

## Effect of Stand-Off Distance on the Mechanical and Metallurgical Properties of Explosively Bonded 321 Austenitic Stainless Steel - 1230 Aluminum Alloy Tubes

Mohammad Reza Khanzadeh Ghareh Shiran<sup>a\*</sup>, Haimd Bakhtiari<sup>b</sup>, Seyed Ali-Asghar Akbari Mousavi<sup>c</sup>,  
Gholamreza Khalaj<sup>d</sup>, Seyed Majid Mirhashemi<sup>e</sup>

<sup>a</sup> Center for Advanced Engineering Research, Majlesi Branch, Islamic Azad University, Isfahan, Isfahan Province, Iran

<sup>b</sup> Advanced Materials Research Center, Faculty of Materials Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Isfahan Province, Iran

<sup>c</sup> Department of Metallurgy and Materials Engineering, School College of Engineering, University of Tehran, Tehran Province, Iran

<sup>d</sup> Young Researchers and Elites Club, Saveh Branch, Islamic Azad University, Saveh, Markazi Province, Iran

<sup>e</sup> Department of Materials Engineering, Science and Research Branch, Islamic Azad University, Tehran, Tehran Province, Iran

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In this research, the effect of stand-off distance on the interfacial mechanical and metallurgical properties of explosively bonded 321 austenitic stainless steel to 1230 aluminum alloy tubes was investigated. Interfacial microstructure was evaluated by optical microscopy and scanning electron microscope. Also, Microhardness tests were also carried out. The results show that with increasing of stand-off distance from 1 mm to 2.5 mm, thickness of intermetallic compounds at the interface increased from 3.5  $\mu\text{m}$  to 102.3  $\mu\text{m}$ , and also shape of interface was transited from smooth to wavy. The microhardness of the sample with 1 mm stand-off distance was 650 HV that increased to 927 HV in the sample with 2.5 mm stand-off distance which is related to intermetallic amount. The proportional amount of strength were 103.2 MPa and 214.5 MPa in the above samples respectively.

**Keywords:** *explosive welding, stand-off distance, intermetallic compound*

### 1. Introduction

Bonding of the stainless steel to aluminum can be effective on the industrial applications due to influence on weight decrease, heating and electrical conduction and strength. Coating of the stainless steel with aluminum via common welding methods, including melting processes is very difficult due to difference in their temperature, physic chemical properties and atomic layers. Establishment of layer of frangible intermetallic compounds, crystal layers and galvanic corrosion at the interface of bonding of the stainless steel to aluminum is out of these problems, as an example<sup>1,2</sup>.

Explosive welding is one of the appropriate processes in order to bond non-homogeneous substances which, through decrease of surface layers of the impurities, establishes metallurgical contact, and very high pressure in the collision point provides conditions of the interface contact. In this method, only compound of the metals in interface gets involved in the metallurgical changes and this is a state-of-solid process which is performed by use of high explosive force and formation of jet. As a result of collision of the flyer plate with base plate with high speed, the exercised pressure in the collision point reaches a quantity in GPa limit, leading to fluid-like behavior of the metals<sup>3,4</sup>.

High input heat, heating and electrical conductivity difference and various thermal capacity of iron and aluminum lead to establishment of stress and formation of intermetallic frangible layers between iron (Fe) and aluminum (Al) while melting and freezing in the interface. In bonding of austenitic stainless steel (FCC) to Al (FCC), intermetallic phases are established with high hardness and low flexibility. Thicknesses of these layers play a basic role in achievement of an appropriate bonding. Therefore, reduction of thickness of layer in the intermetallic compounds of Fe-Al is the most important ongoing problem. Probably, reason for brittleness of metal crystals with unique compounds is that these materials lack the required ability to form the surfaces of slippage; or that; furthermore, possibility of formation of crack exists in them as well. Intermetallic compounds are formed for this reason that strength of connection/bond among the related dissimilar atoms is higher than the strength of connection among similar atoms. Thus, particular crystal structures with regular atomic dispersals are made among the metal in which each atom has been surrounded by dissimilar atoms preferably<sup>5</sup>.

The interface established between steel and aluminum, mainly due to difference in rate of density of two metals, is in wavy form and, under specific conditions, smooth interface can be established as well, and inclination toward creation of state of wavy turmoil and possibility of establishment

\* e-mail: [m.khanzadeh@iaumajlesi.ac.ir](mailto:m.khanzadeh@iaumajlesi.ac.ir)

of eddy in interface of bonding of these two metals is to be developed due to difference density. By the way, due to existence of turmoil/ disturbance in the interface of bonding of these two metals and instable conditions in interface, formation of intermetallic compounds in interface of bonding of these two metals is possible<sup>6</sup>. Due to establishment of stress concentration conditions, these intermetallic compounds in the interface of bonding of two metals may be effective on the strength properties of interface of two alloys. As shown in (Figure 1), this effect is subject to percentage of rate and how to distribute these compounds in the interface of bonding.

These intermetallic medial layers have been usually identified by their very high hardness which several times over hardness of each one of the metals, including iron and aluminum. For example, researches of Tricarico<sup>6</sup> have shown that intermetallic compounds, including  $\text{FeAl}_3$  and  $\text{Fe}_2\text{Al}_3$ , with approximate hardness of 740-900 HV have been established in the bonding area as well, and thickness of these layers depended on welding conditions has been reported up to 100  $\mu\text{m}$  approximately. On the basis of viewpoints of Sauthoff<sup>5</sup>, one of the basic parameters influencing on the formation of the intermetallic compounds is rate of the plastic bowing down of the welded elements as a result of shock wave developed during explosive welding process. Ian Leszczynski<sup>7</sup> believe that these created layers are U-Technique phase of  $\text{Al}+\text{FeAl}_3$ , and rate of  $\text{FeAl}_3$  is increased by heat increase in the interface.

Also, they have referred to this point that  $\text{Fe}_2\text{Al}_3$  phase may have been developed in the interface of bonding. Also, researches have shown that hardness in the smooth interface

in two-part bonding of Al/steel is less than wavy shape that this subject is due to the lessness of rate of bowing energy inculcated in smooth interface compared to bowing energy inculcated in wavy interface. As a result, very little energy has been available in order to form uncommon phases and phenomenon permeation and establishment of intermetallic compounds between two interfaces of bonding of Al/steel. In study of interface of bonding of steel to aluminum, six kinds of intermetallic compound being of Fe-Al type are observed shown in Table 1 so that, in areas next to the steel, the compound is saturated by iron and, in areas to aluminum, the compound is saturated by aluminum. In fact, compounds with high hardness (Higher than 800 HV) and with intermetallic compounds full of aluminum are factor of brittle interface<sup>6,7</sup>.

