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Effect of Heat Treatment on the Intermetallic Compounds and Mechanical Properties of Explosive Weld Interface of three Al 5083, Al 1050 and St 1515 Layers

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Abstract

In this research, the effect of heat treatment on the microstructure and mechanical properties of intermetallic compounds of welding joint interface of three explosive layers of 5083 and 1050 aluminum as flying and intermediary plates and AISI steel sheet as the base plate has been discussed and investigated. To show the effect of temperature and time, the welded samples with stand-off distance of 6, 8, and 10mm and the explosive load of 2.41 were placed on heat treatment in the constant temperature of 315°C and 450°C within a furnace protected by Argon gas for six hours. Laboratory investigations have been conducted by the use of photomicroscope, scanning electronic microscopy, and microhardness assessing tests. Metal compounds of the interface were specified by the use of EDS analysis. In the considered samples before heat treatments, the interface of the joint has been converted from the short wavy state into the vertical wavy state by the increase of stand-off distance from 6 mm to 10 mm, and the average diameter of intermetallic layers has been increased in a range from 0.1±1.89 micrometer to 0.07± 3.13 micrometer as well. Also, microhardness has been decreased by the increase of intermetallic compounds from 266 Vickers in the sample with a stand-off distance of 10 mm to 205 Vickers in the sample with a stand-off distance of 8mm in the steel section. The performance of treatment in temperatures of 315°C and 450°C for six hours has been led to increasing the diameter of the intermetallic compounds layer.

Keywords: Heat Treatment, Explosive Welding, Intermetallic Compounds, Stand-off Distance, Microhardness.

1. Introduction

Scientists are trying to find materials with excellent mechanical properties for industrial applications now. In this same direction, usage of materials or a few coated layer can be an appropriate suggestion. In some industries such as shipbuilding, aerospace, vacuum equipment, automotive industries, and other machinery, use of the aluminum- steel non-homogenous joint is about to develop [1,2]. Joint of aluminum to steel through fusion melting welding methods is very difficult due to their melting temperature difference, physicochemical properties, and atomic layers [3]. Analysis of the samples welded by explosive method confirms the impact of collision speed and stand-off distance on the joint type. The joints achieved from this method have had very appropriate Physical and mechanical properties. Of the major applications of this method in industries, it can be referred to the coating of homogeneous and non- homogeneous metals together for prevention of corrosion, improvement of heat transfer quality, increase of resistance against implemented stresses, improvement of electrical properties, and improvement of wear properties [4,5].

The explosive welding process is an effective method for the joining of each compound of metals. The only metallurgical limitation of the method is the necessity for appropriate flexibility and sufficient fracture toughness of the welded metals to tolerate fast transformation shape change while welding and lack of establishment of fracture in them during the welding process [6]. One of the defects and disadvantages of this method is the high speed of the process causing that, contrary to other methods of welding; the parameters cannot be controlled during the process more accurately. Explosive welding, only, can be applied to the joint of the simple shapes. Also, the intrinsic dangers of explosive materials, sound resulted from the explosion, effects originated from explosion waves and lack of capability of activation is the other defects and disadvantages of this method. In the two-layer joint of steels to aluminum, the probability of establishment of intermetallic compounds in the interface increases due to the existence of the main elements, including iron and aluminum. Intermetallic compounds are formed for this reason that strength of bond among the related dissimilar atoms is higher than the strength of bond among the similar atoms. Therefore, special crystalline structures with atomic dispersion are well organized among the metals in which each atom has been surrounded by the dissimilar atoms

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preferentially [7-9]. From the chemical viewpoint, the reaction of iron with aluminum establishes a few intermetallic compounds being of Fe_xAl_y type because only a little amount of iron can be solved in aluminum and vice versa. Intermetallic compounds occur in temperature under the melting point of aluminum. The ratio of formation of these compounds depends on the type of permeation. Therefore, they are dependent on temperature and time. The increase of the intermetallic layer is expected by the increase of temperature and time [9,10]. In the study of the explosive three-part joint of the $AlMg_5$ $AlKA_3$ and $StCr_{18}Ni_9Ti$ stainless steel pipe in two-step then single-step forms, results showed that all joints have had a wavy and irregular interface with high hardness in the aluminum steel part and flat interface in the aluminum-aluminum part [11]. In research conducted regarding the impact of usage of the middle layer on the explosive cladding. It was specified that usage of the middle layer in this process with wasting of the released kinetic energy resulted from the explosion of the explosive materials and mechanical properties of the weld, especially concerning the lack of formation of the brittle intermetallic materials in the medial layer has had a noticeable improvement which, of course, the middle layer has had a more appropriate efficiency when the explosive materials are employed by higher speed and explosive load [2]. Also while investigating the stand-off distance of the sheets/plates against one another in the explosive joint of three 5038 aluminum, 1250 aluminum, and marine steel layers. It was specified that increase of stand-off distance and explosion load has been led to the conversion of the interface from the smooth shaped state into wavy shaped state and finally the establishment of the fusion parts in the weld interface and formation of intermetallic compounds in this area [3]. In an investigation into the influence of heat treatments on the behavior of explosive joint of 304 steel to Titanium, Akbari Mousavi et al. [12] showed that by the increase of temperature from 650°C to 900°C within one hour, granulation in the under recrystallization Titanium has become coarse, but so many changes have not been observed in the size of the granules. Their research has shown that the width of intermetallic areas of the interface has been increased by the increase of temperature because of the reaction of the alloy elements and the increase of permeation. Also, in their studies conducted on the impact of temperature and time on the explosive joint of low carbon steel to 304 austenitic steel, Findik et al. [13] showed the size of granules, hardness, strength, and flexibility have had tangible changes by performing the heat treatments. They suggested shorter times of the heat treatments because in this case hardness rate, proper strength, and remainder stresses have been decreased as well. Also, through studying of heat treatments of an explosive joint of aluminum to austenitic steel, Lokaj et al. [14] showed that by heat treatments in 250°C for 100 hours, the coarseness of aluminum granules due to increase of its permeation amorphous form of the microstructural interface of the base metals and interface have been decreased greatly. Also, John Banker et al. [15] have studied the change of mechanical properties of joining aluminum to steel by variables of temperature and time. They considered temperature between 200 to 500°C within a range from one to three hundred days. Their results have shown that intermetallic compounds have been formed gradually by the increase of temperature and their thickness has been related to increasing temperature and time directly. This research has been conducted to investigate the impact of temperature and time of heat treatments on the joint of three explosive layers of ($AlMg_5$) 5083 plate as flying/leaping plate 1050 aluminum as intermediary plate and AISI 1515 steel sheet as the base plate and its influence on the metallurgical microstructure of intermetallic compounds of the interface and mechanical properties of the joint.

