Journal of Mechanical Science and Technology 30 (9) (2016) 4299~4306
www.springerlink.com/content/1738-494x(Print)/1976-3824(Online)
DOI 10.1007/s12206-016-0844-8

Investigation of mechanical properties of bimetallic square tubes produced by shape rolling of Al/Cu circular pipes [†]

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(Manuscript Received November 16, 2015; Revised April 12, 2016; Accepted April 27, 2016)

Abstract

We investigated the effect of shape rolling process on the bond strength and mechanical properties of Al/Cu bimetal pipes. A bimetal circular pipe was fabricated by the explosive welding process. Then, the bimetal explosive-welded circular pipe was reshaped to a square tube by means of the shape rolling process. The mechanical properties of explosive welded pipes and shape-rolled tubes at the various stages of the rolling process were experimentally investigated by using the shear testing, micro hardness testing along the thicknesses and measurement of yield. The obtained results show that with the increase of roll gap reduction during the various stages, the hardness increases, while the shear strength decreases. However, their effects on hardness increase are not the same for both materials. Yield stress measurement results indicate that the average yield stress increases during explosive welding and also shape rolling process, but the rate of increase is more intensive in the explosive welding process. Moreover, the morphology of the interface before and after the Shape rolling was examined by Optical microscope (OM) and the presence of the intermetallic compounds at the interface was investigated by the electron microscope (SEM) and EDS analysis. Examination of the interfaces morphology revealed that, due to the brittle nature of the intermetallic compounds at the joining interface, the nucleation and propagation of micro cracks accelerated during the shape rolling process and the amount of micro cracks increases which makes the shear strength decrease.

Keywords: Bimetal square tube; Explosive-welded circular pipe; Shape rolling; Shear strength

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1. Introduction

Current developments in advanced technologies require new materials with special capabilities and characteristics, including corrosion resistance, light weight, high mechanical, electrical and thermal properties for different application requirements in various industries. As a single material by itself cannot satisfy these requirements, numerous works have been carried out to develop new materials like bi- or multi-metals for such purposes. For different applications, bimetals may be produced as sheet, rod, pipe and complex profiles [1]. Many kinds of techniques have been developed to bond multi-layered materials, such as explosive welding [1], rolling bonding [2], diffusion bonding [3], extrusion [4], friction-stir welding [5] and spin-bonding [6]. Among these, explosive welding is well-known for its ability to directly join a wide variety of both similar and dissimilar multi-layer plates, rods and circular pipes with high bonding strength, which cannot be joined by any other techniques. Recently, the bonding interface and mechanical properties of explosive-welded multilayer plates [7-12], pipes [13-15], bars [16], and tubes [17, 18] have received considerable attention and discussion. The fabrication of bimetal or multi-metal products has encountered certain difficulties, and therefore is restricted to simple shapes and geometries such as sheets, circular pipes and rods.

To achieve the final product with desired shape and geometry, a subsequent forming process is being performed on cladded products, which may induce problems of low efficiency and low quality. Therefore, effect of forming process on the joint properties of cladded products manufactured by explosive welding has been investigated. The effect of the cold rolling process on the mechanical properties and bond strength of explosively-welded Al/Cu/Al bimetal plates was investigated by Asemabadi et al. [19]. The fabrication of bimetallic aluminum sheathed copper axisymmetric rods by explosive cladding and subsequent warm extrusion is reported by Mamalis et al. [20]. The microhardness, microstructure and bond strength of the interface of a bimetallic bar was manufactured using an explosive technique method and the process of rolling was investigated by Dyja et al. [21]. In another study, they presented the results of their theoretical and experimental analysis of the rolling process of bimetallic Cu-Steel and Cu-Al rods in stretching passes [22]. However, there are very

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[†] Recommended by Associate Editor Dae-Cheol Ko

Table 1. Chemical compositions and mechanical properties of aluminum and copper materials used in this investigation.

