Investigating the effect of post weld heat treatment on corrosion properties of explosive bonded interface of AA5083/AA1050/SS 321 tubes

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Abstract

The corrosion behavior and microstructural changes in explosively welded AA5083/AA1050/SS 321 multilayer tubes after heat treatment were studied. Heat treatment were performed in 350 and 450 °C for 6 and 8 h. Microscopic results indicated significant changes in the thickness and concentration of alloying elements in locally melting zone with heat treatment temperature. According to electrochemical tests results at samples interfaces, by increasing the temperature and time of the heat treatment process, the energy stored due to explosive welding is reduced, the difference in the concentration of aluminum related to steel in the interface layer decreases, and the corrosion rate (current density) and electrical charge transfer decrease.

1. Introduction

Explosive welding is a method in which the controlled energy of an explosive material is used so that welding surfaces that are spaced apart at a certain standoff distance move at high speed together and collide with each other. As a result of the collision of two surfaces with each other, a localized pasty zone is created in the joint interface, where a metallurgical bond is created between the welding parts. Due to the high pressure impact, a high speed jet is formed from both sides of the interfaces, which creates clean connections at the joint interface and eliminates surface contamination [1]. The formation of this jet is one of the basic conditions for the proper bonding of explosive welding. This welding process is non-fused and from industrial point of view can be applied to binding and coating of various similar and dissimilar metals in two or more layers. Due to the lack of heating during this process, the welds carried out by this method do not have many of the negative properties of the bonded joints with the fusion welding processes, hot rolled or hot molded [2, 3].

Extremely limited studies have been conducted on corrosion of explosive welding. Kengkla et al[4] have investigated the effect of intermetallic compounds on the corrosion behavior of aluminum/steel explosive three-layer joints in military industries. Their results showed that the formation of Al₃Fe, Al₃Fe₂ intermetallic compounds at the joint interface has created a cathodic mode to aluminum and anodic mode to steel. As a result, preferential corrosion attack has occurred near the aluminum boundary and intermetallic compounds. Mudali et al[5] investigated the explosive bond corrosion of titanium and stainless steel 304. Their results showed that the bending stress in the nitric acid environment was standard and the corrosion attack was more concentrated in the joint interface. Acarer [6] studied the corrosion of explosive bond of aluminum to copper. The results showed that galvanic corrosion occurred in the bonding and the aluminum side of bonding had more anodic mode based on the high electronegativity and had more corrosion rate compare to the copper side. Kahramana et al[7] investigated the corrosion of explosive bond of titanium to stainless steel. The results show that in the corrosive environment, the mass change of the bonded plates became more intense with the increase in the
amount of explosive charge due to the plastic deformation and the formation of an oxide layer on the surface. They also investigated the explosive bonding corrosion of Ti-6Al-4V and aluminum plates. Corrosion test results showed that the weight loss rate was high at the beginning of the corrosion tests and then decreased. In addition, increasing the amount of plastic deformation caused by increasing the amount of explosive charge has led to an increase in weight loss of samples in the corrosion test. Rajani et al. comprised the corrosion behavior of fusion bond and explosive bonding of Inconel 625 and carbon steel. According to their results, the corrosion behavior of bonds is more uniform than the fusion welding due to the chemical heterogeneities caused by separation and the formation of secondary phases during solidification of fusion welding.

In this research, the effect of heat treatment time and temperature on the corrosion behaviors of the aluminum and steel bonding interface is investigated.

### 2. Experimental methods

Stainless steel 321 with aluminum alloys AA1050 and AA5083 tubes were used to produce three-component tube by explosive welding process. In the present study, the effect of post weld heat treatment (PWHT) on corrosion behaviors of explosive bonding interface of AA5083/AA1050/SS 321 tubes has been investigated. Chemical compositions of explosive welded tubes have been shown in table 1.

AA1050 and AA5083 were considered as flyer tube in explosive welding The SS 321 tube has been considered as a base tube with a thickness of 4.5 mm and a length of 200 mm. Table 2 represents the dimensions of the flyer and base tubes.