2. Materials and Methods

The alloys used in the explosive welding process to establish a three-part plate are AISI 1515 steel and Al 1050 aluminum alloy and Al 5083 type in which their chemical compounds and physical and mechanical properties have been given at Table. 1. and Table. 2..

Table. 1. Chemical composition of the pipes (wt. %) [16].

Element (%at)	**Al**	**Zn**	**V**	**Cu**	**Ni**	**Ti**	**Cr**	**Mg**	**S**	**P**	**Mn**	**Si**	**C**	**Fe**
AISI 1515	-	-	-	-	-	-	-	-	0.050	0.040	0.600	0.600	0.180	**Ba.**
Al 1050	Bal.	0.002<	-	0.001<	-	0.007<	-	0.001<	-	-	-	0.070	-	**0.260**
Al 5083	Bal.	0.250	-	0.150	-	0.150	0.050-0.250	4.000-4.900	-	-	0.400-1.000	0.400	-	**0.400**

Table. 2. Mechanical and physical properties of the used alloys [16].

Materials	**Sound Speed (m/s)**	**Melting Temperature (°C)**	**Young Module (GPa)**	**Hardness (MPa)**	**Hardness (Hv)**	**Yield Strength (MPa)**	**Density (kg/m^3)**
AISI 1515	4804	1540	210	1765	160	355	7850
Al 1050	4996	650	69	294.2	30	100	2710
Al 5083	5090	570	70	804	82	320	2660

The selection of 1050 aluminum alloy as the intermediary layer is due to the reduction of intermetallic compounds in the interface. In order to weld Al-Zn-Mg alloys into steel directly, usage of an intermediary layer being of net aluminum kind between two alloys is suggested to establish an appropriate connecting bond due to extensive freezing limits and relatively low density of the alloy.

This affair is due to a higher melting point and approach to zero freezing scope and higher heating conductance of aluminum which decreases the rate of fusion phase formed in the aluminum-steel joint interface. The joint interface among Al /Al –Zn- Mg will be in form of sinus shaped wave which this affair leads to the collision points from both two directions and thus surface waves are formed and developed.

At first, metals were sandblasted and then freed and cleansed from rust and corrosion completely. Later on steel base plate with dimensions of 20 mm x250 mm x300 mm, 1050 aluminum intermediary plate with dimensions of 10 mm x 255 mm x 305 mm, and 5083 aluminum flying plate with dimensions of 7 mm x 260 mm x310 mm were cut in the rectangle-shaped form. The surface of the plates was washed by CaOH solution, Ethanol 95%, and Acetone and then washed with water and dried before the test. The variables used in designation for the purpose of joint of alloy plates being of Al 1050 and Al 5083 types to alloy plate being of AISI 1515 type were as follows:

a. Change in the stand-off distance among the flying intermediary and base plates.

b. Change in the speed of the explosive material through the change in the percentage of the compound of the constituent materials of explosive material.

In the welding process, there are two various stand-off distances of 8 and 10 mm and the plates have been welded together in complete parallel from. In order to join the plates explosive material which is a mixture of ammonium nitrate with carbonaceous materials and liquid fuel including gasoline was used by the compound of 94.5 of nitrate and 5.5% of gasoline.

Also in order to perform the process of the explosion of this material, the M8 detonator type was used.

After the performance of the welding post, thermal heat treatments were conducted on the samples at 25°C under laboratory medium conditions.

Due to investigation into the impact of stand-off distance, temperature, and time of heat treatments on the intermetallic compounds, some samples of plates with various stand-off distances were provided firstly. After the performance of the required tests before the fulfillment of heat treatments, the samples according to Table. 3., were placed under heat treatments in the furnace protected by Argon gas with the pressure of one Bar in 350 and 450°C for 6 hours and then cooled in the air environment.

Previous studies on the explosive joint of aluminum to steel had been conducted by domestic and foreign researchers in a temperature range from 250 to 650°C with short term periods of 5 and 60 minutes and with long term periods of 1 and 100 minutes. Therefore the selection of the temperature of 315 and 450°C in this research is due to the criticality of this temperature for the steel-aluminum joint considering these articles [17,18].

Samples with dimensions of 10×10×30 mm were prepared. To make the samples ready for metallography, the surface of the samples was sandpapered firstly by the sandpapers with dimensions of 60 to 1200 mm and polished by apparatus and felt and using aluminum oxide solution. Then it was engraved chemically to provide pictures of the photomicroscope by glycerigia solution (glycerin + chlorideric acid). A scanning electron microscope equipped with EDS analysis (Energy Dispersive X-ray Spectrometry) has been used to compare and study the shape and penetrating the layer of existing cracks.

Table. 3. Nomination of the samples based on the standoff distance, temperature and time of heat treatments.

No of sample	Cooling environment	Diameter of the explosive material (mm)	Time (hr)	Temperature (˚C)	Standoff distance (mm)
No1	Air	50	6	315	8
	Air	50	6	450	8
No2	Air	50	6	315	10
	Air	50	6	450	10
No3	Air	50	6	315	8
	Air	50	6	450	8

Before and after the performance of the heat treatments, the Vickers microhardness test with exerting the force of 100 gr and period of loading exertion of 10 seconds was conducted from various areas of intermetallic layer diameter and areas surrounding it. It was carried out according to ASTM E 348-11 reference standard [19]. In a laboratory temperature of 25◦C. Samples of microhardness test with a situation of 25, 50, 75, and 100 mm were conducted from the interface according to Fig. 1..

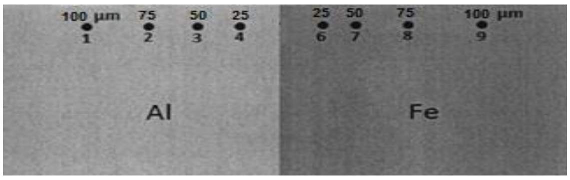


Fig. 1. Schematic of the spots selected to carry out the microharness test.