		Aluminum	Copper
Mechanical properties	Tensile strength (MPa)	212	251
	Hardness vickers (HV)	83	95
Chemical composition	Cu	< 0.0002	Base
	MN	0.01	< 0.0004
	Si	0.6	0.016
	Mg	0.35	0.0004
	P	< 0.0001	0.014
	Fe	0.15	0.035
	Al	Base	0.004

limited works on the fundamental fabrication characteristics of bi-layered noncircular seamless tubes, which have widespread applications and many advantages compared to the round pipes. Recent advances in high temperature and high pressure applications in natural gas, electrical, and chemical industry, where service conditions demand different requirements in the bore of a tube from those on its outside surface, have created a significant demand for the industrial applications of bimetallic noncircular seamless tubes. These tubes have many advantages over the circular ones, such as the facility to fit, the increase of torque in twist and the weight reduction in structural parts. Although there are some analytical [23], experimental-analytical [24-26], and numerical [25, 27] studies to analyze the reshaping process to produce the single layer noncircular tubes, no reported research exists for the reshaping process of bimetallic circular pipes.

The present research concerns the effect of the cold rolling process on the mechanical properties of two-layer explosive-welded Al/Cu pipe. To investigate this objective, the morphology of the interface before and after the shape rolling was examined and the presence of the intermetallic compounds at the interface was investigated. Explosive welded circular pipes and cold-rolled tubes underwent shear strength tests, and also the hardness distributions were measured across the thicknesses of the samples. The yield stress throughout the microhardness profile was measured to evaluate materials strength during the process.

2. Materials and methods

The aluminum and copper circular pipes used in the explosive welding process were of 4.5 and 2 mm thickness, respectively. Also, the outer diameter of bimetal pipes was 80 mm. The chemical composition and mechanical properties of these materials are given in Table 1.

We used a parallel layers arrangement for the experimental setup of the explosive welding process (Fig. 1). The explosive materials were AMATOL (10-90), of detonation velocity equal to 3500 m/s and density equal to 800 kg/m^3.

To investigate the effects of the shape rolling process on the mechanical properties and joint microstructure of Al/Cu circular pipes into square tubes, samples were cold rolled at roll gap reductions equal to 2, 4, 6, 8, 10 mm in ambient temperature.

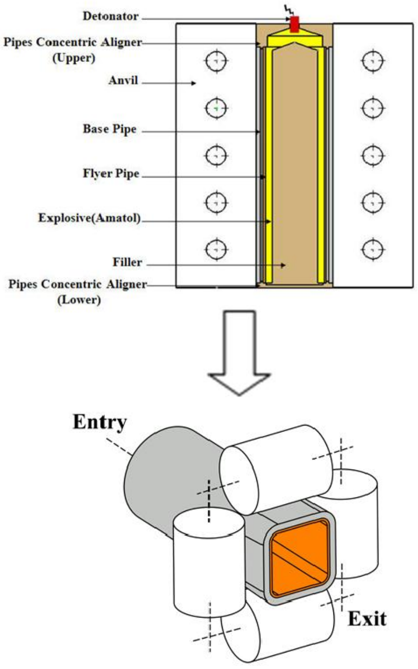


Fig. 1. Schematic view of the explosive welding and shape rolling process.

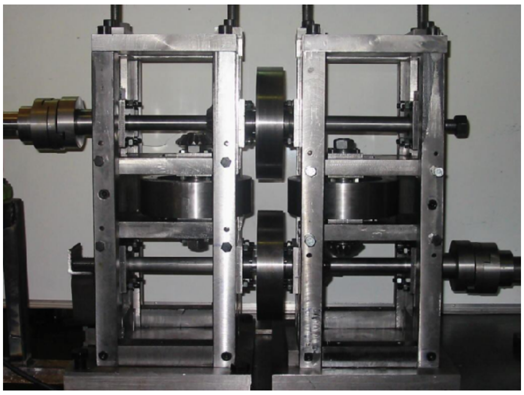


Fig. 2. The test rig for shape rolling.