The flyer tubes were considered 40 mm longer the base tube, so that the explosion reaches to its stable state during welding in the desired length i.e. 20 cm and also causes the lower and upper edges of the tubes to fully bond to each other [10, 11]. Characteristics of explosive welding tests have been shown in table 3. Figure 1 illustrates set-up of tubes and explosive welding equipment.

In order to post weld heat treatment (PWHT), samples were cut and placed in an Argon-protected furnace at temperatures of 350 °C and 450 °C for 6 and 8 h according to table 4 and then cooled in air.

After polishing, the samples were etched by glycerin and chloric acid solution to prepare microscopic images. Scanning electron microscope (SEM) model VEGA TESCAN-LMU equipped with energy dispersive x-ray spectrometry (EDS) was used to compare and examine the shape and composition of interface layer.

Electrochemical measurements were performed with AUTOLAB model PGSTAT 302 N potentiostat using samples with a surface area of 1 cm² in a 3.5% NaCl solution. All electrochemical tests were done at room temperature. A three-electrode cell was used for electrochemical measurements; the working electrode was the test material whereas a saturated calomel electrode (SCE) was used as the reference electrode and a platinum electrode was used as the counter electrode. Anodic polarization measurements were performed at a scan rate of 1 mV s⁻¹. Electrochemical impedance spectroscopy (EIS) measurements were performed at the frequency ranged from 10 KHz to 10 mHz with five points/decade and an amplitude of sinusoidal wave of 10 mV. Time to reach stable state was 90 min. ZSimpWin 3.22 software was used to analyze the results of EIS. [12].

### Table 1. Chemical compositions of explosive welded tubes (wt%).

| Material | Fe | Al | Zn | Ni | Ti | Cr | Mg | Mn | Si | C |
|----------|----|----|----|----|----|----|----|----|----|---|
| SS 321  | Bal. | —  | 10 | 0.3–0.7 | 18 | —  | 2  | 1  | 0.08 | — |
| AA1050  | 0.26 | Bal. | <0.002 | —  | <0.007 | —  | <0.001 | —  | 0.07 | — |
| AA5083  | 0.4 | Bal. | 0.25 | —  | 0.15 | 0.25–0.05 | 4–4.9 | 1–0.4 | 0.4 | — |

### Table 2. Dimensions of the flyer and base tubes in explosive welding.

| Material | Length (mm) | Thickness (mm) | inner diameter (mm) | External diameter (mm) |
|----------|-------------|----------------|---------------------|-----------------------|
| AA5083   | 240         | 5              | 96                  | 106                   |
| AA1050   | 240         | 1.5            | 118                 | 121                   |
| SS 321   | 200         | 4.5            | 126                 | 135                   |
Table 3. Characteristics of explosive welding tests.

| Outer diameter of steel base tube (mm) | Inner diameter of steel base tube (mm) | Outer diameter of aluminum 1050 flyer tube (mm) | Inner diameter of aluminum 1050 flyer tube (mm) | The outer diameter of aluminum 5083 flyer tube (mm) | Inner diameter of aluminum 5083 flyer tube (mm) | Standoff distance 5083/1050 (mm) | Standoff distance 1050/321 (mm) | Charge thickness (mm) | Type of explosive material | Explosive speed (m/s) |
|--------------------------------------|--------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|--------------------------------|--------------------------------|------------------------|------------------------|---------------------|
| 135                                  | 126                                  | 121                                           | 118                                           | 106                                           | 96                                             | 6                              | 2.5                            | 15                     | Amatol 80/20            | 2504                |
3. Results and discussion

3.1. Microstructure evaluation by optical microscope

The wavy interface images created in the longitudinal direction of the bonding have been shown in figure 2. As it can be seen from figure 2(a), the bonding interface, is in short-wave form. During the explosive welding process, a layer subjected to severe plastic deformations has been created in the interface of two metals due to the high force intensity and very little time. In addition, new phases are observed in limited areas of the wavy interface. This intermediate phase is one of the properties of explosive welding, which is caused by local melting at the interface. Due to the distance between the flyertube and the intermediate tube (6 mm) and the spacing of the intermediate tube and the base tube (2.5 mm), the collision rate of the intermediate tube with the base tube is low, which results in plastic deformation resulting from the collision, and thus the interface is performed in a short wave form.