3. Results and Discussions

As observed in Fig. 2. the interface of the first sample joint is in the short wavy form. While performing the explosive weld process a layer has been established in the interface of two metals due to the intensity of very high force and very little time in which the layer has been placed under severe form change. According to Fig. 2., the diameter of the intermetallic layer formed at the interface of the aluminum intermediary plate and steel base plate of sample 2 joint with the stand-off distance of 10 mm compared to sample 2 joint with the stand-off distance of 8 mm has been increased and it's average reaches 0.09±1.54 micrometer. By the increase of kinetic energy of the collision, the shape of the interface compared to sample1 with a stand-off distance of 8 mm has become wavier [3,20]. The increase of stand-off distance and dynamic angle of the collision has been led to increasing of transformation in the aluminum-steel joint interface. Also considering a high-density difference between aluminum and steel one fusion thin layer has been established, leading to the establishment of various compounds in the interface. This is due to the appearance of local heat and cutting stress with a high rate in the joint interface (a: The first sample, b: The second sample and c: The third sample). Pictures of the Fig. 3. Suggest the formation and growth of intermetallic compounds in the aluminum and steel joint interface by the increase of temperature and time of heat treatments. The increase of temperature and time of heat treatment has been led to the activation of the permeation mechanism and formation of intermetallic compounds in the joint interface. Considering that intermetallic compounds have been formed while welding, this task leads to the higher facility in permeation of the aluminum and iron atoms when performing the heat treatment of the sample. Studies of Banker, Samadzic, and benak, showed that in the explosive joint of aluminum to steel, the width of the area of the intermetallic compound is to be increased by the increase of temperature and time of the heat treatments [15,21,22].

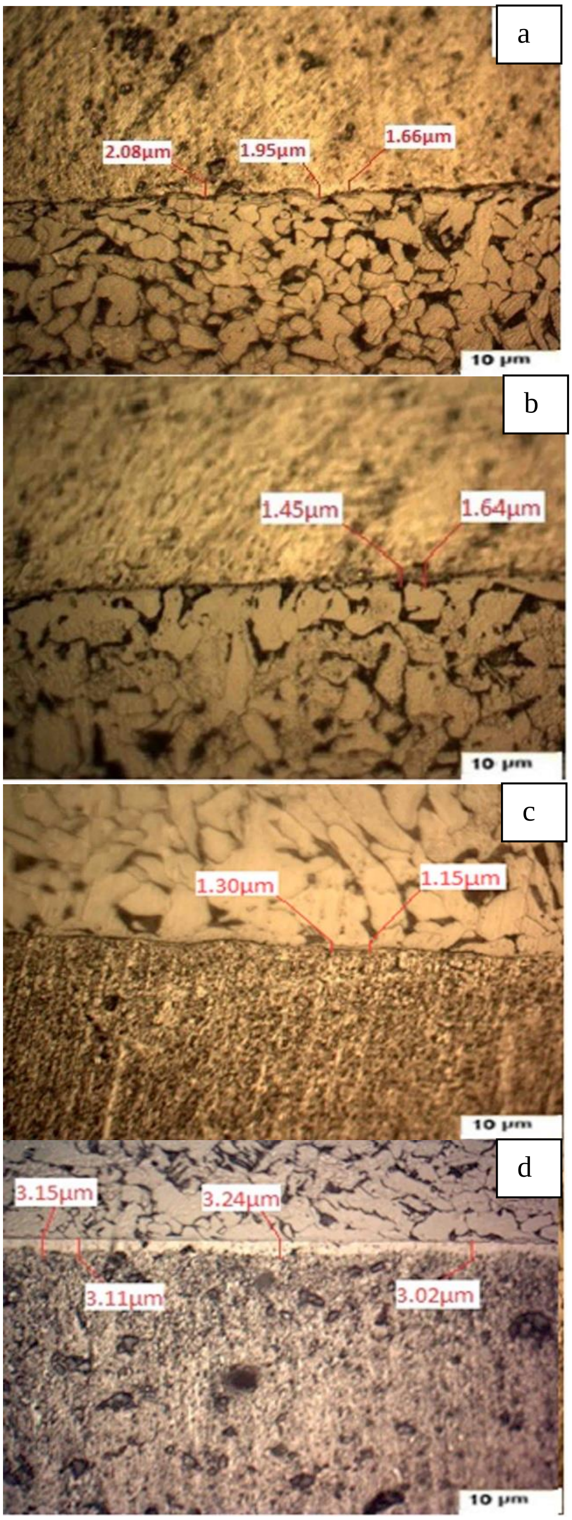


Fig. 2. The Joint interface of the samples before heat treatments in magnification of 500. a) The first sample b) The second sample c) The third sample.