## 2. Materials and Research Method

The alloys used in the explosive welding process are taken into account for the purpose of establishment of two-part tube, 321 austenitic stainless steel and 1230 aluminum alloy which their chemical compound has been shown in Table 2. 321 austenitic stainless steel with length of 200 mm, thickness of 4.5 mm, internal diameter of 126 mm and external diameter of 135 mm has been selected as the base tube and 1230 aluminum alloy tube as the flyer tube in the explosive welding which dimensions of the samples have presented in Table 3. The metal aluminum had low strength and thickness; therefore, it was placed inwardly as the flyer

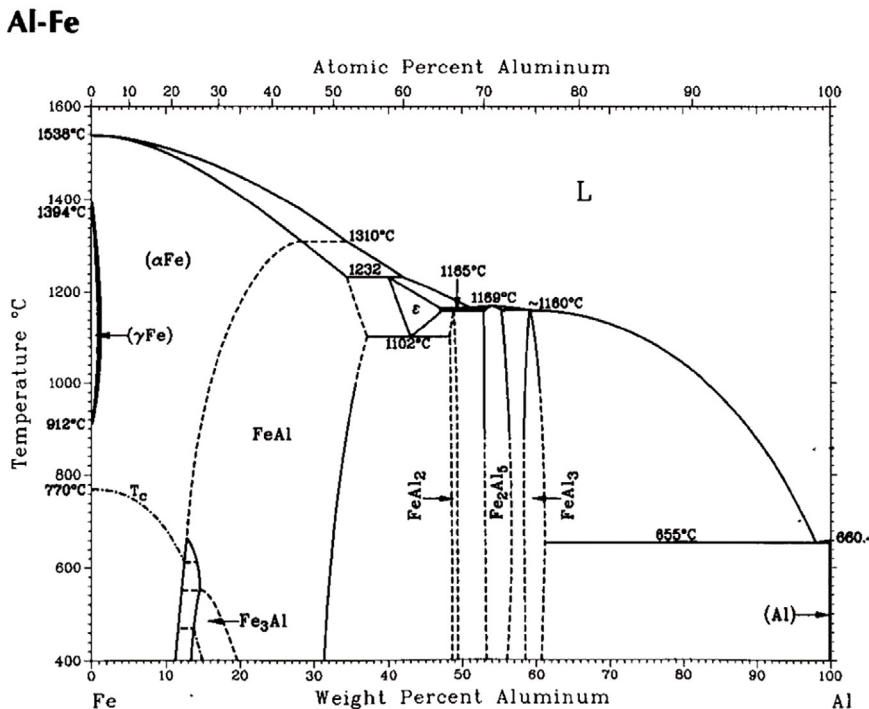


Figure 1: Phase diagram Fe-Al<sup>6</sup>

**Table 1:** Intermetallic compounds Fe-Al <sup>7</sup>

Density (gcm <sup>-3</sup> )	Micro hardness(HV)	Structure	Quantity Al (at-%)	Phase
6.67	250 - 350	bcc	25	Fe <sub>3</sub> Al
5.37	400-520	bcc	50	FeAl
...	650-680	bcc	63	Fe <sub>2</sub> Al <sub>7</sub>
4.36	1000-1050	Rhombohedral	66/67	FeAl <sub>2</sub>
4.11	1000-1100	Orthromobic	69.7-73.2	Fe <sub>2</sub> Al <sub>5</sub>
3.95	820-980	Monoclinic	74-76	FeAl <sub>3</sub>

**Table 2:** Chemical compound of the explosive welding tubes

Element (wt-%)	C	Si	Mn	P	S	Mg	Cr	Ti	Ni	Cu	V	Zn	Al	Fe
AISI321	0.08	0.75	2	0.04	0.03	...	18	...	10.5	...	...	...	...	Balance
AA1230	...	0.7	0.05	...	...	0.05	...	0.03	...	0.1	0.05	0.10	Balance	0.7

**Table 3:** Dimensions of 1230 aluminum tube

No of tube	Length (mm)	Thickness (mm)	External dia. (mm)	Internal dia. (mm)
1	240	1.5	121	124
2	240	1.5	120	123
3	240	1.5	119	122
4	240	1.5	118	121

tube so that bonding is to be performed easily by the plastic deformation resulted from explosion.

Quantity of hardness of the austenitic stainless steel and aluminum was 200 and 40 HV, respectively. In order to bond the samples, explosive material of Amatol with compound of trinitrotoluene (T.N.T) and aluminum nitrate was used. For the purpose of bonding of the samples No 1 and No 2, compound of 79% aluminum nitrate and 21% T.N.T with explosion speed of 3650 m/s was used and, for samples No 3 and No 4, compound of 95% aluminum nitrate and 5% T.N.T with explosion speed of 2504 m/s was used.

This research has carried out experimentally in which stand- off distance was selected as variable. Four stand- off distance of 1, 1.5, 2 and 2.5 mm were considered for bonding of the samples of No 1 to No 4, respectively. In (Figure 2), regulatory system of this research which is in form of load/ explosion from internal and explosion to external welding has been shown. Characteristics of the welding tests have been shown in Table 4.

For the purpose of structural studies, the samples were sand papered by emery No 60 to 2500 firstly and, after polishing with aid of the diamond-like dough and/or Al<sub>2</sub>O<sub>3</sub> solution, they were studied and observed under various magnifications in the interface area and intermetallic compounds established in it by optical microscope, scanning electron microscope and EDS analysis (Energy Dispersive x-ray spectrometry). In order to prepare one sample according to (Figure 3), sample were isolated by hand stone or mill/cuter, and the isolated samples become mount (were mount) by the apparatus. After polishing, their surface was washed by alcohol and

dried, and then they became etched chemically by solution of (Glycerin + Nitric acid, Chloride acid). Thickness of layer of intermetallic compounds, were measured as well. Shape of interface and intermetallic compounds were analyzed by optical microscope, Metallux 3 model.