The exit cross section is a square shape with round corners and the flat widths. The corners were taken as circular arcs tangent to the flat sides. Fig. 1 shows the schematic view of the explosive welding and shape rolling process.

2.1 Test rig

To make experimental observations of the reshaping process, we used a test rig (Fig. 2). As can be seen from the figure, it is a four roll mill with adjustable roll gap. The rolls were made of steel CK45. All four rolls were designed so that when

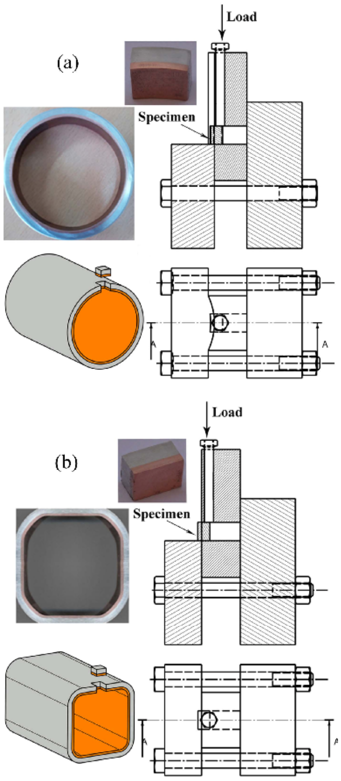


Fig. 3. Schematic of samples and the supplemental fixture for shear test of joints: (a) For explosive welded circular pipe; (b) for shape rolled square tube.

assembled a free space of square or rectangular shape could be formed between them. In this way, the pipe could be fed into this space for deforming it into the desired shape. The axes of each two opposite rolls were parallel as shown in Fig. 2. The power transmission system was so designed that all rolls had equal speeds. For this purpose, two coupled gearboxes and motors with an output power of 1.1 kW and output speed of 20 rpm were used.

2.2 Microstructural work

To study the quality of the interface bonding and the evaluation of the effect of the subsequent rolling process on the interface, the samples were cut along the rolling direction for shape rolled tubes and along the explosion direction for explosive welded pipes, too. For a better grinding and polishing operation, the samples were mounted and then ground by emery papers of grade numbers 80-4000 and polished to 3 μm finish. Their interfaces were analyzed through an Optical microscope (OM). The presence of intermetallic compounds at the interface was investigated by an electron microscope (SEM) equipped with Energy dispersive X-ray spectroscopy (EDS).

2.3 Mechanical test

The shear strength of the bonded joints was evaluated by means of two specially designed fixtures to test specimens from the clad circular pipe and the flat part of shape rolled tube, in an Instron instrument in the compression direction with a loading speed of 0.5 mm/min. Fig. 3 shows the design of these fixtures and shear strength test specimens. The samples were cut on specific locations (10 mm from the head) of the pipe and square tube. Samples were 12 mm wide and 10 mm long and were cut at the longitude of the pipe and square tube so that their width was in the circumferential direction.

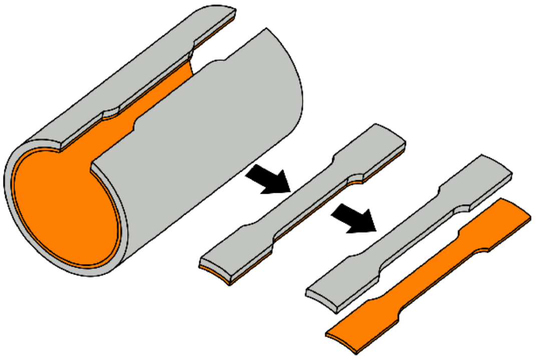


Fig. 4. Tensile sample prepared from the bimetal circular pipe.