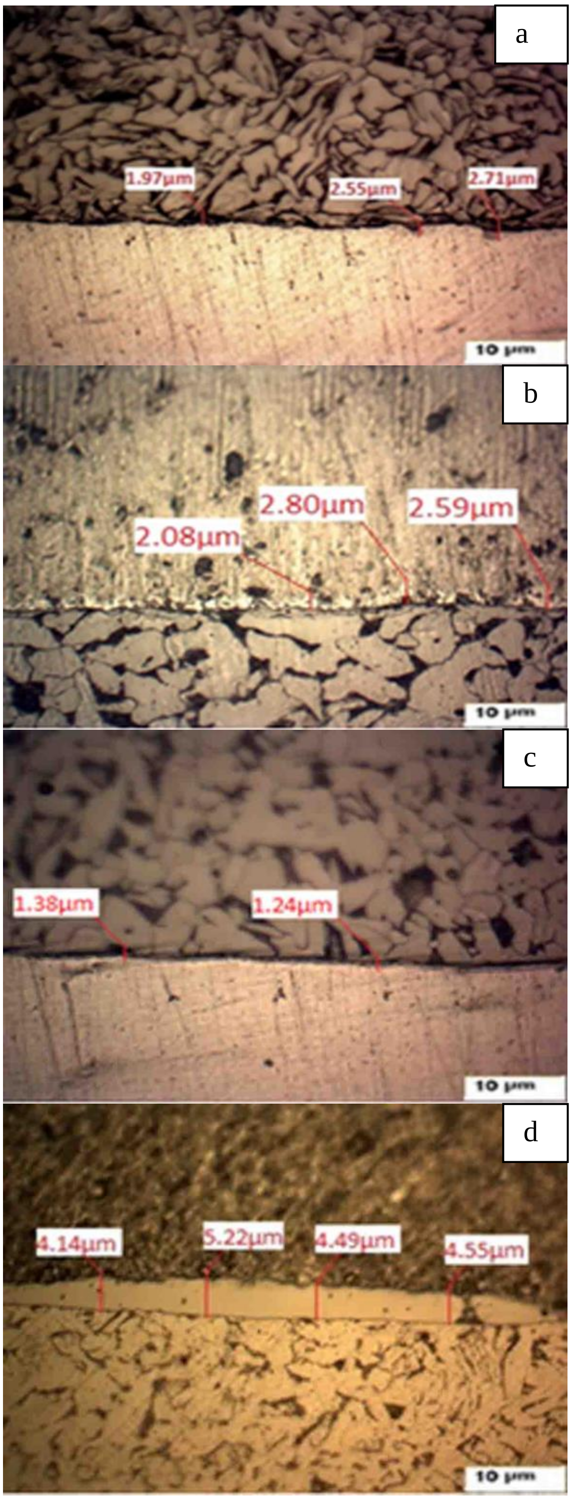


Fig. 3. The Joint interface of the samples after heat treatments in 315°C for 6 hours in magnification of 500. a) The first sample b) The second sample c) The third sample.

In Fig. 4., new phases are observed in the limited areas of the wavy interface by the increase of temperature of heat treatments. This middle phase is one of the characteristics of explosive welding established as a result of the establishment of local heat and cutting stress with a high rate of the joint interface [23].

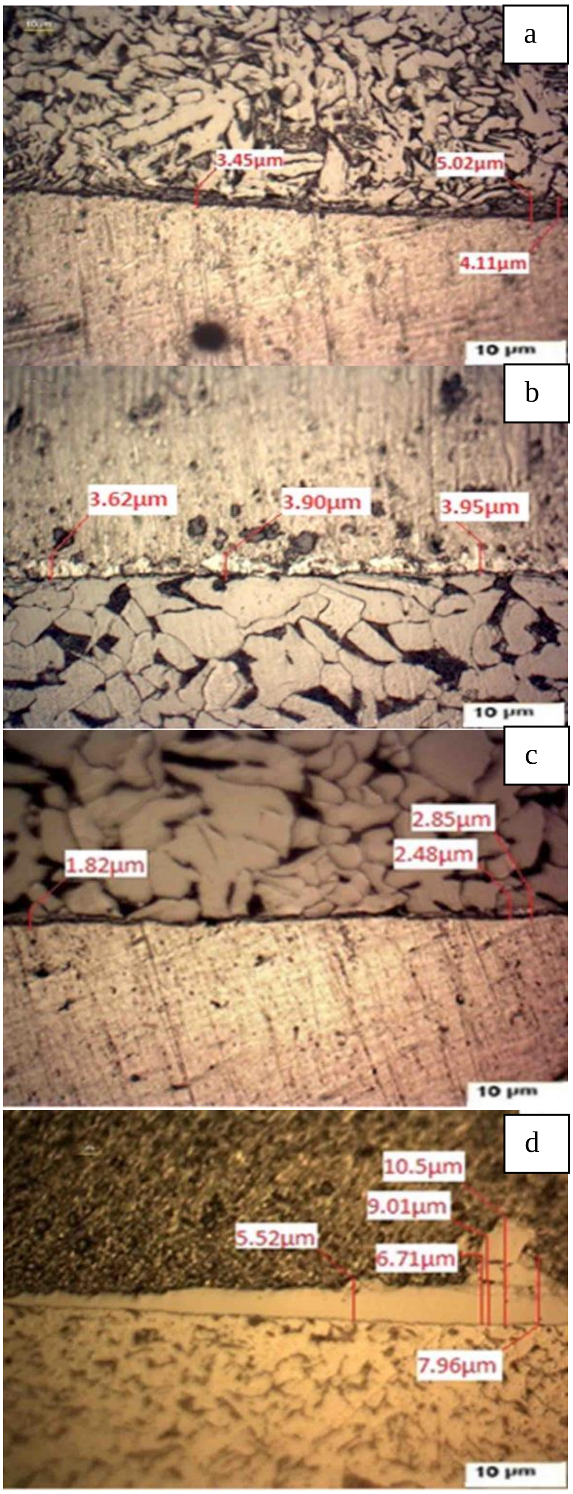


Fig. 4. Joint interface of the samples after heat treatments in 450°C for 6 hours in magnification of 500. a) The first sample b) The second sample c) the third sample.

layer placed under intensive form change shows itself in form of granule shape change in the metallography pictures. Generally, the granules have been dragged along the explosion. Consuming kinetic energy is one of the criteria applied for the determination of the plastic form change while performing explosive welding.

Thus, higher plastic change occurs in the interface by the increase of consuming kinetic energy. By the increase of plastic form change the behavior of the material is to be inclined towards higher fluidity which finally will be led to the establishment of waves with higher wavelength and amplitude.

In Table. 4., the effect of temperature and time increase of the heat treatments, the dynamic angle of collision, and the speed of spotty movement on the increase of intermetallic layer diameter is specified. It was observed that by the decrease of temperature, the diameter of the penetrative layer has had a less increase in the fixed time. Studies of Samardzic, Banke also showed that in the explosive joint of aluminum to steel, the width of the area of the intermetallic compound is decreased by the decrease of temperature and time of heat treatments [21,22].

In a comparison of intermetallic layer diameter of the first and third samples according to Table. 4. before heat treatments, it was seen that the stand-off distance between the base plate and intermediary plate of both two samples is equal, but the stand-off distance between the flying plate and intermediary plate of this two sample is different from each other and is higher in sample one.

Since the intensity of collision depends on two variables of mass and speed, consuming kinetic energy in sample 1 has been higher than sample3. In Table. 4., characteristics of explosive welding parameters have been expressed for the welded samples. Considering the increase of the consuming kinetic energy and higher stand-off distance, the intensity of collision and hit stroke in the first sample is higher than the third sample. Therefore, the size of the intermetallic layer and local fusion established in the first sample is higher than the third sample.

The average diameter of the layer of intermetallic compounds before heat treatments have been measured to be equal to 0.1± 1.89 micrometers in the first sample and 0.7±1.22 micrometers in the third sample.