In order to study mechanical properties of the samples, mechanical tests, including test of tensile, shear and microhardness strength were carried out on the welding samples. In order to evaluate tensile shear properties, some samples were provided on the basis of standard of the ASTM D 3165-95<sup>8</sup>. This test was carried out by the Instron apparatus. According to this standard, the samples must be designed in such a manner that both flyer metal and base metal have a groove with an appropriate distance from each other. Length of the test area (L) can be considered as a variable, but the length suggested in the standard is 12.7 + 0.3 mm. Also, distance of edge of the apparatus's jaw up to edge of the groove in each metal is in a range from 50.8 mm to 63.5 and distance of direction of placement of the apparatus's jaw on the sample is equal to 25.4 mm. Rate of the tensile force in this standard has been determined to be 1.27 mm/min. Dimensions and apparent shape of the samples, according to the standard, have been shown in (Figure 4).

Vickers microhardness test, by Buhler model apparatus, with an implemented force of 50 gr was carried out on the basis of ASTM E 384-11<sup>9</sup> from various areas of thickness of the intermetallic layer, and average of three microhardness of the sample's intermetallic compounds for the purpose of performance of comparison and, also, effect of the stand- off distance on them.

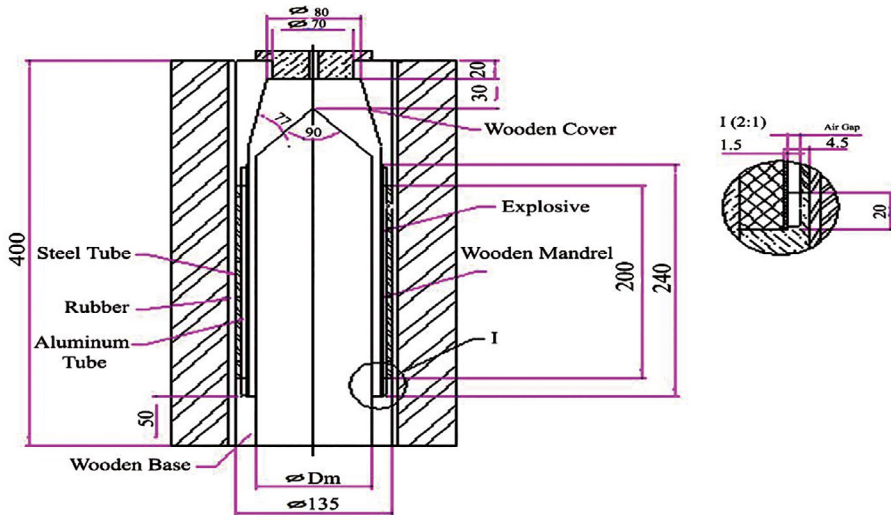


Figure 2: Regulatory system of explosive welding

Table 4: Characteristics of the explosive welding tests

Test No	Stand-off distance	Thickness of the explosive material (mm)	Explosive material	Explosion speed (m/s)	External dia. of Flyer pipe (mm)	Internal dia.of base pipe (mm)
1	1	10.7	Amatol	3650	124	126
2	1.5	10.8	Amatol	3650	123	126
3	2	7	Amatol	2504	122	126
4	2.5	6.95	Amatol	2504	121	126

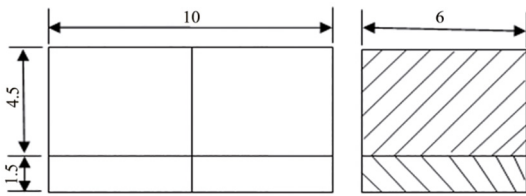


Figure 3: Dimensions of the metallographic samples

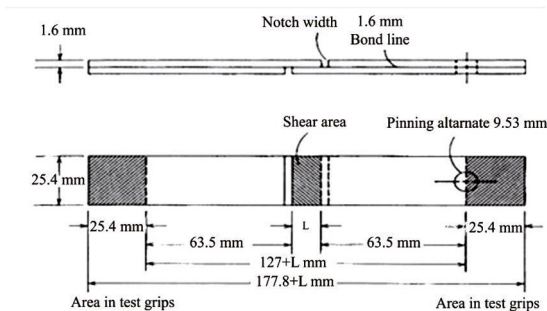
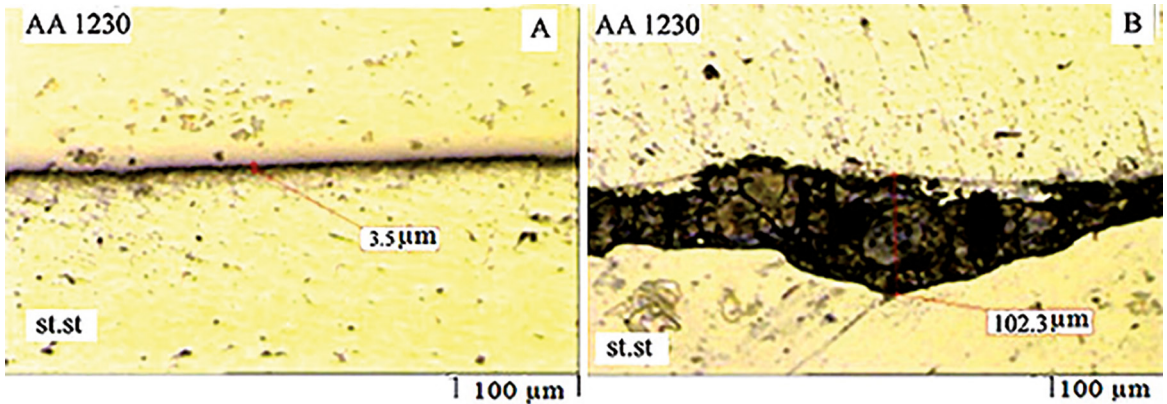


Figure 4: Shape and dimension of the sample in order to carry out tensile-shear test according to the standard ASTM D 3165-95<sup>8</sup>

### 3. Results and Discussion

#### 3.1 A Study of Micro Structure Optical Microscope

Microstructures of the samples and their interface have been shown in (Figure 5). Figure 5(a) shows bonding interface in the sample with stand- off distance of one mm which is almost smooth and very little amount of the intermetallic compounds is observed in it, yet in the sample with stand-off distance of 2.5 mm shown in the (Figure 5(b)), shape of interface has been transited from smooth to wavy. As shown in (Figure 5), thickness of layer of intermetallic compound in interface of the samples' bonding has been increased by increase of stand-off distance. Due to increase of stand-off distance and thickness of explosive force, speed of the flyer plate has increased and higher plastic deformation has occurred in the interface of bonding. By increase of the collision's speed, collision pressure has been increased and dynamic angle of collision and consumed kinetic energy in the collision point has been increased as well. A part of the consumed kinetic energy in the interface turns into potential energy and causes that the sheets transform within collision



