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Effects of heat treatment on the intermetallic compounds and mechanical properties of the stainless steel 321–aluminum 1230 explosive-welding interface

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Abstract: The effects of heat treatment on the microstructure and mechanical properties of intermetallic compounds in the interface of stainless steel 321 explosively bonded to aluminum 1230 were investigated in this study. Experimental investigations were performed by optical microscopy, scanning electron microscopy, and microhardness and shear tensile strength testing. Prior to heat treatment, increasing the stand-off distance between samples from 1 to 2.5 mm caused their interface to become wavy and the thickness of intermetallic layers to increase from 3.5 to 102.3 μm. The microhardness increased from HV 766 in the sample prepared at a stand-off distance of 1 mm to HV 927 in the sample prepared at a stand-off distance of 2.5 mm; in addition, the sample strength increased from 103.2 to 214.5 MPa. Heat treatment at 450°C for 6 h increased the thickness of intermetallic compound layers to 4.4 and 118.5 μm in the samples prepared at stand-off distances of 1 and 2.5 mm, respectively. These results indicated that increasing the duration and temperature of heat treatment decreased the microhardness and strength of the interface of explosively welded stainless steel 321−Al 1230 and increased the thickness of the intermetallic region.

Keywords: intermetallic compounds; explosive welding; heat treatment; stand-off distance; mechanical properties.

1. Introduction

Bonding aluminum to steel by fusion welding techniques is difficult to achieve because of the differences in temperatures, mechanical and physical properties, and atomic layers of the metals. Explosion welding, an advanced technique in solid-state welding, uses the controlled energy of an explosive material to bond two welding surfaces placed apart at some determined stand-off distance by approaching each other with high speed. Collision of the two surfaces causes a local plastic field to form in the bonding interface, which constitutes a band with a metallurgical bond, by the sharing of electrons between the welding components. A high-speed jet forms from the two bonding surfaces because of the high impact pressure, which leads to a clean bonding surface in the interface and removal of surface contamination. Formation of this jet is one of the fundamental conditions for the creation of an appropriate bond in the explosion welding process [1–5].

The bonds resulting from this method, similar to other techniques in solid-state welding, experience no metallurgical problems attributable to the presence of a melt in the welding region; thus, this technique can be used as a sufficient method for bonding a wide variety of similar or dissimilar metals with different mechanical and chemical properties [6–7].

Explosion welding can be widely used in two-layer or multi-layer coatings in the chemical industry, power plant

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production, aerospace, the automotive industry, vacuum equipment, pressure vessels, and heat exchangers. Coating of tubular connections and cylindrical surfaces to produce hollow shafts and cylinders is also one of the main applications of this technique. Despite its many benefits, however, explosion welding presents some important metallurgical problems. The intensive tensile waves resulting from the explosion shock could lead to metallurgical changes, shock hardening, and decreases in flexibility, ductility, and impact strength, which mainly occur along the shock wave's path. Shocking hardening can be caused by doublet expansion or transformation of the ferrite phase to martensite due to the explosion welding pressure. This metallic transformation could provide significant grid strain energy, which causes an increase in hardness. Dislocations move rapidly because of the explosion wave, and this movement is effective in forming cavities. The percentage and concentration of these point defects in final products could be related to increases in hardness and ductility [7–8].

The presence of iron and Al and the bond strength between dissimilar atoms, which is usually higher than the bond strength between similar atoms, increase the possibility of intermetallic compound formation in the welded interface [7–9]. From the chemical viewpoint, reaction of Fe with Al forms several Fe_xAl_y intermetallic compounds; Table 1 shows the properties of some of these compounds [4].

Table 1. Properties of several intermetallic compounds Fe_xAl_y [4]

Phase	Al content / at%	Structure	Microhardness, HV	Density / ($g \cdot cm^{-3}$)
Fe_3Al	25	bcc	250–350	6.67
FeAl	50	bcc	400–520	5.37
Fe_2Al_7	63	bcc	650–680	—
$FeAl_2$	66–67	Rhombohedral	1000–1050	4.36
Fe_2Al_5	69.7–73.2	Orthromobic	1000–1100	4.11
$FeAl_3$	74–76	Monoclinic	820–980	3.95

Intermetallic compounds form at temperatures below the melting point of Al, and their formation rates depend on the penetration type, temperature, and duration of heat treatment. By increasing the duration and heat treatment temperature, the thickness of the intermetallic layers could be expected to increase [10–11]. Experimental data have revealed the insignificant growth of intermetallic compounds exposed to thermal stresses less than 300°C. By contrast, samples in which the temperature is equal to 500°C or higher show marked increases in the expansion of the Fe/Al compounds in the interface. Therefore, the steel-to-Al bond should be heated to a certain temperature to prevent decreases in strength due to the formation of intermetallic compounds [7–8].