After heat treatments, the diameter of the penetrative layer in the first sample under 315°C and 450°C for 6 hours is respectively equal to 0.3±2.41 and 0.6±4.19 micrometers and in the third sample is respectively equal to 0.07±31 and 0.4±2.38 micrometers. Considering Table. 4., it is specified that the permeation mechanism has become active in both two samples by the increase of temperature and time of heat treatments, and the formation of the intermetallic compounds and increase of penetrative layer diameter have shown an increase.

But, due to higher consuming kinetic energy and the stand-off distance of the first sample compared to the third sample, the intensity of collision hit stroke has been higher as well; therefore, the diameter of the intermetallic layer and the penetrative layer has become wider.

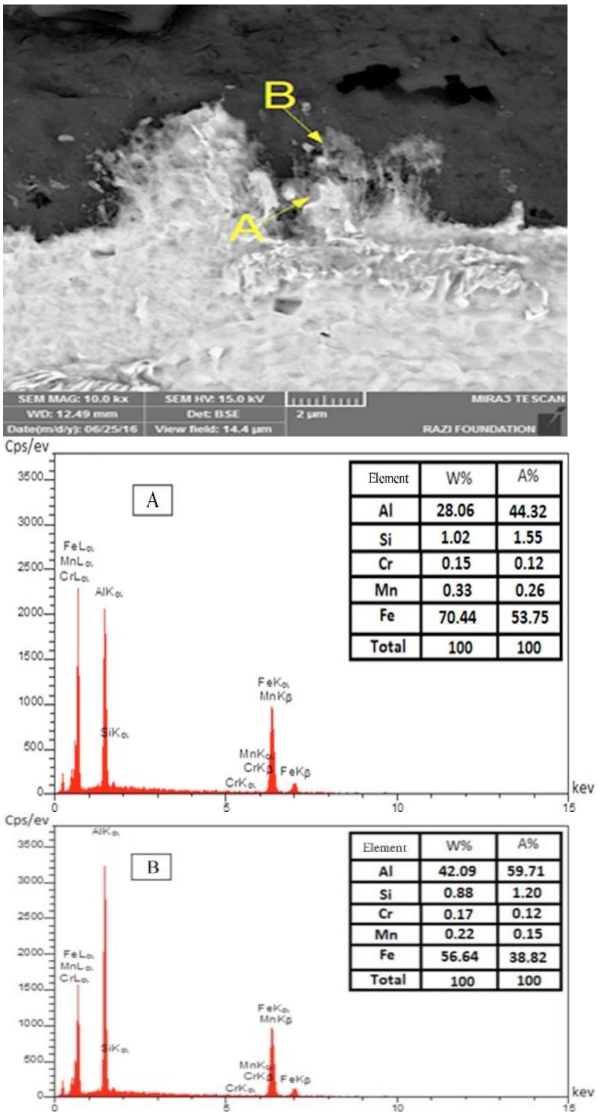
As it is specified in the pictures of photomicroscope, scanning electronic microscope, and also Fig. for sample No1 (The first sample) before heat treatments, the diameter of these layers is less compared to their diameter after the performance of heat treatments at 315°C and for 6 hours.

In Fig. 5. and Fig. 6., EDS analysis of the compounds available in the interface has been shown.

According to Fig. 5., two types of intermetallic compounds (A and B) were observed in the results achieved before the performance of heat treatments. Considering the ratio of the atomic percentage of elements in the obtained spots and the Iron-aluminum phasic diagram of these layers, the existence of Fe_3Al intermetallic compounds in spot A and $FeAl_2$ intermetallic compounds in spot B is probable [23,24].

Table. 4. Size of layer of intermetallic compounds in the samples of the first, the second and the third groups, (Cooled environment in air and time of heat treatment was 6 hr).

No of sample	Average of diameter after heat treatments in 450°C (µm)	Average of diameter after heat treatments in 315°C (µm)	Average of diameter before heat treatments (µm)	Stand-off distance between intermediary plate and base plate (mm)	Stand-off distance between flying plate and intermediary (mm) plate	Diameter explosive material (mm)
No1	4.19±0.1	2.41±0.3	1.89±0.1	8	10	2.41
No2	3.82±0.1	2.49±0.3	1.54±0.09	6	6	2.41
No3	2.38±0.1	1.31±0.07	1.22±0.07	8	8	2.41



A

Element	W%	A%
Al	28.06	44.32
Si	1.02	1.55
Cr	0.15	0.12
Mn	0.33	0.26
Fe	70.44	53.75
Total	100	100

B

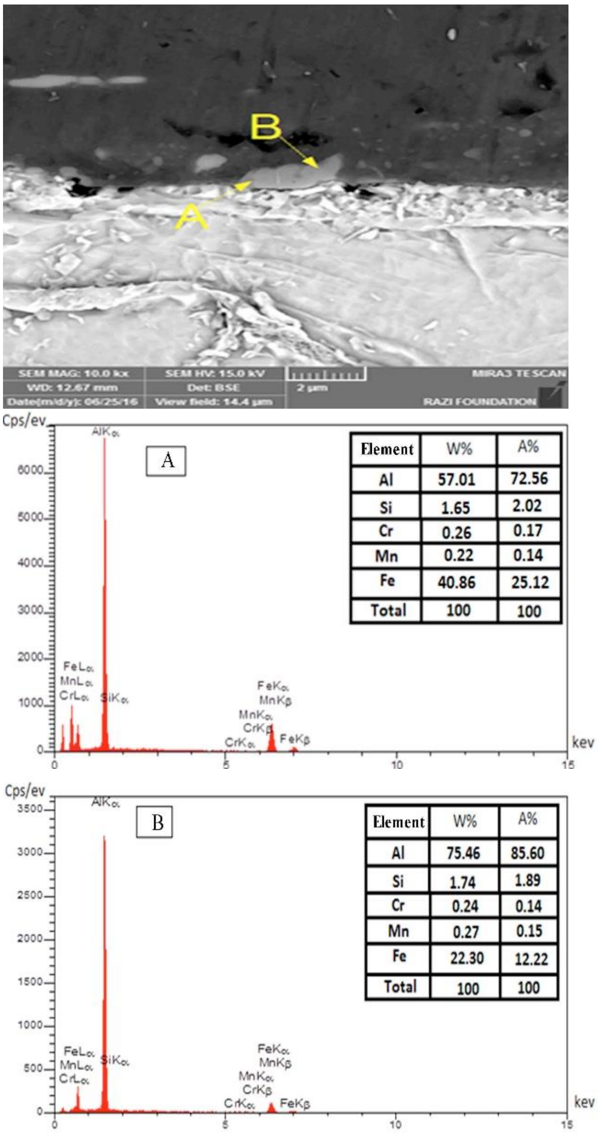
Element	W%	A%
Al	42.09	59.71
Si	0.88	1.20
Cr	0.17	0.12
Mn	0.22	0.15
Fe	56.64	38.82
Total	100	100

Fig. 5. Pictures of scanning electronic microscopy and EDS analysis from the intermetallic compounds specified in the interface of the first sample (Not- being heated operations).