**Figure 5:** Interface of the samples' bonding with different stand- off distance. (a) AS1 sample with stand- off distance of 1 mm. (b) AS4 sample with stand- off distance of 2.5 mm.

surface; by increase of the consumed kinetic energy, higher plastic deformation is established in the interface and, through this increase, behavior of the material has inclined toward more fluidity led to establishment of the waves with more wave and amplitude in the interface. Increase of stand- off distance and dynamic angle of the collision has led to increase of deformation of the flyer plate while colliding and a more intense deformation has established in the interface. Increase of collision speed has been led to raising of pressure from proof stress of two metals in the collision point. Speed of the flyer plate's movement has been increased by increase of stand- off distance and explosive force and, also, due to existence of difference in density and speed of wave's movement in the metals, pressure momentum in two directions of the interface has changed by increase of speed of the flyer plate's movement, and, as a result, collision point, while bonding, has been involved in oscillation. By increase of the collision speed, these oscillations have increased, and materials, in proximity to the collision point, have lost their strength in higher volume and shown quasi-fluid plastic behavior<sup>10,11</sup>.

As a result, wave length in the interface of bonding has been increased gradually by increase of the collision speed.

### 3.2 A study of microstructure by scanning electron microscope

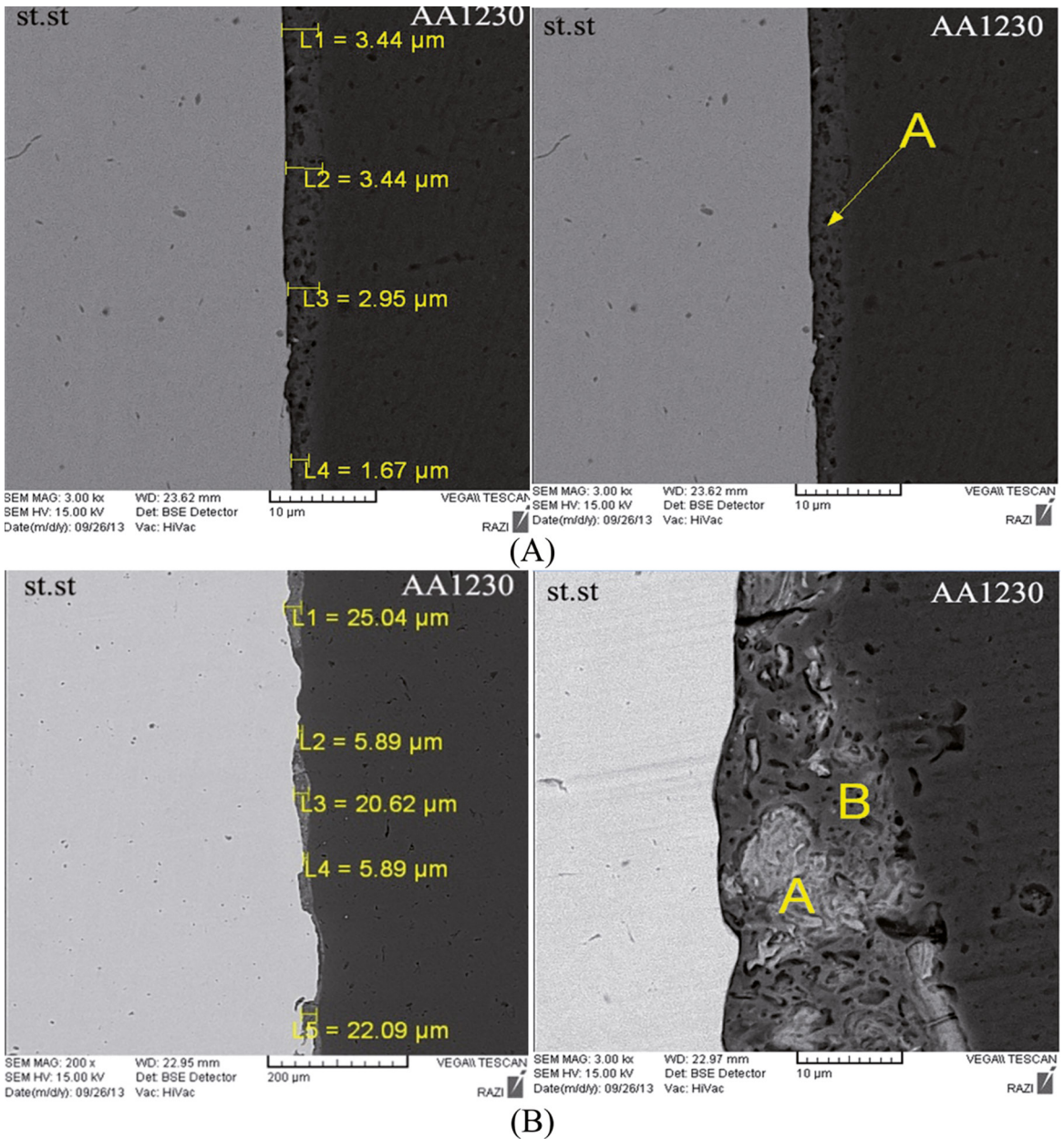
(Figure 6(a)) has shown pictures of scanning electron microscope regarding AS1 sample interface and thickness of the layers in some points. In the obtained results, it has been observed that compound of the area includes 96% of atomic aluminum and 2.2% of atomic percent. (Figure 6(b)) has shown microstructure of interface and intermetallic layer of AS2 sample with stand- off distance of 1.5 mm. Thickness of layer of intermetallic compounds is 6-25  $\mu\text{m}$  approximately which has been increased compared to thickness of layers of AS1 sample.

Two kinds of A and B intermetallic compound in this layer was specified by analysis. In (Figure 7), analysis of

their elements has been presented. In B point, the compound includes 92.2 (percentage of) aluminum and 4.6 (percentage of) iron.