Samardzich *et al.* [12] demonstrated that the rate of decrease in bonding strength after annealing at 450°C is larger than that after annealing at 315°C due to the formation of intermetallic layer; the increases in temperature and amount of nickel, chromium, and silicon can also increase the contents of intermetallic compounds. Lowering the heat treatment temperature does not significantly affect the strength of intermetallic compounds, but increasing it to 450°C increases the presence of intermetallic compounds, which, in turn, play an effective role in failure of the part.

Investigations on the effect of the post-welding heat treatment temperature and duration on the explosion bond of low carbon steel to austenitic steel 304 revealed that increasing the heat treatment duration from 1 to 4 h at a constant temperature of 250°C causes the decrease in microhardness due to the coarsening of the structure; thus, short durations have been suggested for heat treatment [13]. Lokaj and Benak [14] indicated that heat treatment at 250°C for 100 h significantly decreases the microhardness of the base metals and their interface because of the increases in the penetration of Al, coarsening of the structure, and formation of an amorphous interface.

The difficulty of bonding of Al to steel by fusion welding, the applications of these materials to the military and naval industries, the formation of thin melting layers through the bonding interface under high temperature operating conditions, and the formation of various intermetallic compounds during welding metals with different densities require determination of an appropriate heat treatment after welding to obtain optimal mechanical and structural properties. Therefore, the aim of the current study is to investigate the microstructures of intermetallic compounds in the bonding interface between steel and Al, and determine the influence of heat treatment on the mechanical properties of these intermetallic compounds.

2. Materials and methods

The materials used in the explosive welding process to create double layer tubes were stainless steel 321 and Al 1230; the chemical compositions of these alloys are provided in Table 2.

Table 2. Chemical compositions of the explosion welding tubes wt%

Material	C	Si	Mn	P	S	Mg	Cr	Ti	Ni	Cu	V	Zn	Al	Fe
AlSI321	0.08	0.75	2.00	0.04	0.03	—	18.00	—	10.50	—	—	—	—	Balance
AA1230	—	0.70	0.05	—	—	0.05	—	0.03	—	0.10	0.05	0.10	Balance	0.70

Stand-off distance and heat treatment were chosen as variables in this investigation. Table 3 provides details of the tests and labels the samples based on their stand-off distance, temperature, and duration of the heat treatment. In the welding process, four different stand-off distances of 1.0, 1.5, 2.0, and 2.5 mm were considered, and the tubes were placed completely parallel and coaxial to each other with these distances. Fig. 1 indicates the adjusted system for explosion welding of the samples. The base tube was made from Cr18Ni9Ti steel with a thickness of 4.5 mm and a length of 200 mm. The outer and inner diameters of this tube were 135 and 126 mm, respectively. The Al 1230 alloy tube was considered as the flyer tube in the explosion welding process with a thickness of 1.5 mm and a length of 240 mm. The hardnesses of the austenitic stainless steel and Al 1230 are HV 200 and HV 40, respectively. Amatol, which is a combination of trinitrotoluene or trinitrotoluene (T.N.T) and ammonium nitrate, was used as the explosive material. To bond tubes at stand-off distances of 1.0 and 1.5 mm, a combination of 79wt% ammonium nitrate and 21wt% T.N.T and an explosion rate of 3650 m/s were used. As well, 95wt% ammonium nitrate and 5wt% T.N.T and an explosion rate of 2504 m/s were used to bond tubes at stand-off distances of 2 and 2.5 mm.