The shear strength was calculated by dividing the maximum pushing load by contact area of two layers. Also, to be more accurate, the shear strength test was performed three times for each sample, and the average value was reported as the final shear strength. To determine the yield stress of each layer (Al and Cu) before and after the explosive welding, a tensile test was performed. Tensile samples of dog-bone geometry with the gauge length parallel to the pipe axis were extracted from longitudinal direction of the pipe according to the ASTM E8M (Fig. 4). Tensile test involved using a hydraulic Instron tensile machine, with strain rate of 5 mm/min at room temperature.

Note that for tensile testing of explosive welded samples, the layers were separated from each other by using Wire electric discharge machining (WEDM), and then tensile samples were prepared from them (Fig. 4). A similar process was applied to prepare samples from shape rolled tubes.

To measure the hardness of the cold-rolled samples in different roll gap reductions, a transverse cross section was cut along to the rolling direction (explosion direction) from the flat and circular corner regions. Under the load of 50 g and duration of 10 s, the hardness distribution across the thickness of the samples was obtained as a profile from the bottom surface of the two-layer Al/Cu sample to its top surface, and results were reported as Vickers micro-hardness based on ASTM E384-11. Also, for explosive welded pipe, a microhardness test was performed the same as cold rolled samples. Due to the low thickness of intermetallic compounds at the interface, for measuring the micro hardness in these regions, a load of 10 gr was used.

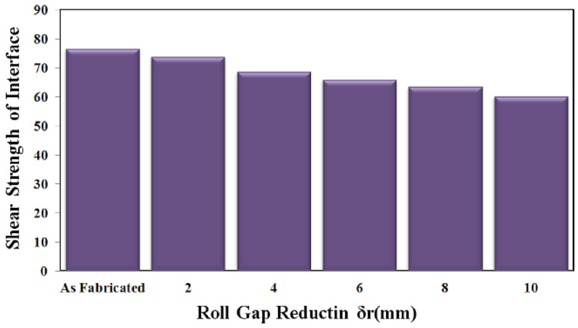


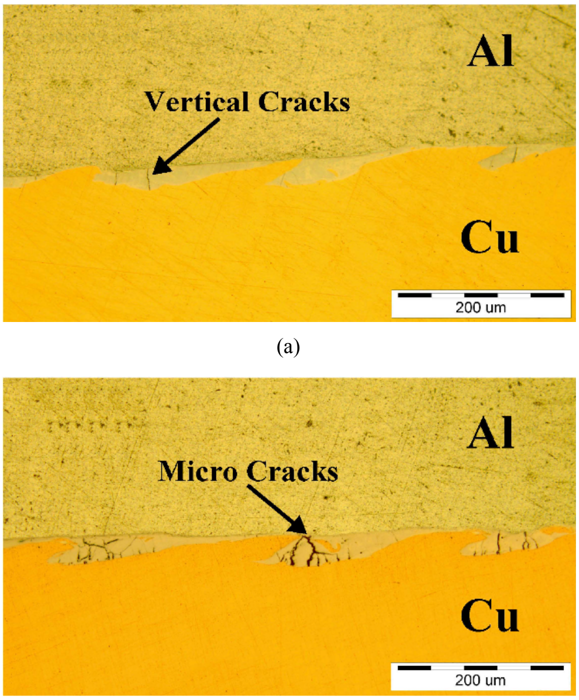
Fig. 5. Shear strength of the interface of (Al-Cu) bimetal Specimens of explosive welding and shape rolling.

3. Results and discussion

To analyze the effect of shape rolling process of explosive welded Al/Cu pipes on shear strength, the microstructure of interface, microhardness and yield strength results will be presented in this section.

3.1 Shear strength

Shear strength tests were performed on the bonding interface of the samples which were prepared from the explosion bonded specimens and also after the shape rolling at different roll gap reduction, respectively. As the first examination, in order to show that the contact between the layers was not just a mechanical lock, test samples were cut as shown in Fig. 3. It was observed that the layers were still bonded to each other after being cut, demonstrating the integration of interface is maintained and therefore no separation was observed at the interface of aluminum and copper multilayer products. The results of the performed tests for the quality of the Al/Cu joints in respect of the maximum shearing stresses for samples before and after shape rolling are presented in Fig. 5. It can be seen from the data shown in the figure that the shearing strength of the joint has decreased during shape rolling process. Similar results also were reported by Dyja et al. [21]; a drop in the shear strength of the joint after the rolling of explosive welded copper/steel rods.