Reason for this much difference is closeness of this compound to aluminum metal, but, in point A next to austenitic stainless steel, their atomic proportion is 3:1. Interface of bonding of aluminum to steel is asymmetrical due to the density difference of two wavy-eddy alloys. Also, due to highness of the stand- off distance among aluminum plates and higher collision speed of the flyer plate, higher collision kinetic energy has been transferred to interface and led to establishment of wavy-eddy-shaped interface. In the explosive welding, two metal to metal and metal to frozen molten interfaces can be achieved in the interface. As a result of collision of the flyer plate, consumed kinetic energy has been converted into potential energy and led to deformation of the collision surfaces. If amount of the plastic deformation is not enough, short waves are established and positional melting area is not appeared. By increase of collision kinetic energy, intense deformation is occurred beneath the wave and it's corona, and, as a result of the high collision pressures, vortexes/eddies are formed in the interface of bonding and these vortexes may create topical/ positional melting areas in some areas of interface. According to Zolbin<sup>12</sup>, internal heat formed on the basis of high pressure resulted from shocking waves of explosion, intense plastic deformation and creation of lack-of-exit heat as a result of the vortex caught in front of some waves has been established due to deformation from kinetic energy into heating energy during confrontation and/or adiabatic heat arisen from the gases imprisoned among the plates.

These positional regions have been surrounded by the around cold metal, and they are under a high cooling speed about  $10^5$ - $10^7$  °k/s. These small regions have been observed in proximity to vortex/eddy of waves of (Figure 6(b)). Also, EDS analysis for the sample was accomplished from inside of the shown region related to the front of the established vortexes. Results of these analyses observed in (Figure 7)



**Figure 6:** Pictures of the SEM from the changes of thickness and intermetallic compounds specified in the interface. (a) AS1 sample with stand-off distance of 1 mm. (b) AS2 sample with stand-off distance of 1.5 mm.

suggest formation of a combined compound from two alloys in these positional areas based on turbulent and rotator movement of the caught (trapped) jet established from both two base and flyer plates in these areas. Formation of the leaping jet from both two base and flyer plates and its rotator/movement have been observed by other researchers as well<sup>13,14</sup>.

For non-homogenous compounds, on the basis of reflection of jet from the plate with less density, pressure is implemented on the plate with higher density and, thus, the vortex/eddy formed in the behind of waves contains more

materials of flyer plate and the vortex formed in front of waves contains more materials of base plate. Based upon this, it has been noted that a lot of aluminum-flyer plate elements are presented inside the vortex areas behind the waves. Also, results show that analysis of these compounds in proximity to the various waves has changed and become non-homogenous by change of welding parameters shown in (Figure 7). By increase of the stand-off distance due to increase of pressure, collision energy and temperature resulted from it, rate of these areas in the interface, particularly in proximity to the vortex of the waves has been increased.

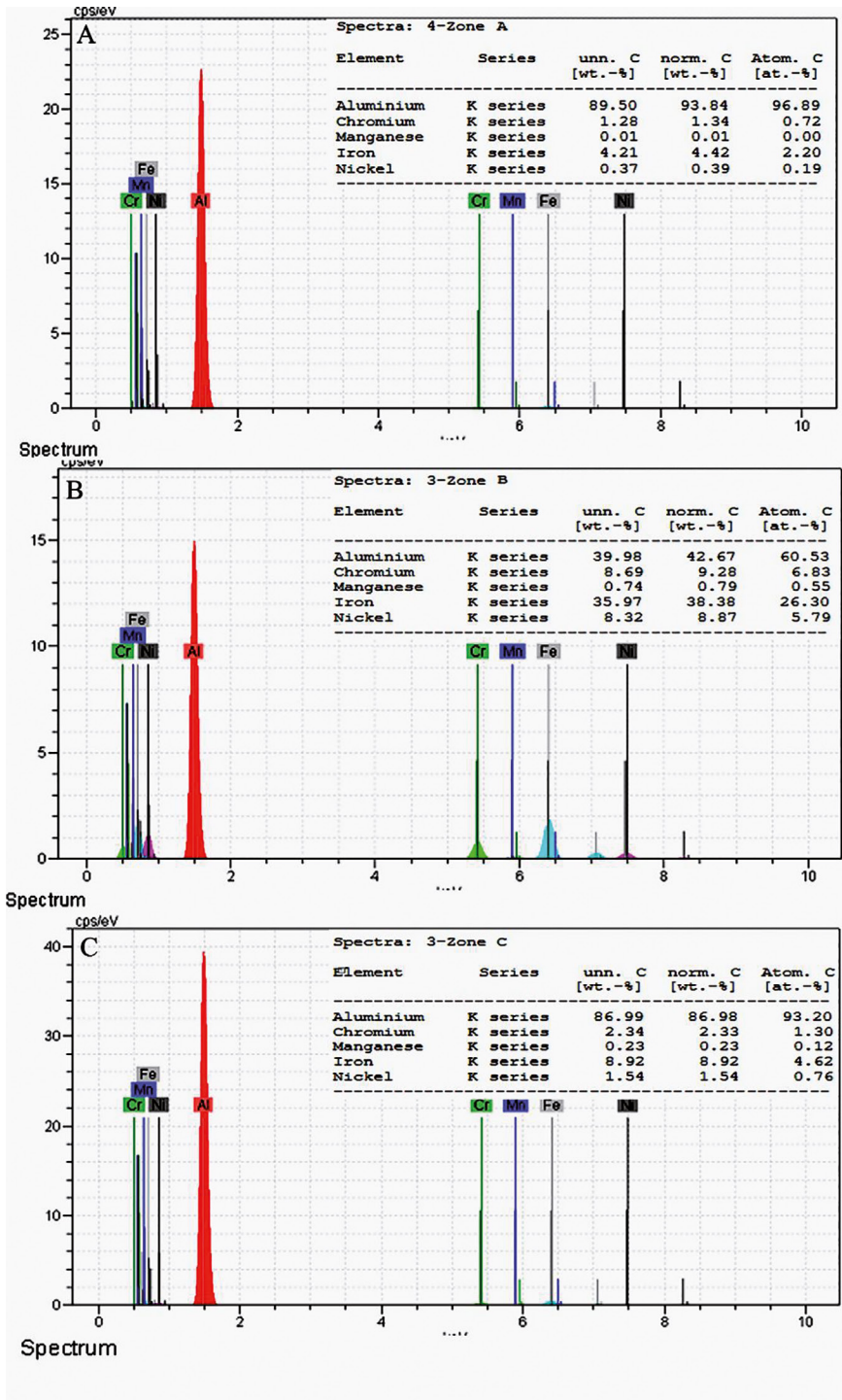
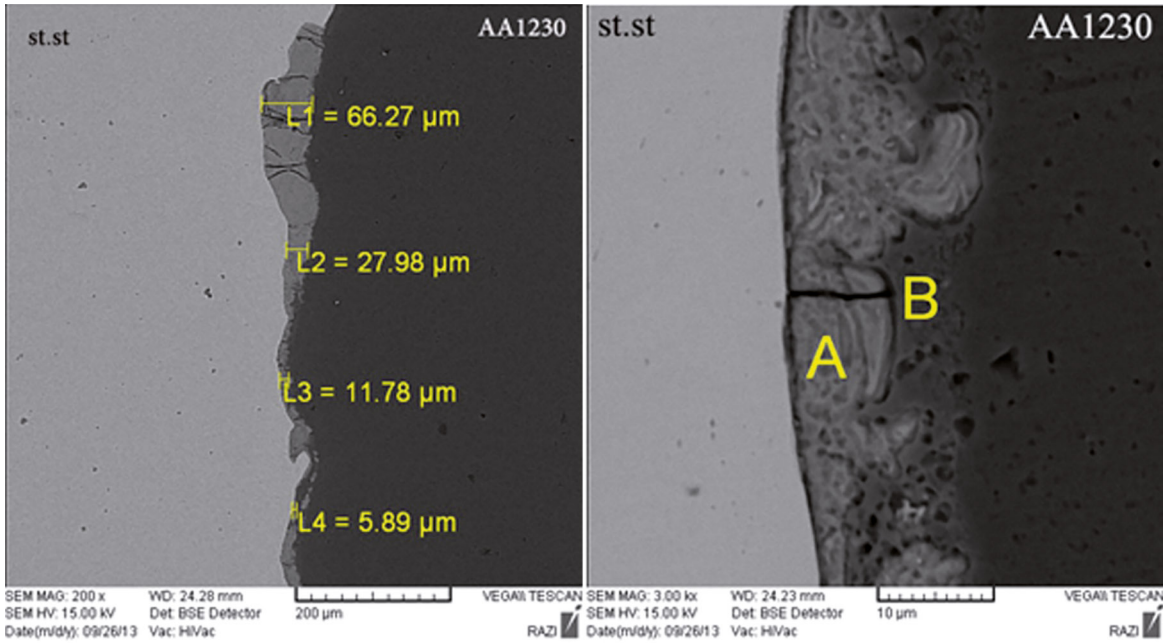