Table 3. Characteristics of the welding tests and heat treatment

Test No.	Stand-off distance / mm	Thickness of the explosive material / mm	Explosive material	Explosion speed / ($m \cdot s^{-1}$)	External diameter of flyer tube / mm	Internal diameter of base tube / mm	Heat treatment temperature / °C	Heat treatment time / h
AS1	1.0	10.70	Amatol	3650	124	126	450	6
AS2	1.5	10.80	Amatol	3650	123	126	450	6
AS3	2.0	7.00	Amatol	2504	122	126	450	6
AS4	2.5	6.95	Amatol	2504	121	126	450	6
AS5	2.0	7.00	Amatol	2504	122	126	350	6
AS6	2.2	7.00	Amatol	2504	122	126	450	8

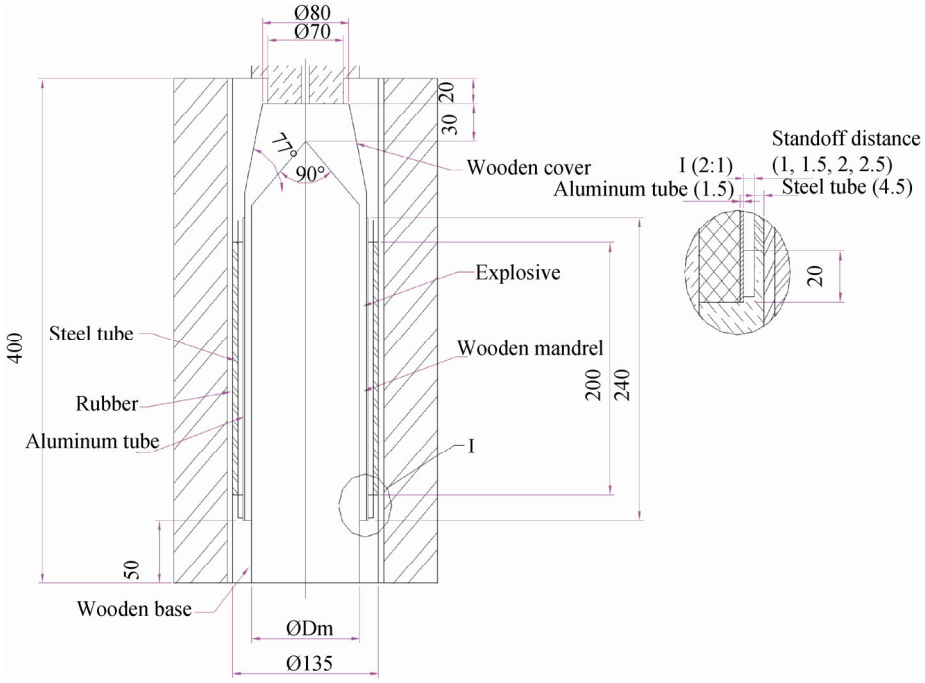

Fig. 1. Adjusted system for the explosion welding of Al 1230 to steel 321 (unit: mm).

2.1. Post-weld heat treatment

After welding, post-heating was applied to the samples. Heat treatment was performed in the furnace under the following conditions: argon protection; pressure, 100 kPa; temperature: 350 and 450°C; duration: 6 and 8 h. The samples were cooled to room temperature afterward. Temperatures of 350 and 450°C were considered as the critical temperatures of steel–Al bonding.

2.2. Structural and metallurgical tests

2.2.1. Optical microscopy

To study the microstructures of the bonding interfaces and intermetallic compounds, as well as changes to these structures, especially the shapes of the generated waves, small samples were cut along a line perpendicular to the bonded regions as verified by ultrasonic tests. The samples were ground with 60#–2500# emery papers to a constant surface roughness and then polished. Thereafter, the surfaces of the samples were washed with alcohol, dried, and etched with glyceregia (glycerin + nitric acid + hydrochloric acid). Reference standards ASTM E3-11 [15], ASTME407-07 [16], ASTME 883-11 [17], and ASTM B487-02 [18] were used for sample preparation, metal micro-etching, optical microscopy, and measurement of the thickness of intermetallic compound layers, respectively. The microstructures of the interface and intermetallic compounds were analyzed by an optical microscope (Metallux 3) at different magnifications.

2.2.2. Scanning electron microscopy

A scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectrometer (EDS) (VEGA\\TESCAN-LMU) was used to compare and investigate the shapes and sizes of the intermetallic compounds and interfacial cracks. A high vacuum was created in the vacuum column, and bonding interfaces were investigated at different magnifications.