(a)

(b)

Fig. 6. Cross-section optical image of Al/Cu interface of bimetallic pipe: (a) After explosive welding process; (b) after the last stage of shape rolling process.

3.2 Microstructural observation

Fig. 6(a) shows an image of the interface of explosive-welded bimetal circular pipe. As can be observed, the morphology of the joint was characterized by a wavy pattern that was predominant along the longitudinal axis of the pipe. Note that no delamination was identified in the present case. Due to the low melting point of aluminum and high hardness of both pipes as given in Table 1, the resistance to severe plastic flow and dissipation of kinetic energy of the impacting materials in the form of heat at the interfacial zone increased the interfacial temperature above the melting point of materials, and consequently led to formation of an intermetallic layer along the interface [28, 29]. Therefore, typical vertical cracks can be observed in the melted zone (Fig. 6(a)). The presence of vertical cracks in these areas suggests that the behavior should not be as ductile as Cu and Al. The cracks were always limited to the melted zone and did not show any tendency for propagation across the base materials, either in the copper or in the aluminum tube. To examine the joint region more precisely, microanalysis was made by SEM image and the EDS method. The results of this microanalysis are given in Fig. 7 and Table 2. As shown by EDS analysis, the intermetallic phases can be Al_2Cu and AlCu and Al_4Cu_9. Failures may have occurred during the subsequent processes, such as reshape rolling being caused predominantly by stresses in the bond zone and intensifying metallurgical weakness due to explosive cladding. Fig. 6(b) shows an image of the interface of the aluminum and copper tube after the last stage of the shape rolling process. By analyzing the interface, we concluded that the wavy pattern of the Al/Cu interface was maintained, but the intermetallic inclusion was affected by the loading during shape rolling process, because of the brittle nature of intermetallic compounds. It can be seen that at the interface and inside the intermetallic layer, the amount of cracks increases after the shape rolling and, as a consequence, the joint strength is reduced.

3.3 Hardness measurement

Fig. 8 shows the variation of micro-hardness profiles before and after shape rolling with various roll gap reduction at flat

Table 2. EDS spectra from the regions marked with A, B and C in Fig. 7.

	Al (at.%)	Cu (at.%)	Intermetallic compound
Point A	66.19	33.81	Al_2Cu
Point B	52.11	47.89	AlCu
Point C	31.31	68.69	Al_4Cu_9

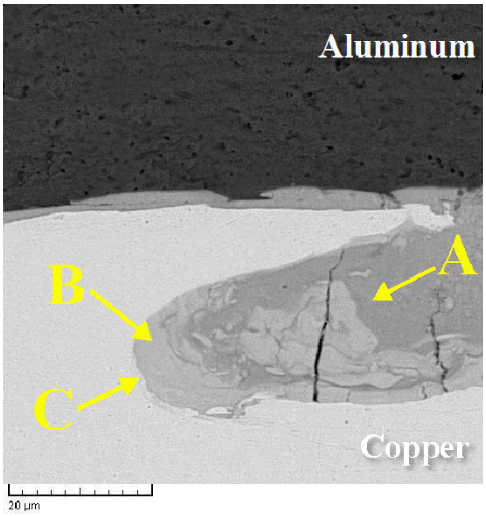


Fig. 7. Cross-section SEM image of Al/Cu interface of bimetallic pipe after explosive welding.

and corner part of square tubes. By comparing the microhardness distributions in the finished explosive welded bimetallic pipes and shape rolled ones, it can be noticed that the entire hardness values of welded pipes are larger than the original materials.

After shape rolling at the first pass, copper and aluminum tubes in the flat part experienced an increase in hardness values. However, no significant changes were observed in hardness values of the corner part. The flat part experiences more work hardening and plastic deformation through the thickness during shape rolling in comparison to the corner part, Fig. 8(b).