The reason for this difference in spot A compared to spot B is the proximity of the compound to aluminum metal. In spot A compared to spot B is the proximity of the compound to aluminum metal.

Also, EDS analysis for the sample was accomplished from inside of the shown area.

The results of these analyses have been suggested by the establishment of a compound in the local areas of the alloy. For none homogeneous compounds and on the basis of jet reflection from the plate with less density, the pressure is exerted mainly on the plate with higher density, and therefore the vortex formed in behind of wave contains more materials of the base plate. Also, results show that the analysis of these compounds in the proximity of different waves has changed by the change of welding parameters and become none homogeneous. In area A shown in Fig. 6., the atomic percentage of aluminum compared to iron is respectively 72.56 and 25.20 and in area B, it is 85.60 and 12.22 respectively. Considering the Iron-aluminum phasic diagram, the analysis shows that the layer of the intermetallic compound in spot A is placed in the Fe_2Al_5 area and, in spot, B is placed in the Fe_4Al_{13}+FCC-Al area [7,12,23].



A

Element	W%	A%
Al	57.01	72.56
Si	1.65	2.02
Cr	0.26	0.17
Mn	0.22	0.14
Fe	40.86	25.12
Total	100	100

B

Element	W%	A%
Al	75.46	85.60
Si	1.74	1.89
Cr	0.24	0.14
Mn	0.27	0.15
Fe	22.30	12.22
Total	100	100

Fig. 6. Pictures of scanning electronic microscope and EDS analysis from the intermetallic compounds specified in the interface of the first sample (Being heated operations in the 315°C and time span of 6 hours).

Fig. 7. has shown the picture of crack and dark-colored tiny holes in the joint area of the interface of the second sample with 450°C heat treatments. By the increase of heating, empty places have joined together and also the density of the spotty defects has increased due to the passage of the shocking waves. Since the penetration of atoms is performed more by the empty place mechanism, the thermodynamic balance of empty place, while penetrating has been disrupted by an increase of

temperature, and a few empty places have been added to the system to reach balance; then, empty places are attached, forming the hole and crack [12]. One of the characteristics of the middle phase in the interface, contrary to many alloy pairs mentioned in the resources, is in the existence of crack or each sort of the other disconnections in it. Usually, the melted knots established in the interface are frozen at a high rate because of proximity to a great metal mass which, thus, will be led to the establishment of freezing cracks or defects.

In Fig. 8., Map Scan analysis of the first sample is observed. Also, in this analysis, the method of distribution and rate of penetration of elements can be observed clearly. By progression from aluminum direction to steel direction, the ratio of aluminum penetration has been decreased.

Blue colored areas, red-colored areas, yellow-colored areas, and dark-colored areas specify the rate of iron distribution, the rate of aluminum distribution, the rate of silicon distribution, and rate of formation of intermetallic compounds and aluminum- steel penetration respectively.

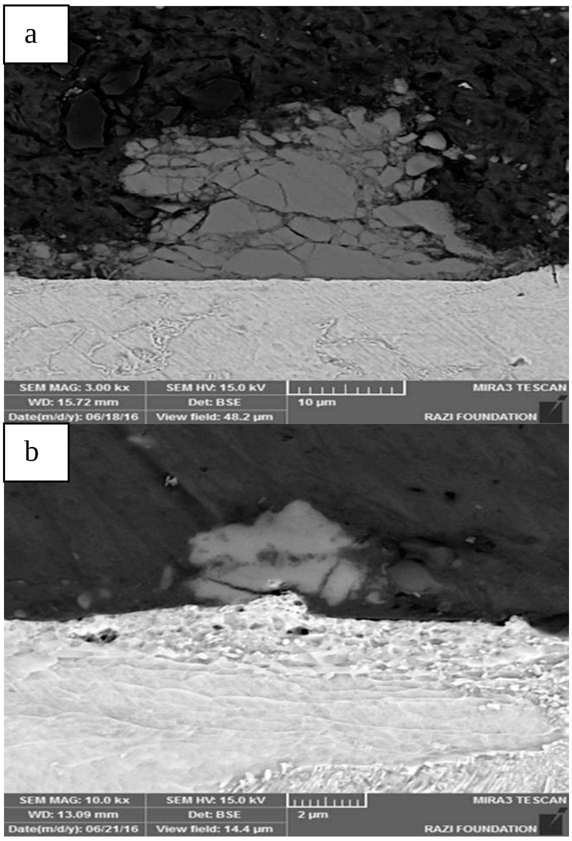


Fig. 7. EDS analysis of pictures of the scanning electronic microscope from crack and tiny holes in the interface of the second sample of heated operations in 450°C and time span of 6 hours.

The taken analysis showed that by the increase of temperature and time, the mechanism of penetration and formation of the intermetallic compound in the joint interface becomes active.

The formation of intermetallic compounds, while performing explosive welding in the fourth sample has been led to the higher facility of penetration of aluminum and iron atoms when conducting the heat treatments of the samples according to the analysis. In some sections, the formed intermetallic layer includes a few layers from various compounds that this affair will be led to the crispness of the sample.