2.3. Mechanical property investigations

To investigate the mechanical properties before and after heat treatment, mechanical tests, including the shear tensile strength test and microhardness test, were performed on the welded samples.

2.3.1. Shear tensile strength

To test shear tensile strength, samples were prepared based on the ASTM D3165-95 [19] standard. According to this standard, samples should be designed in a manner such that both the flying metal and the base metal are at an appropriate distance from each other. The length of the test region (L) can be considered as a variable, but the recommended length in the standard is (12.7 ± 0.3) mm. The distance between the jaw and the groove edge in each metal should be equal to 50.8–63.5 mm, and the distance of the jaw location on the sample should be 25.4 mm. The rate of the tensile load in this standard was determined as 1.27 mm/min.

2.3.2. Microhardness

In this survey, the Vickers microhardness test was performed based on the ASTM E384-11 [20] reference standard at the laboratory temperature of 25°C by the model Wilson® VH3300 Buehler device. A force of 0.49 N was applied to different regions of the bonded tubes with different thicknesses, and the average of three microhardening tests was considered as the microhardness of the intermetallic compounds. The effect of the stand-off distance was also considered.

3. Results and discussion

3.1. Investigation of the microstructures of the samples by optical microscopy

The shapes of waves generated along the longitudinal axis before and after heat treatment are indicated in Figs. 2 and 3, respectively. Fig. 2 reveals that the thickness of the intermetallic compound layer of the bonding interface increases when the stand-off distance is increased. Increases in stand-off distance and thickness lead to an increase in the explosive load of the flying plate and more plastic deformation in the bonding interface. The impact pressure is increased by increasing the impact speed; increases in the impact dynamic angle and kinetic energy consumed at the impact point are also observed. The impact kinetic energy increases, and the shape of the interface becomes wavier. Akbari Mousavi *et al.* reported that increasing the explosive load and stand-off distance during explosive bonding of Al 5083/Al 1250/marine steel causes the temperature at the impact point to rise significantly and the interface to become wavy [21].

The speed of the flying plate increases as a result of increases in stand-off distance and explosive load. According to differences in density and wave speed in the metals, the compressive momentum at the two sides of the interface changes via increases in the speed of the flying plate. Thus, the point of impact fluctuates during impact, which increases on account of the impact speed, and the materials in the vicinity of the impact point lose their strength and show plastic behavior. The shape of the interface at the two sides of the interface is wavy and non-uniform because of the