The images obtained from the optical microscope in figures 2(b) and (c) indicate the formation and growth of intermetallic compounds in the bonding interface of aluminum and steel with increasing temperature and heat treatment time. The average diffusion layer produced after heat treatment at 350 °C and 6 h is 77 μm, which increased to 89 μm by increase heat treatment time to 8 h. Increasing the heat treatment time leads to the activation of the diffusion mechanism and the formation of intermetallic compounds in the bonding interface.

Table 4. Samples coding based on heat treatment time and temperature.

| Sample | Temperature (“C) | Time (hr) |
|--------|-----------------|-----------|
| S0     | As weld         | As weld   |
| S1     | 350             | 6         |
| S2     | 350             | 8         |
| S3     | 450             | 6         |
| S4     | 450             | 8         |

Figure 1. Set-up of tubes and explosive welding equipment.
These compounds make it easier to diffuse aluminum and iron atoms during heat treatment in comparison to the formation of intermetallic compounds during explosive welding (figure 2(a)).

Figures 2(d) and (e) illustrate the formation and growth of intermetallic compounds in the bonding interface of aluminum and steel with increasing temperature and heat treatment time. By comparing samples with and
without PWHT, it can be seen that the thickness of the melt layer is gradually decreased with increasing temperature and time of heat treatment (figure 2).

3.2. Microstructure evaluation by SEM
Figure 3 represent SEM images of the interface of samples and the thickness of the layers in some points. As it can be seen from figure 3(a), the wave-vortex interface has been created and the average thickness of the interface layer is 49 μm before the heat treatment. For this sample the thickness of interface layer is less than those samples after the heat treatment at 350 °C and 6 and 8 h (figures 3(b) and (c) respectively). The reason of this matter was the effect of the heat treatment and diffusion of the alloying elements, which also expanded the intermetallic compounds.

Table 5 shows the results of elemental analysis of the compounds in the interfaces carried out using EDS. In the results obtained before heat treatment, it was observed that the interface structure compounds included 81.71 percent of aluminum atom and 12.6 percent of the iron atom. According to the atomic ratio of the elements in the obtained points and the iron-aluminum phase diagram, there is a probability of intermetallic compounds of FeAl$_3$ [13]. For non-homogeneous compounds based on jet reflexes from lower density tubes, the pressure is mainly applied on the tube with a higher density. As a result, the vortex formed at the rear of the wave containing mostly intermediate tube material and the vortex formed in front of the waves is mostly containing the base tube material. In table 5, the atomic percent of the elements for the sample S1, heat treated in 350 °C for 6 h, contain 74.71% aluminum and 17.61% iron. For sample S2, heat treated in 350 °C for 8 h, contain 71.89% aluminum and 19.55% iron. According to the atomic ratio of the elements in the obtained points and the iron-aluminum phase diagram, there is a probability of intermetallic compounds of FeAl$_3$ and Fe$_2$Al$_5$ [14]. Compared
to the changes in the percentage of aluminum and steel elements, it is clear that the conditions for the diffusion of the provided elements and the intermetallic compounds have been created in the samples by increasing the time at 350 °C before and after the heat treatment [15].
The impedance of a layer was determined by the EDS (indicated by the mark in figures) and has been shown in table 5. The interface between aluminum and steel is an asymmetric vortex wave form because of the difference in density. In figure 3(c) for S3, the aluminum and iron atomic percent are 63.56 and 26.15, respectively. According to the iron-aluminum phase diagram, the analysis shows that the intermetallic layer contains Fe2Al7 [16]. According to the intermetallic layer has been shown in figure 3(d), the atomic percent of aluminum and iron is 60.50 and 28.27, respectively which the intermetallic layer is probably Fe2Al7 and FeAl due to the atomic ratio of the elements in the obtained points and the phase diagram of iron-aluminum [17, 18].

The images obtained from the electron microscope indicate the formation and growth of intermetallic compounds in the aluminum/steel bonding interface with the increase of temperature and time of heat treatment. Increasing the temperature and operating time leads to the activation of the diffusion mechanism and the formation of intermetallic compounds at the interface. If intermetallic compounds are formed during explosive welding, it is easier to diffusion the iron and aluminum atoms during the heat treatment of samples [12].

