	37.650
Ni	Ka	9.54	2.338
Cu	Ka	162.98	49.508

Fig. 5. The EDS analysis results of diffusion layer formed at copper/stainless steel bonding interface after heat treatment for 32 h at 300 °C.

Fig. 4 showed the changes of diffusion layer's thickness in the copper/stainless steel interface after heat treatment at 300 °C for different times. The thickness of diffusion layer and the grain size (in the copper side) was increased with heat treatment time. In fact, in Fig. 4a, there was no diffusion layer, but when the time was increased to 16 h (Fig. 4b), the thin diffusion layer was formed. Fig. 5 showed the EDS analysis results of diffusion layer formed at copper/stainless steel bonding interface after heat treatment for 32 h at 300 °C. Diffusion layer was composed of 49.5 wt.% Cu, 37.6 wt.% Fe and 10.3 wt.% Cr. According to Fe–Cu, Fe–Cr, and Cu–Cr binary phase diagram, it was obvious that there is no intermetallic at 300 °C [15]. The sufficient diffusion in the interface

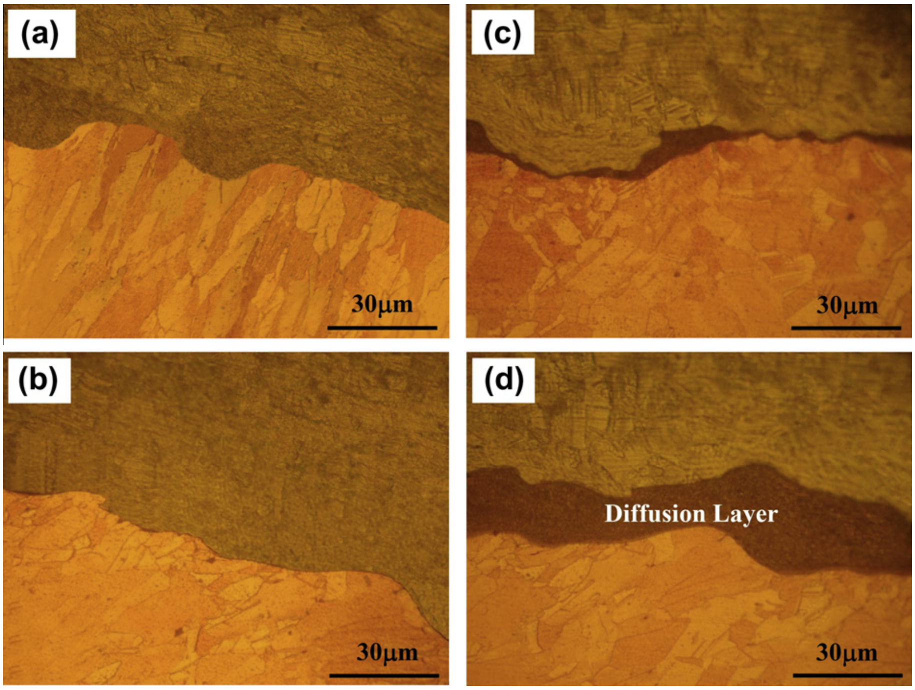


Fig. 4. The OM figures of copper/stainless steel joints after the heat treatment at 300 °C for: (a) 8, (b) 16, (c) 24, and (d) 32 h.

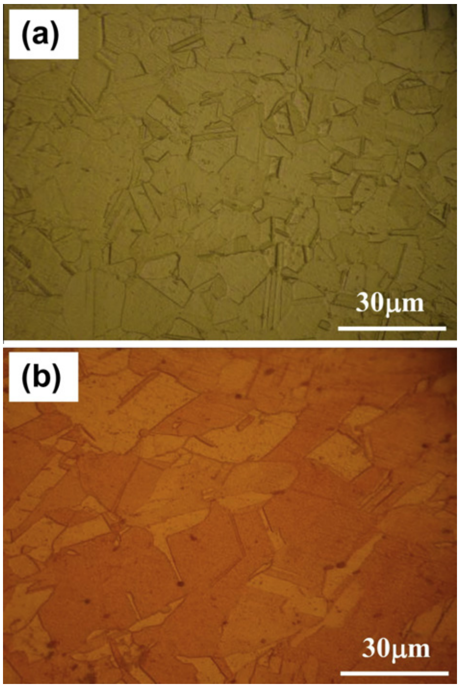


Fig. 6. The microstructure of: (a) copper and (b) stainless steel at away from the interface.

without formation of the melting and intermetallic zone indicated that copper and stainless steel as a couple can be explosively welded. In some cases, the post heat treatment of explosively welded dissimilar metals leads to formation of intermetallic compound. Bae et al. [16] investigated the effect of post heat treatment on bonding interfaces in Ti/mild steel/Ti clad materials. They have analyzed the result of diffusion layer's thickness at Ti/mild steel interface with post heat treatment temperature. Thickness of diffusion layer increased with post heat treatment ranges from 500 to 900 °C. The EDS analysis results of diffusion layer formed at Ti/mild steel bonding interface indicated that diffusion layer was composed of 67.10 wt.% Fe and 32.18 wt.% Ti. This compositional compound was verified as ε or $(\varepsilon + \zeta)$ intermetallic compound from the Fe–Ti binary phase diagram [15].