Figure 7: EDS Analysis from specified intermetallic compounds. (a) AS1 sample – (b) AS2 sample of region A – (c) AS2 sample of B

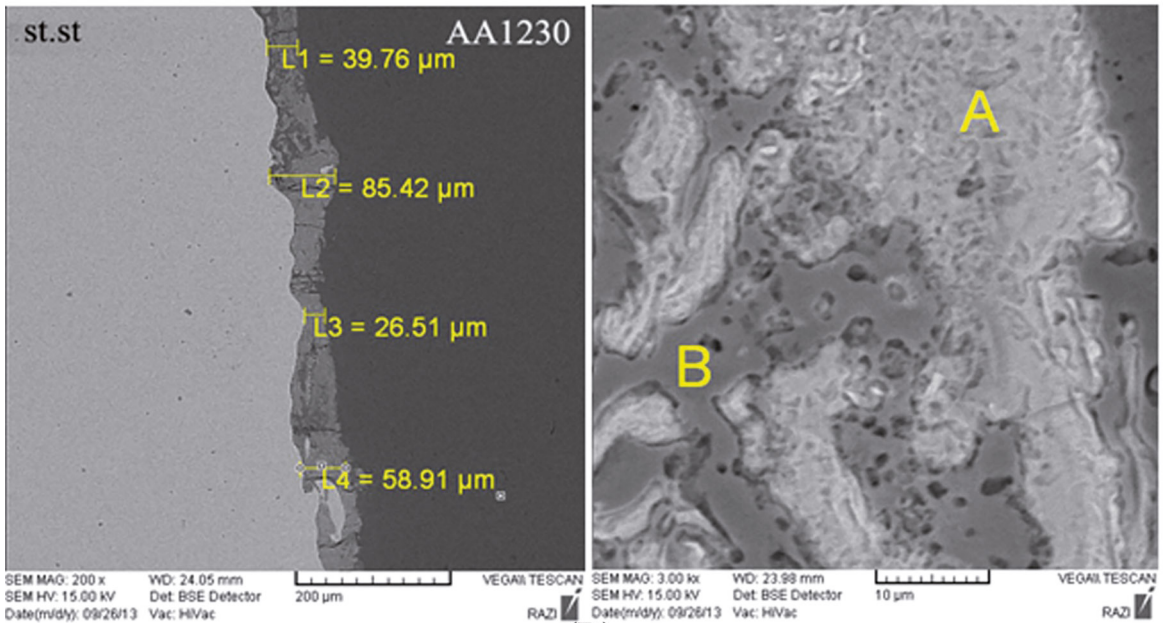
In AS3 sample as shown in (Figure 8), thickness of the intermetallic layer has fluctuated in a range from 6 to 66.2  $\mu\text{m}$  and shape of interface has been wavy. In this sample, two intermetallic areas of A and B have been specified which proportion of iron to aluminum in point A is 1:3.5, and considering that this layer has been consisted of 70.4%

(percentage) of atomic aluminum and 19.3% (percentage) of atomic iron, the analysis shown in (Figure 9(a)), with regard to iron-aluminum diagram, shows that the compound layer locates in  $\text{Fe}_2\text{Al}_3$  area.