By comparing table 5, it can be seen that the atomic percent of aluminum is gradually reduced with increase in temperature and time of heat treatment, but the atomic percent of iron and chromium are increased.

### Table 5. The atomic percent of the elements in interface derived from figure 3.

| Sample | Al (at%) | Fe (at%) | Cr (at%) | Ni (at%) | Al/Fe | Intermetallic compound |
|--------|----------|----------|----------|----------|-------|-------------------------|
| S0     | 81.71    | 12.60    | 3.60     | 2.06     | 6.48  | FeAl                   |
| S1     | 74.71    | 17.61    | 4.62     | 3.05     | 4.24  | FeAl–Fe2Al5            |
| S2     | 71.89    | 19.55    | 5.35     | 3.19     | 3.68  | FeAl–Fe2Al3            |
| S3     | 63.56    | 26.15    | 7.00     | 3.27     | 2.43  | Fe2Al                  |
| S4     | 60.51    | 28.27    | 7.73     | 3.47     | 2.14  | Fe2Al–FeAl             |

Figures 3(d) and (e) represent the interface microstructure and intermetallic layers for samples S3 and S4. An intermetallic compound of this layer was determined by the EDS (indicated by the mark in figures) and has been shown in table 5. The interface between aluminum and steel is an asymmetric vortex wave form because of the difference in density. In figure 3(c) for S3, the aluminum and iron atomic percent are 63.56 and 26.15, respectively. According to the iron-aluminum phase diagram, the analysis shows that the intermetallic layer contains Fe2Al7 [16]. According to the intermetallic layer has been shown in figure 3(d), the atomic percent of aluminum and iron is 60.50 and 28.27, respectively which the intermetallic layer is probably Fe2Al7 and FeAl due to the atomic ratio of the elements in the obtained points and the phase diagram of iron-aluminum [17, 18].

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### 3.3. Potentiodynamic polarization test results

Figure 4 shows the polarization curves of explosive welding samples after heat treatment. The electrochemical parameters extracted from these curves, such as corrosion potential ($E_{corr}$), pitting corrosion potential ($E_{pcp}$), corrosion flow density ($i_{corr}$) (corrosion rate), anodic and cathodic Toefl slopes have been obtained through Toefl extrapolation method and represented in table 6.

The anode branches are different in shape and are affected by various explosive welding parameters. According to the results of table 6, the corrosion potential has remained almost constant with increase in heat treatment temperature and time and the corrosion density has dropped from 175.39 to 19.64 μA cm$^{-2}$, due to the reduction in the energy of interface caused by the release of stored energy, which reduces corrosion.

For all the samples, a very poor passive layer was formed at the potential of the corrosive environment which was removed by potential increase of this layer, quickly. The S1 sample had the most protective layer that created on the surface after immersion; due to the more aluminum content rather than the other samples.

### 3.4. Results of electrochemical impedance spectroscopy

The EIS was used to investigate the surface layer created by the samples in a corrosive environment. Nyquist diagrams and Bode plots for post weld heat treated samples have been shown in figure 5. EIS data have obtained using the equivalent circuit presented in figure 6, which is in good accordance with experimental results and represented in table 7.

It can be seen from figure 5 that the impedance loops obtained in the Nyquist curve have a slight compression relative to a full semicircle, which is known as depletion. The deviation from the full semicircle is attributed to the frequency dispersion, as well as the surface heterogeneities and mass transfer resistance. This difference is described by the non-ideal behavior of the dual layer as a capacitor. Therefore, it is need to utilize from a constant phase element (CPE) instead of the non-ideal capacitive behavior of the dual layer to obtain more accurate results due to the distribution of comfort times caused by heterogeneity of the micro or nano levels, such as the roughness, porosity, impurities, inhibiting absorption and diffusion, etc. The impedance of a constant phase element is expressed using below equation [7]:

$$Z_{CPE} = \left[ Y_0 (\omega)^n \right]^{-1}$$

where $Y_0$ indicates relative factor (admittance) and $n$ is surface roughness coefficient (phase variance). The larger the number $n$, the more consistency and uniformity is obtained in welding interface. In this case, the corrosion current is lower because the corrosion current is proportional to the contact surface of the metal with solution. The greater defects and discontinuities result in the higher effective contact surface of the solution and the metal,
thus increasing the corrosion current. CPE for the n amount of 0, 1 and −1, indicates pure resistance behavior, pure capacitance and pure inductive, respectively. In present study, the Nyquist curves diameters (figure 5) are considered as the polarization resistance ($R_p$); In other words, only the existing capacity loops are related to the load transfer resistance between the metal and the outer Helmholtz layer (OHP). The observations indicate that metal corrosion is controlled by a load transfer process.

The electric dual layer can be described with the help of an equivalent circuit and presenting a proper model of the metal/solution interface. The corresponding electrical equivalent circuit for the samples in the solution is shown in figure 7(a) by presenting a schematic model of the potential distributions at the metal/solution interface (figure 7(b) and the dual layer resistance (figure 7(c). In the presence of inhibitors, the polarization resistance ($R_p$) consists of charge transition ($R_{ct}$), preventing layer resistance on the metal surface ($R_f$), all stored particles (inhibitory molecules, corrosion products, etc) at metal/solution interface ($R_d$) and the resistance of the diffusive layer ($R_a$) ($R_p = R_{ct} + R_f + R_a + R_d$) [12].

Dual layer capacity ($C_{dl}$) is calculated using below equation:

$$f (-Z''_{max}) = \frac{1}{2\pi C_{dl} R_{ct}}$$

(2)

where ($-Z''_{max}$) indicates the maximum value of impedance imaginary component of.

Table 7 presents the results of electrochemical impedance spectroscopy of explosion-welded samples at NaCl (3.5%) solution after 90 min of immersion. The highest polarization resistance was related to the S4 sample series equals to 3219 Ω.cm² and after that, the S3 sample was 2141 Ω.cm²; the lowest amount was for the S1 sample series. According to EDS analysis results at samples interfaces (table 5), by increasing the temperature...
and time of the heat treatment process, the stored energy due to the welding process is reduced, the difference in the concentration of aluminum and steel in the interface layer decreases, and the corrosion rate (current density) and electrical charge transfer decrease.

According to table 7, the number n in sample S1 is less than that of S4 and therefore the corrosion current in S1 is greater, which reduces the electrical charge transfer resistance. By comparing samples S3 and S4 with

Figure 5. Nyquist diagrams (a) and Bode plots (b) of samples from explosive welding after heat treatment.
variable treating time, when the treating temperature is constant, S4 with more treating time has a greater $n$ number (0.82) and S3 is in next place ($n = 0.80$) due to the increase in treating time and reduce the energy stored in the interface. According to the results of the atomic percent of the locally melting layers (table 5) and the results of the electrochemical tests (table 6), it can be concluded that the corrosion resistance is reduced due to the sudden change of concentration in the interface layer and also with reducing the thickness of this layer, the potential for corrosion caused by galvanic cells gradually decreases with increasing the temperature and time of the heat treatment process.

4. Conclusions

In the current study, corrosion behavior and microstructure evaluation of explosion-welded SS321/AA1050/AA5083 tubes with different post weld heat treatments were studied and the following results were obtained:

1. According to the results of microscopy, the thickness of the local melting layer decreased gradually with increase in temperature and time of the heat treatment process, and the aluminum atomic percentage has been gradually reduced, but the atomic percent of iron and chromium have been increased.

2. Images obtained from electron microscope indicate the formation and growth of intermetallic compounds in the aluminum/steel interface with increasing heat treatment time and temperature. Increase the heat treatment time and temperature leads to the activation of the diffusion mechanism and the formation of intermetallic compounds at the interface.
3. Element analysis using EDS identified the intermetallic compounds of Fe₃Al, FeAl₂ and Fe₂Al₅ compounds in the interface based on the atomic ratio of the elements and the iron-aluminum phase diagrams.

4. With increasing temperature and time of the heat treatment process, the corrosion resistance increases gradually due to the reduction of the sudden change in the concentration of melting layer and also the reduction of the thickness of this layer and the corrosion potential of the galvanic cell gradually decreased.

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