Similar qualitative patterns, with only an upwards shifting due to more work hardening for different roll gap, were identified. In Fig. 8(d), after the final pass, the average value of copper hardness in the flat part of tube reached 135.3 Vickers; while in the aluminum part, the hardness average value increased from 104.8 to 113.4 Vickers. It is obvious that the hardness of Al and Cu layers in the corners increased very slightly in comparison to the flat area at the final pass. Furthermore, from Fig. 9, at the interface, the hardness is distinctly higher than that of both the aluminum and the copper. This is due to the formation of intermetallic phases which have high hardness and brittle nature. The microhardness values inside the intermetallic layer were recorded approximately as 600 HV0.01.

3.4 Yield stress average

Several studies have been performed for estimating the yield stress throughout the micro-hardness profile. In this case, the following incremental formula based on an empirical methodology proposed by Nobre et al. [30] was used. Eq. (1) relates the linearity between relative increments of hardness and yield stress:

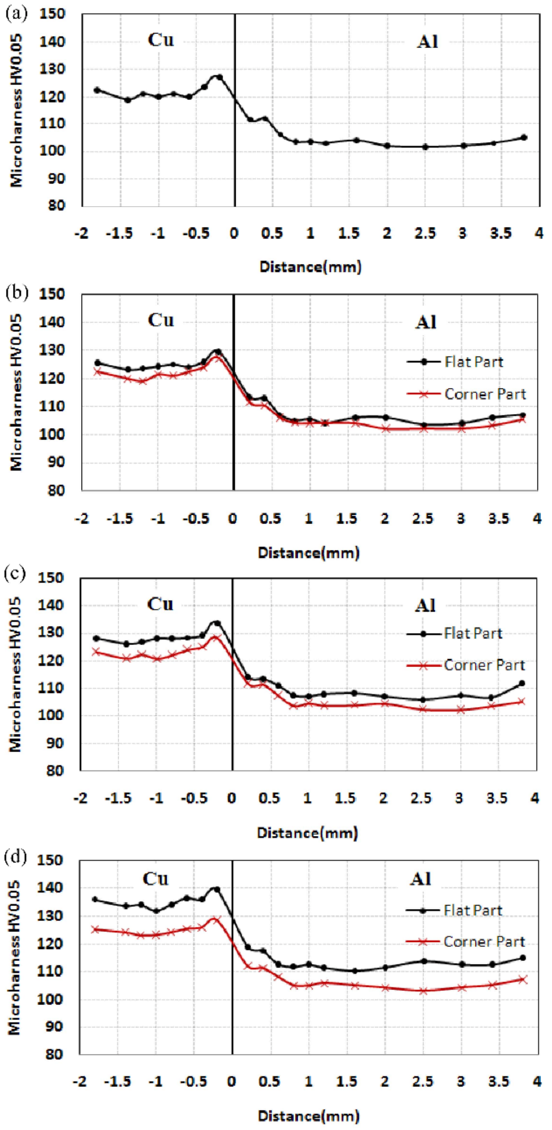


Fig. 8. Micro-hardness profile across the aluminum/copper joints: (a) as fabricated and shape rolling with; (b) 2 mm; (c) 6 mm; (d) 10 mm roll gap reduction.

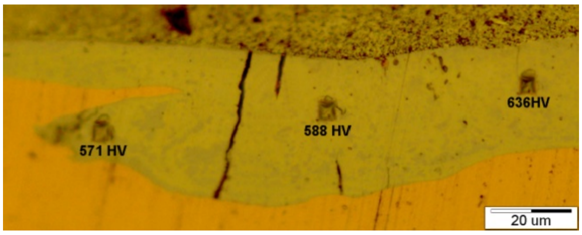


Fig. 9. Results of the micro hardness tests in intermetallic layer.

Table 3. Hardness and yield stress of Al and Cu.