As shown in (Figure 8(a)), fine cracks, being perpendicular to the interface, are specified which have been reported in



(A)



(B)

**Figure 8:** Pictures of SEM from changes in thickness and specified intermetallic compounds of the interface. (a) AS3 sample with stand-off distance of 2 mm –(b) AS4 sample with stand-off distance of 2.5 mm

the researchers' results. Heating stress fields and bowing of residue resulted from difference of heating conductance of two metals have increased thickness of layer of the intermetallic compounds which have a frangible and brittle nature. As shown in Figure 8(b) and (Figure 9(b)), by increase of the stand-off distance up to 2.5mm in AS4 sample, interface and it's compounds are wavy shaped completely and with higher width compared to AS3 samples through conditions of equal

speed of explosion. Deformation from smooth and direct shaped interface to wavy shaped interface has been related to increase of the plastic bowing resulted from collision. Also, it has been observed that amount/ size of waves relates to speed and angle of collision and change in the wave lengths results from change in collision angle. Factor of changes in the plastic bowing which considers both two factors of



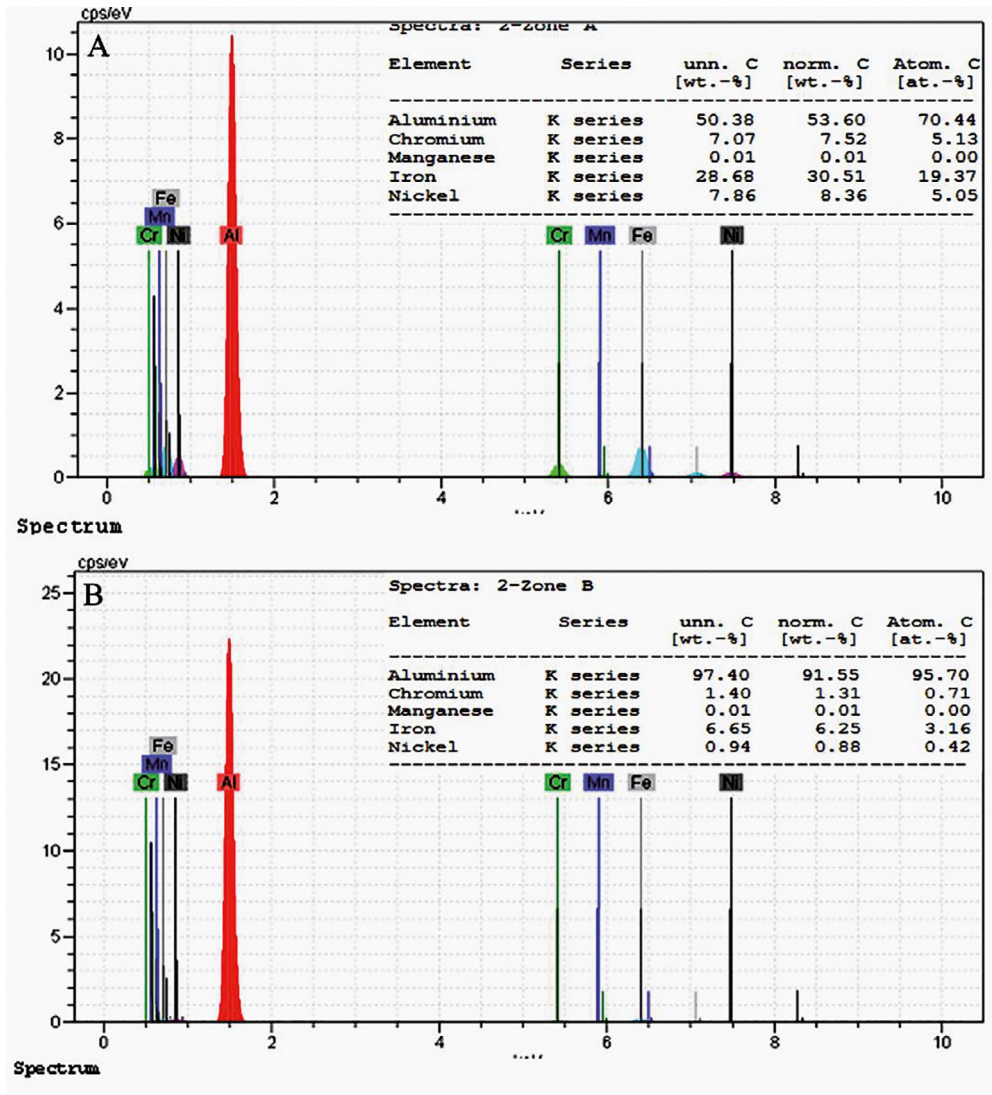


Figure 9: EDS analysis from specified intermetallic compounds. (a) AS3 sample of A area – (b) AS3 sample of B areas

collision angle and collision speed, along with shear stress, has been mentioned as deformations of the interface<sup>15,16</sup>.

Thickness of layer of the intermetallic compounds in this sample has been measured from 2.6 to 85.4  $\mu\text{m}$ . In (Figure 10(a) and (b)), two areas specified by scanning electron microscope have been shown. Layer A consists of 74.5% (Percentage) of atomic aluminum, 17.4% of atomic iron, and layer B includes 92% (percentage) of atomic aluminum and 5.4% of atomic iron.

### 3.3 Microhardness assessment test

In the explosive welding, flyer plate and base plate are exposed to intense stressful wave resulted from explosion of the explosive material. These intense stressful waves cause metallurgical changes leading to increase of microhardness. Microhardness is a function of the chemical; compounds,

percentage of alloying elements, intermetallic compounds, heating changes, explosion force and stand- off distance<sup>16</sup>.

Table 5 has shown results of the microhardness test. Microhardness in the intermetallic area of AS1 HV and in the intermetallic area of AS2 with stand- off distance of 1.5 mm has been 766 HV. Reason for increase of microhardness of AS2 sample compared to AS1 sample is that increase of stand- off distance has increased speed of flyer plate and dynamic angle of collision and, therefore, collision kinetic energy has increased as well, and an intense plastic deformation has occurred in interface bonding and increased shocking hardness resulted from waves of microhardness explosion<sup>17</sup>. Microhardness in the AS3 sample with stand- off distance of 2 mm has obtained to be equal to 780 HV and in the AS4 sample with stand- off distance of 2.5 mm has obtained to be equal to 927 HV. Also, here, microhardness has increased due to the reasons mentioned above by increase of stand- off distance.