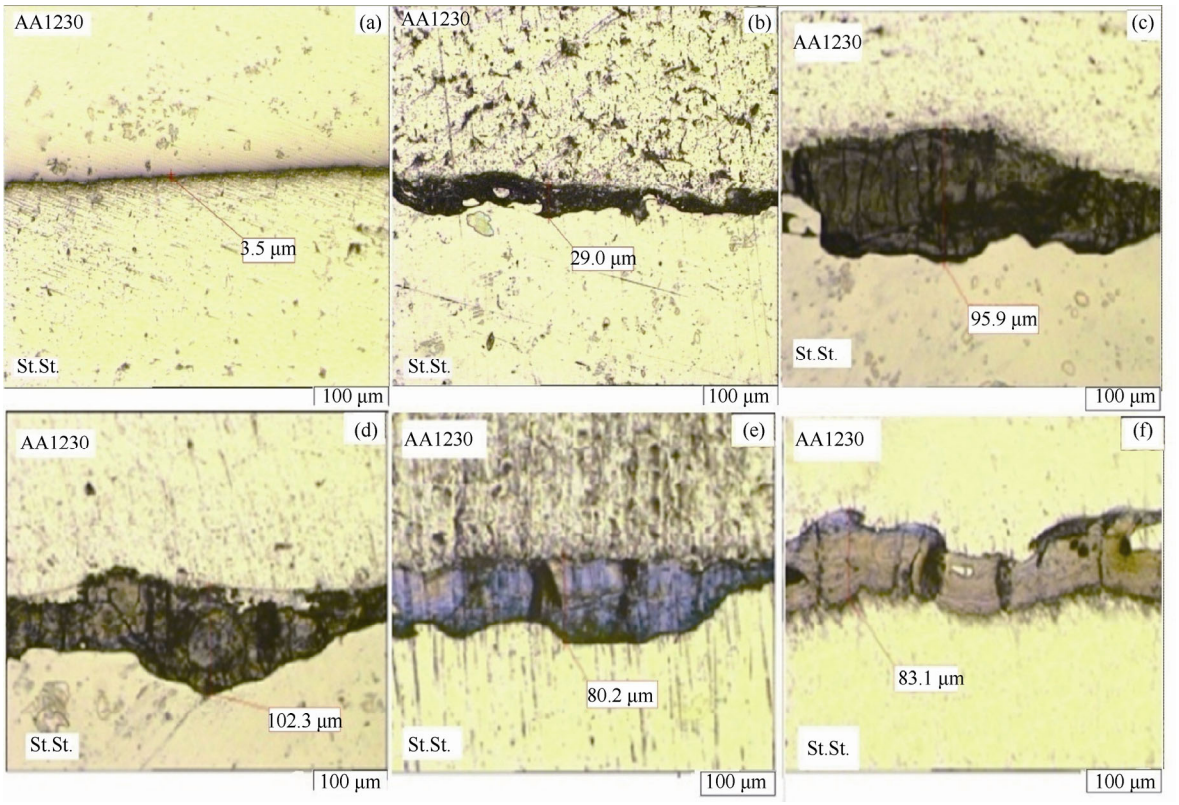

Fig. 2. Bonding interfaces of the samples before heat treatment (St.St. represents stainless steel): (a) AS1; (b) AS2; (c) AS3; (d) AS4; (e) AS5; (f) AS6.

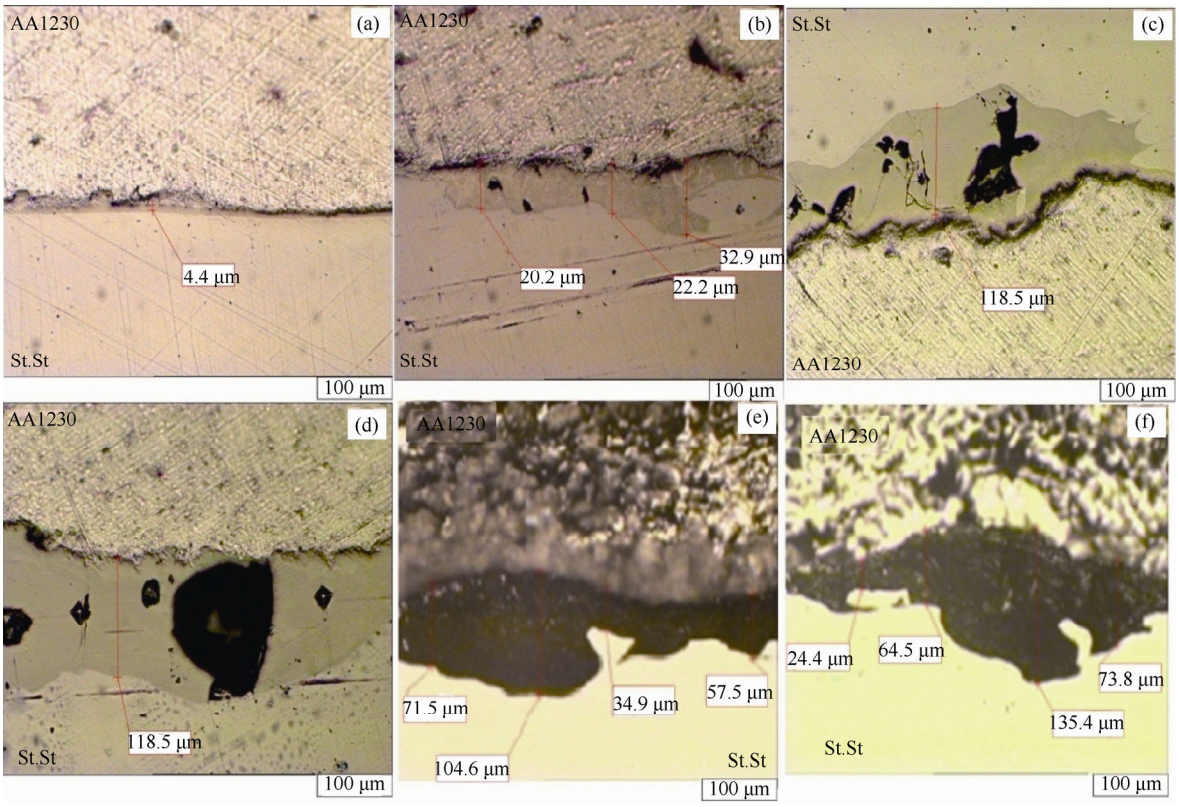

Fig. 3. Bonding interfaces of the samples after heat treatment (St.St. represents stainless steel): (a) AS1; (b) AS2; (c) AS3; (d) AS4; (e) AS5; (f) AS6.