Fig. 6 illustrated the microstructure of copper and stainless steel at away from the interface. Comparison of Figs. 3, 4 and 6 indicated that the grains of the copper side at near to the interface were elongated parallel to the impact direction. Elongated grains were observed up to 50 μm away from the interface and up to 1 μm near to the interface of the base and flyer plates. This is possibly due to deformation of these grains at near to the copper/stainless steel interface resulting in a deformation hardening. However, at the stainless steel side, it was not observed grains elongation as that of the copper side.

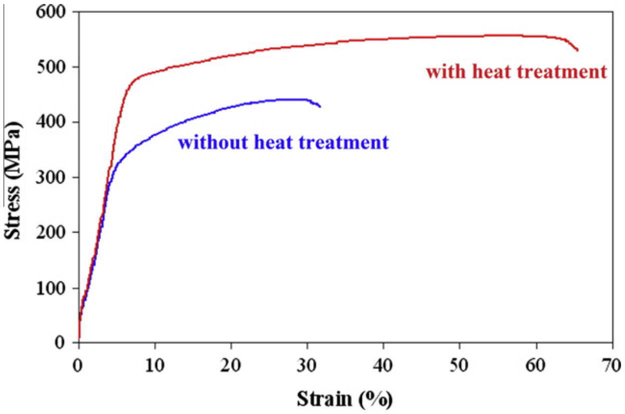


Fig. 8. The stress–strain curves of explosively welded copper/stainless steel couple before and after the heat treatment.

3.2. Mechanical properties

Microhardness measurements were made across the copper/stainless steel (with post heat treatment for 32 h) interface of both the joints using a load of 100 g. The microhardness profile across the interface is shown in Fig. 7. The measurement points were 50, 100, 200, 400, and 600 μm from bonding interface in both sides. Depending on the away from copper/stainless steel interface, the microhardness values showed variations. The maximum hardness was obtained near the welding interface for both sides. The reason for the increase of hardness of interface area is the cold deformation due to the high speed crash of exploded plates. It means that the surface of both metals was exposed to maximum deformation during the collision while explosive welding was carried out. Deformation during the crash of bonding plates is limited with a very narrow thickness close to the interface. So the hardness of the middle area remains almost unchanged. These results are

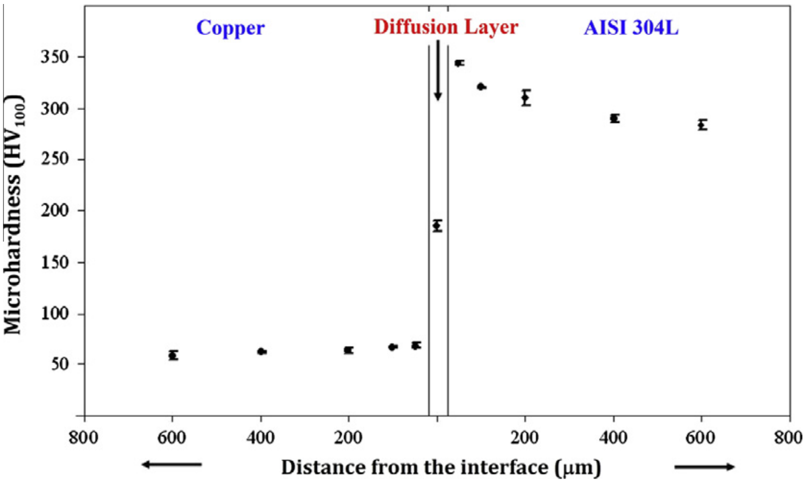


Fig. 7. The microhardness profile across the copper/stainless steel interface.