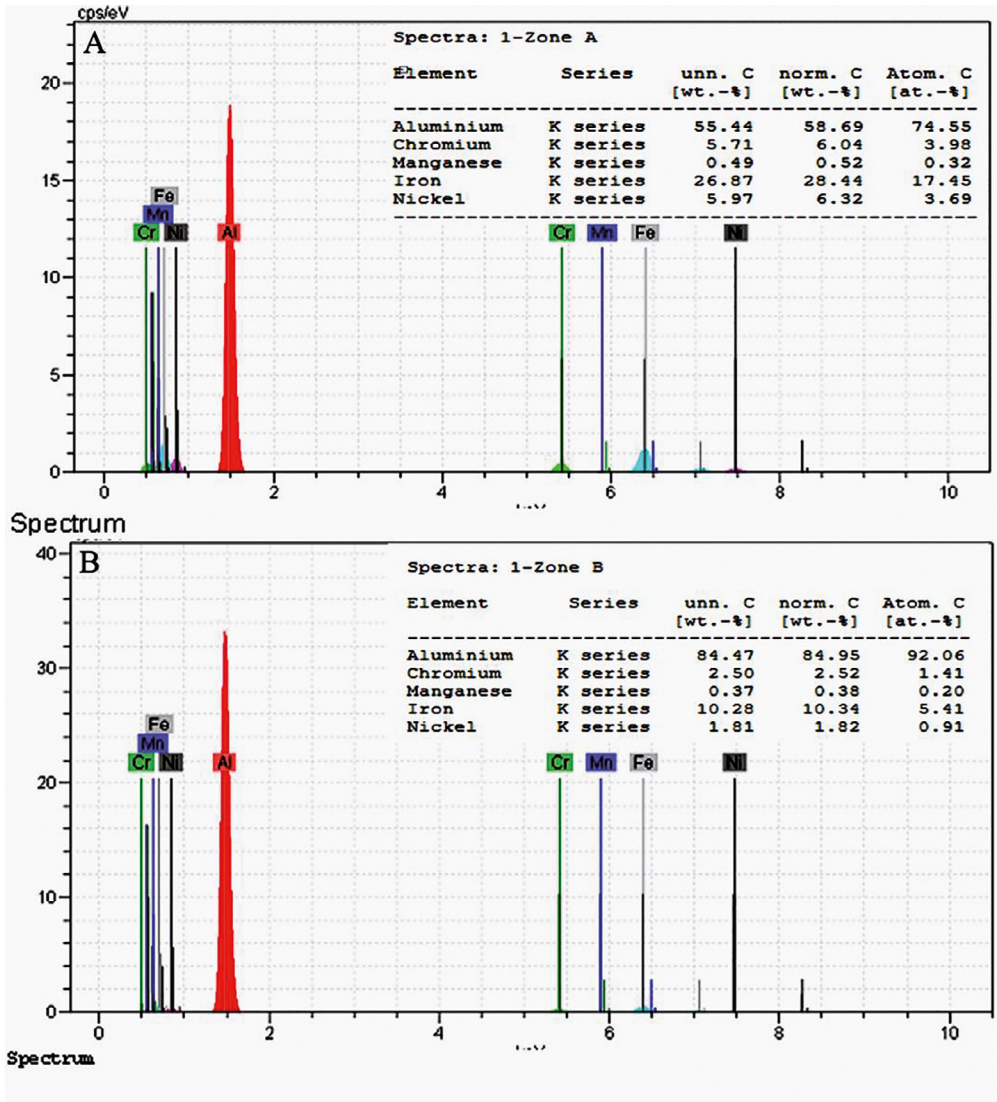


Figure 10: EDS analysis from specified intermetallic compounds. (a) AS4 sample of A area – (b) AS4 sample of B area

Table 5: Microhardness of layer of intermetallic compounds in different stand-off distance

Sample	Thickness of explosive materials (mm)	Stand-off distance (mm)	Explosion speed (ms <sup>-1</sup> )	Microhardness (HV)
AS1	10.7	1	3650	650
AS2	10.8	1.5	3650	766
AS3	7	2	2504	780
AS4	6.95	2.5	2504	927

### 3.4 Tensile – shear test

Results of the tensile – shear test presented in table 6 showed that rate of tensile – shear strength in the AS1 and AS2 samples has obtained to be 103.2 and 156 MPa, respectively. As the results show, amplitude of waves, due to plastic deformation, has been higher and a mechanical lock has established in it which is effective on increase of strength by increase of stand- off distance in AS2 to 1.5

mm<sup>18</sup>. In AS3 and AS4 samples, it has been observed that, by increase of stand- off distance from 2 mm to 2.5 mm due to above mentioned reason, strength from 181.11 MPa in the AS3 sample has increased to 214 MPa in AS4 sample. Optimum bonding is subject to length, amplitude of waves and rate of intermetallic compounds of interface. In this research, AS4 sample with welding speed of 2504 m/s has been the best strength sample. Mechanical lock established

due to increase of wave length leads to improvement of mechanical properties shown in Table 6 of this problem.

**Table 6:** Tensile-shear strength of layer of intermetallic compounds with various stand-off distance

Sample	Thickness of explosive materials (mm)	Stand-off distance (mm)	Explosion speed (ms <sup>-1</sup> )	Strength (MPa)
AS1	10.7	1	3650	103.2
AS2	10.8	1.5	3650	156.57
AS3	7	2	2504	181.11
AS4	6.95	2.5	2504	214.5

#### 4. Conclusion

In this research, effect of stand-off distance on the mechanical and metallurgical properties of the explosive bonding of 321 austenitic stainless steel tubes to 1230 aluminum was studied, and, by study of the tests, following results were achieved:

1. By increase of the stand-off distance from 1mm to 2.5 mm, thickness of layer of the intermetallic compounds has been increased from 3.5 to 102.3 due to higher plastic deformation originated from high collision kinetic energy.
2. By increase of stand-off distance due to plastic deformation and higher wavy shape of interface, decrease of atomic percentage of aluminum and increase of atomic percentage of iron, nickel and chromium, microhardness of the intermetallic compounds has been increased from 650 HV in a sample with stand-off distance of 1 mm to 927 HV in a sample with stand-off distance of 2.5 mm.
3. Due to brittle nature of the intermetallic compounds, fine cracks have been established along a direction being perpendicular to interface of bonding.
4. By increase of explosive force, shape of seam/fissure of bonding has become wavy higher and increased thickness of layer of the intermetallic compounds with brittle and fragile nature.
5. Increase of stand-off distance from 1 mm to 2.5 mm has led to the more plastic deformation and higher wavy shape of the bonding's interface and increased strength from 103.2 MPa to 214.5 MPa.
6. In this research, AS4 sample with stand-off distance of 2.5 mm and welding speed of 2504 m/s has been the best sample with respect to bonding. Due to increase of wave length, established mechanical lock has been led to improvement of the mechanical properties.

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