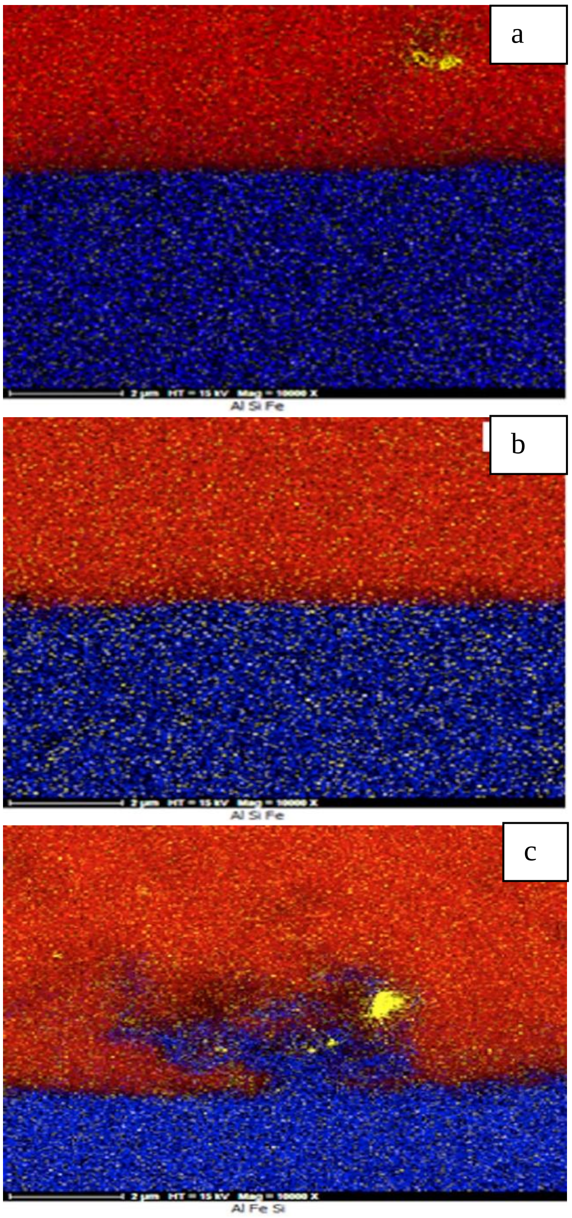


Fig. 8. Map scan pictures of the scanning electronic microscopes from intermetallic compounds specified in the interface in the first sample: a) sample of not – being heated operations b) sample of heated operations in 315°C and time span of 6 hours c) sample of heated operations in 450°C and time span of 6 hours.

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In the hardness profile, a few main factors lead to an increase of hardness in the areas surrounding interface. A principal factor in the increase of hardness is the occurrence of plastic form change occurring in the layers next to the interface. As it is observed in Fig. 9. For sample No 2 before carrying out heat treatments, the hardness maximum relates to the steel layer at a distance of 25 micrometers from the interface in the explosive weld sample. At this distance, the hardness of the steel section has reached 266 Vickers and the hardness of the aluminum section has reached 66.4 Vickers. The increase of hardness in the spots of the interface is due to the establishment of plastic bowing down curvature and the impact of the shock resulted from the explosion wave on the surface of the joint. The increase of microhardness of the joint interface by an increase of stand-off increase had been reported by other researchers, including Akarer, Durghotlu, and Tricarico [2,7,25]. In addition to hardness at a distance of 25 micrometers from aluminum- steel joint interface, some increase is observed in other sections as well so that the hardness of steel in spots of 50, 75, and 100 micrometer is 240, 233, and 228 Vickers and in the aluminum section of joint with these same distances of the interface is 64.3, 60.2 and 53.8 Vickers, respectively. This hardness increase is due to the impact of shock resulted from returned waves. After the performance of heat treatments in temperatures of 315°C and 450°C and a time span of 6 hours, it was observed that amounts of hardness in various layers have been decreased due to hardness work and plastic transformation (form change) in direction of thickness of the heat-treated samples. By the increase of temperature and possibility of elimination of linear and spotty defects resulted from the passage of shock waves and release of residual tensions originated from welding, détente has been accomplished and led to a decrease of the microhardness of the samples following the performance of heat treatments [26,27].

Considering the heat treatments and impact of the increase of temperature and time on the increase of the elements penetration mechanism, the rate of microhardness of interface has been increased and higher [7,25]. In Fig. 10., hardness changes of the samples have been shown before and after heat treatments in the third sample under temperatures of 315°C and 450°C and a time span of 6 hours.

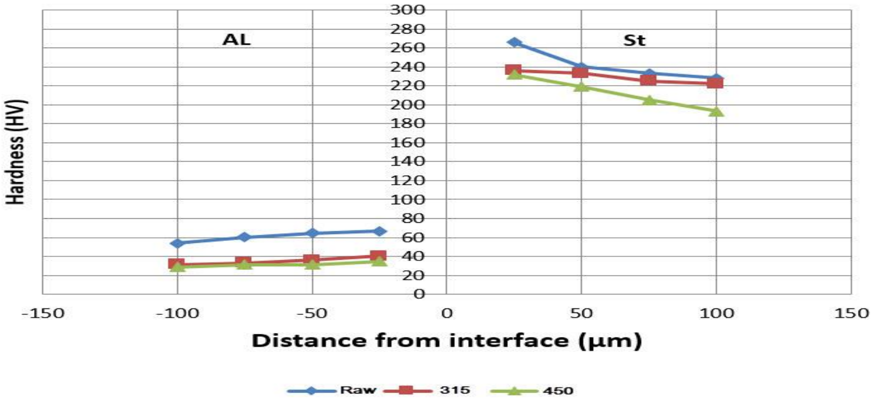

Fig. 9. Changes in hardness in the various sections (Time frames) of the second sample before and after heat treatments.

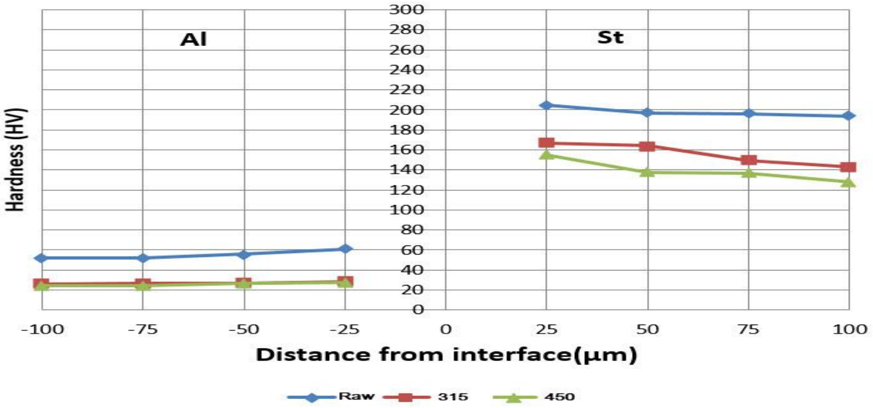

Fig. 10. Changes in hardness in various sections (Time frames) of sample No 3 before and after the heat treatments.