changes in the dynamic angle of the impact, discontinuity of the speed in the free surfaces, and the generation of waves [22]. Fig. 3 demonstrates that, in general, heat treatment increases the thickness of the intermetallic compound layer, although the thickness of the intermetallic layer increases more significantly at a high temperature than at a low one. For example, the thickness of the intermetallic layer of AS5 was 104.6 μm after heat treatment at 350°C for 6 h, while that of AS3 was 118.5 μm after heat treatment at 450°C for 6 h (Table 4).

Table 4. Maximum interface layer thickness, hardness, and shear tensile strength of the welded samples before and after heat treatment

Test No.	Before heat treatment			After heat treatment		
	Maximum thickness / μm	Hardness, HV	Shear tensile strength / MPa	Maximum thickness / μm	Hardness, HV	Shear tensile strength / MPa
AS1	3.5	650	103	4.4	600	87
AS2	29.0	766	156	32.9	666	135
AS3	59.9	780	181	118.5	646	176
AS4	95.9	927	214	102.3	766	181
AS5	80.2	946	181	104.6	1027	245
AS6	83.1	857	181	135.4	946	220

3.2. Investigation of the microstructures of the samples by scanning electron microscopy

Increasing the stand-off distance can increase the impact temperature to the melting point of the metals, resulting in a melting vortex. Solidification of this vortex causes the thickness of the intermetallic layer to increase. Changes in the interface condition and shape are due to the changes in the impact condition, especially the impact dynamic angle [23–24].

Figs. 4–7 show the SEM images of the interfaces and layer thicknesses of some regions of the samples. Figs. 4 and 5 clearly show that the layers were thicker after heat treatment than before treatment. This change may be attributed to several reasons, including penetration of alloy elements due to differences in the physical properties of the materials, removal of linear and point defects, and residual stress due to welding. Figs. 6 and 7 show the SEM images