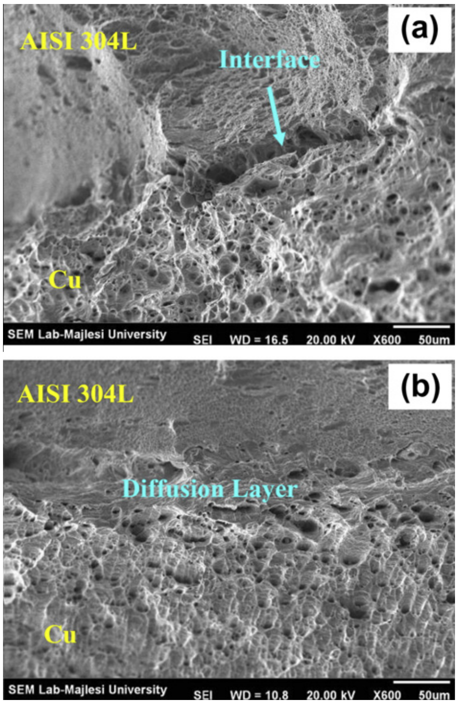


Fig. 9. The fracture surfaces of explosively welded copper/stainless steel couple: (a) before and (b) after the heat treatment.

consistent with the previous works [4,5,8,9,12–14]. However, the increased value of the hardness for stainless steel was more than the copper. This is attributed to higher strain hardening of the stainless steel with respect to the copper. Also, this figure showed that the average hardness of diffusion layer (due to post heat treatment) was 185 HV, while the hardness of copper and stainless steel near to interface were 68 and 344 HV, respectively. It can be concluded that the ductility of diffusion layer is more than the stainless steel. This can be attributed to penetration and resolving of copper into the diffusion layer (Fig. 5).

Like this study, Durgutlu et al. [13] and Findik [9] have indicated that a hardness increment is observed in interface copper/stainless steel due to collision of two plates during the explosion welding. In their articles, the average hardness of copper and stainless steel were 130 and 420 HV, respectively, while in the present work, the average hardness of copper and stainless steel are 60 and 300 HV, respectively. The reason for the decrease of hardness in the parent metals is due to post heat treatment in this study.

Fig. 8 illustrated the effect of post heat treatment on the tensile strength of explosively welded copper/stainless steel couple. This figure indicated that the tensile strength and elongation were increased by post heat treatment. The tensile strength of the copper/stainless steel couple before and after the heat treatment was 440 and 550 MPa, respectively. The reason for the increment of strength is attributed to formation of diffusion layer in the post heat treated sample. As can be seen in Fig. 4, in the sample without post heat treatment, there was no diffusion layer, but after heat treatment for 32 h at 300 °C, a thick diffusion layer was formed. This layer can act as a barrier to dislocations during tensile test, giving rise to enhanced strength. In the other hand, according to Fig. 4, it is obvious that the grains close to diffusion layer are fine. In fact, the diffusion layer can help prevent grain growth during continuous recrystallization, thereby increasing the tensile strength. The tensile elongation of the copper/stainless steel couple before and after the heat treatment was 30% and 60%, respectively. The reason for the increase of elongation is due to decreasing the dislocation density and also, coarsening of grains away from diffusion layer (Fig. 6) during post heat treatment.

3.3. Fractography

A scanning electron microscopic study was undertaken in order to clarify the rupture mechanisms in the interface before and after the heat treatment. The fracture surfaces after the tensile test are shown in Fig. 9. Clearly, the interface of sample with post heat treatment (Fig. 9b) exhibited a typical ductile fracture showing deep equiaxed dimples. Ductile tensile fractures in most materials have a gray fibrous appearance with equiaxed or hemispheroidal dimples [17]. However, the interface of sample before heat treatment (Fig. 9a) showed brittle fracture due to high degree of shock hardening that may cause brittle fracture in ductile materials [18]. This was also supported by tensile test results in which tensile elongation of the interface was increased by post heat treatment.

As can be seen from the results of this investigation, the explosive welding and post heat treatment processes can be a useful procedure for producing high-strength and high-ductility copper/stainless steel couple. This couple can be used at heated media and due to diffusion in interface no tearing is expected. Although no investigations have been reported on the influence of the heat treatment on the microstructure and mechanical properties of explosively welded copper/stainless steel 304L, our results suggest that the heat treatment process might very useful in this regard as well.

4. Conclusions

The explosive welding and heat treatment processes used in this study provided an effective method for manufacturing high-strength and high-ductility copper/stainless steel couple. The microstructure and mechanical properties of the couple were investigated. The conclusions drawn from the results can be summarized as follows:

1. The bonding at the copper/stainless steel interface had wavy morphology.
2. Due to selection of welding parameters properly, there was no melting and intermetallic zone.
3. The thickness of diffusion layer was increased with heat treatment time.
4. The grains of the copper side at near to the interface were elongated parallel to the impact direction.
5. The maximum hardness was obtained near the welding interface for both sides. However, the increased value of hardness for stainless steel was more than copper.
6. The tensile strength and elongation were increased by post heat treatment.
7. The interface of sample with and without the post heat treatment was exhibited ductile and brittle fracture, respectively.

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