Table. 5. Study of numerical results achieved from the conducted tests.

No3	No2	No1	Test No
8	10	8	**Stand-off distance of aluminum and steel plates**
2.41	2.41	2.41	**Explosive load**
0.2±1.91	1±2.45	0.5±2.33	**Average diameter of intermetallic compounds area before heat treatments (μm)**
0.3±1.31	0.2±2.54	0.7±2.41	**Average diameter of intermetallic compounds area after heat treatments in 315°C (μm)**
0.3±2.71	0.4±3.86	0.2±4.67	**Average diameter of intermetallic compounds area after heat treatments in 450°C (μm)**
197	240	-----	**Microhardness of the steel section sample before heat treatments at distance of 50 μm (HV)**
164	233	-----	**Microhardness of the steel section of sample after heat treatments in 315°C at distance of 50 μm (HV)**
137.7	219	-----	**Microhardness of aluminum part of sample after heat treatments in 450°C at distance of 50 μm (HV)**
55.9	64.3	-----	**Microhardness of aluminum part of sample prior to heat treatments at distance of 50 μm (HV)**
27	35.8	-----	**Microstructure of aluminum part of sample following the heat treatments in 315°C at distance of 50 μm (HV)**
26.8	31.4	-----	**Microstructure of aluminum part of sample after heat treatments in 450°C at distance of 50 μm (HV)**

As observed, the rate of microhardness in the sample No 3, before heat treatments, at a distance of 25, 50, 75, and 100 micrometers are equal to 205, 197, 196, and 194 Vickers in the steel section respectively, and 60.9, 55.9, 52.2, and 52 Vickers in the aluminum section. This hardness increase is due to the impact of shock resulted from the returned waves. It is natural that by the implementation of heat treatments, it is expected that the hardness peak of the interface is eliminated. By the increase of temperature of heat treatments, hardness amounts have been dropped because of a decrease of tensions available in the interface and also recrystallization of the granules. After the performance of heat treatment in the temperature of 315 and 450°C and period of 6 hours, it was observed that due to hardness work and plastic transformation (shape change) of the diameter of the samples under heat treatments, amounts of hardness have decreased in the various layers. The rate of the hardness of the sample in temperature of 315°C and period of 6 hours in the steel section and distance of 25, 50, 75, and 100 have been reported to be equal to 167, 164, 149.7, and 143.1 Vickers respectively and 28.2, 27, 26.4 and 26.3 Vickers in the aluminum section.

By the fulfillment of heat treatments in 450^{0}C for 6 hours, this quantity has been decreased up to 155, 137.7, 136.9, and 127.7 Vickers in the steel part and 27.5, 26.8, 24.4, and 24.3 Vickers in the aluminum part respectively. By the increase of temperature of heat treatments, amounts of hardness have been dropped due to the decrease of stresses available in the interface and recrystallization of the granules.

Microhardness is a function of chemical compounds, the percentage of alloy elements, intermetallic compounds, heating changes, explosive load, and stand-off distance [14,25]. By the increase of temperature and possibility of elimination of linear and spotty defects resulted from the passage of shock waves and release of residual stresses originated from welding, détente (stress- elimination) has been accomplished and led to the reduction of samples microhardness after the performance of the heat treatments [26,27]. Considering the presented table, the reason for the decrease of microhardness of sample 3 compared to sample 2 is that decrease of stand-off distance has decreased the speed of movement of the flying plate and dynamic angle of collision and therefore collision kinetic energy has been decreased as well, and the less plastic transformation shape change has been established in the joint interface leading to decrease of shock hardness resulted from waves of the microhardness explosion [25, 28].

Table. 5. shows a summary of the observed results, and it has been observed in the results that in the samples of heated operations, the movement speed of flying plate and dynamic angle has been increased by the increase of stand-off distance leading to increasing of collision kinetic energy, the establishment of intensive plastic transformation in the joint interface and enhancement of the shocked hardness resulted from explosive waves of the hardness of the sample before the performance of heat treatments. Following the heat treatments, this hardness has been decreased.

4. Conclusions

In this research, the impact of heat treatments on the intermetallic compounds of the explosive joint interface of three aluminum- steel layers and it’s properties with various stand-off distance was investigated and the following resulted were achieved:

1. Results of metallography show that steel-aluminum interfaces changes from the simple state into wavy state and vortex wavy state, and the conversion of these interfaces is conducted considering the change of stand-off distance in the sheets/ plates and explosive load.
2. Local fusion areas near the waves in the aluminum- steel interfaces have been established due to the increase of the stand-off distance and the increase of collision energy which this area has been converted into a joined fusion bond in the test sample with stand-off distances of 8 mm and 10 mm.
3. By the increase of temperature of heat treatments, the mechanism of penetration becomes active and the diameter of the penetrative and intermetallic layer has been increased remarkably and the intermetallic layer formed in some parts includes a few layers of various compounds, leading to the crispness of the sample.
4. The performance of heat treatments at a temperature of 450°C for six hours has decreased the rate of microhardness in samples 2 and 3 compared to the rate of that before the performance of the heat treatments. This has been due to the elimination of spotty defects resulted from the passage of shock waves, the performance of annealing heat treatments, and the decrease of residual stress originated from welding.
5. By the increase of temperature of heat treatment from 315°C to 450°C, the rate of microhardness in the tested spots has been decreased because of the increase of penetration of elements and also the decrease of aluminum in the intermetallic compounds and increase of the diameter of the intermetallic compounds layer.
6. By increasing the temperature of heat treatments from 315°C to 450°C, dark-colored tiny holes in parallel with the interface have been established considering high penetration speed difference, disruption of the thermodynamic balance of empty place and higher joining of them with one another due to heat.
7. After the performance of heat treatments, the concentration of stress and cracks has been increased and thus strength decreased by the increase of heat up to 450°C and increase of the diameter of the intermetallic compounds layer.

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