Stage	Roll gap (mm)	Aluminum		Copper	
		Hardness	Yield stress	Hardness	Yield stress
Row material	NA	83	172	95	200
Explosive welded	NA	104.8	235	121.8	265
Shape rolled	2	106.8	240	125.2	273
	6	109.1	250	128.4	281
	10	113.4	260	135.3	300

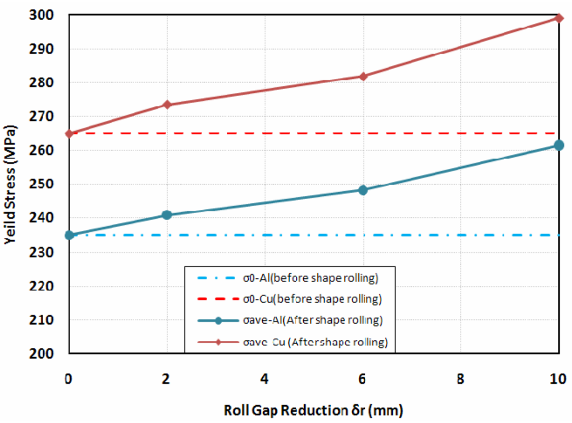


Fig. 10. Average yield stress of each layer.

$$\sigma_y = \sigma_{y0}(1 + \gamma \frac{\Delta HV}{HV_{y0}}), \quad (1)$$

where ΔHV, σ_{y0} and HV_{y0} correspond to hardness variation, the yield stress and hardness of the bulk material, respectively, and γ is a constant (scale factor). The result of yield strength is shown in Fig. 10.

The average hardness and yield stress values of the Al and Cu layers for row material, explosive welded and during various roll gap reductions are detailed in Table 3. Results indicate that the yield stress average of each layer increases during explosive welding (32% and 44% for aluminum and copper, respectively) and also shape rolling process (13% and 10% for aluminum and copper, respectively). This means that the explosive welding effect on yield strength increase is more than of shape rolling. However, their effects on yield strength are not the same for both materials. Sui et al. [31] completely explained the effect of the various process parameters on distribution of plastic strain during the explosive welding process of Al/St tubes. Considering that the plastic deformation in the explosive welding process is much more than in the shape rolling process, therefore, the effect of work hardening and as a result the percent of increase in hardness and yield stress after explosive welding process can be much greater in comparison to the shape rolling process.

4. Conclusions

The mechanical properties of square tube produced by shape rolling of two-layered explosive-welded Al/Cu pipe were investigated experimentally. The shear strength, microstructural observation, hardness distribution and yield stress were studied and the following can be concluded:

- The results of the performed tests for the quality of the Al/Cu joints in respect of the maximum shearing stresses before and after shape rolling revealed that the shearing strength of the joint decreases during shape rolling process. Although the shape rolling decreases the shear strength, the process of explosive welding and its parameters could accelerate this reduction of strength.
- By investigating the interface after the last stage of shape rolling, it was concluded that the wavy pattern of the Al/Cu interface is kept during the shape rolling process. But, the intermetallic inclusion was affected by the loading during shape rolling process, because of the brittle nature of intermetallic compounds. It can be seen that at the interface and inside the intermetallic layer, the amount of cracks increases after the shape rolling and, as a consequence, the joint strength can be reduced.
- During the shape rolling at the different passes, copper and aluminum in the flat part of the tubes experience an increase in hardness values and the largest hardness increase has been observed in the copper layer. However, the hardness of both Al and Cu layers increased very slightly in the corners due to less work hardening and plastic deformation.
- The yield stress average of each layer increases after shape rolling process during the various stages. Although, shape rolling effect on yield strength increase was lower in comparison with the effect of previous explosive welding process. However, their effects on yield strength increase are not the same for both materials.

Nomenclature

σ_{y0}	: Yield stress of balk material
σ_y	: Yield stress of deformed material
HV_{y0}	: Hardness of balk material
HV_y	: Hardness of deformed material

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