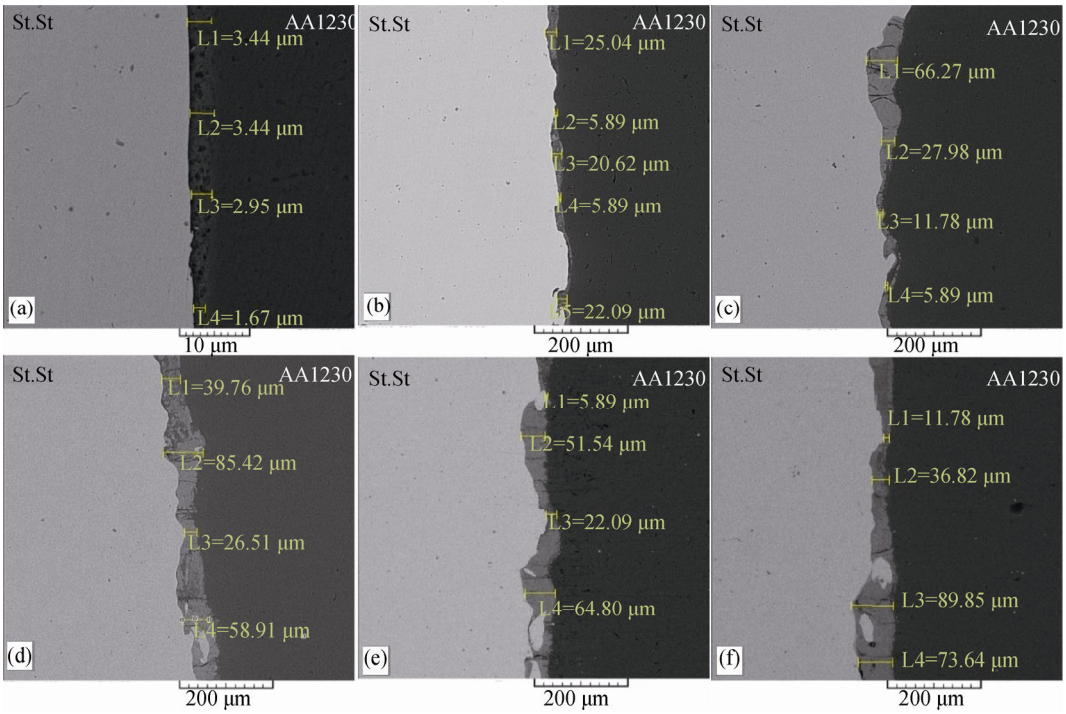

Fig. 4. SEM images of the thickness variations of the samples before heat treatment (St.St. represents stainless steel): (a) AS1; (b) AS2; (c) AS3; (d) AS4; (e) AS5; (f) AS6.

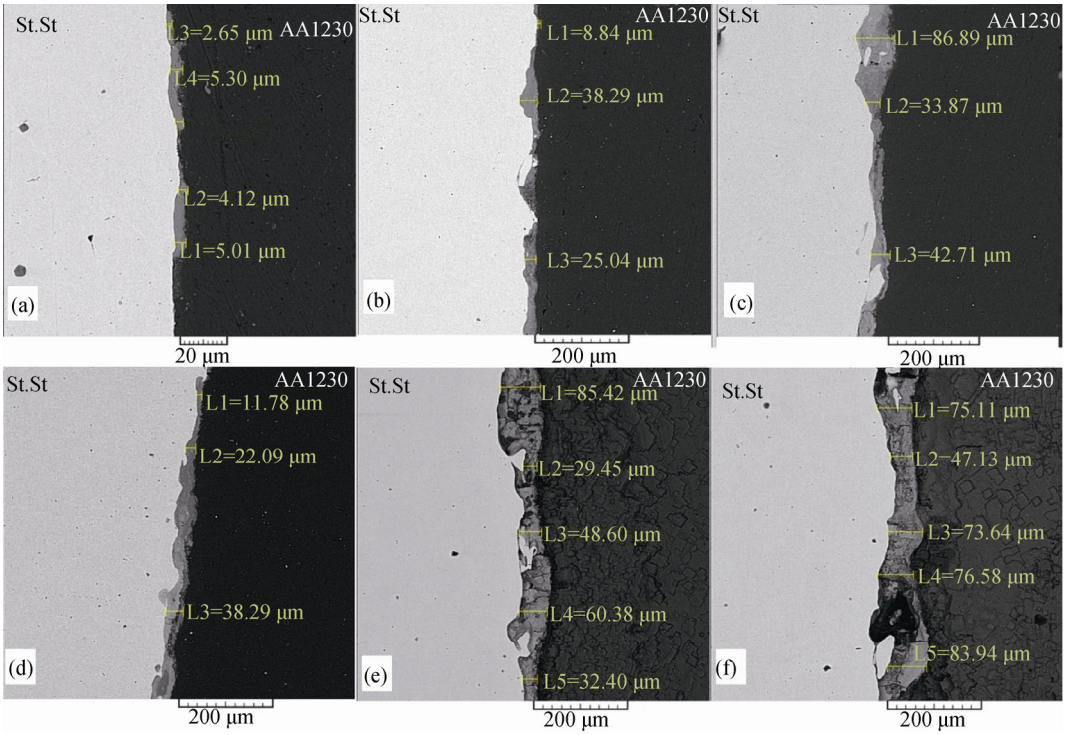

Fig. 5. SEM images of the thickness variations of the samples after heat treatment (St.St. represents stainless steel): (a) AS1; (b) AS2; (c) AS3; (d) AS4; (e) AS5; (f) AS6.

of the intermetallic regions before and after heat treatment, and Figs. 8 and 9 illustrate the atomic percentages of the interface composition of the samples before and after heat treatment. The atomic percentage of the interface composition before and after heat treatment was determined by EDS. According to the atomic ratios and the phase diagram of Fe/Al, the intermetallic layer may be located in the FeAl, $FeAl_3$, and Fe_2Al_5 regions.

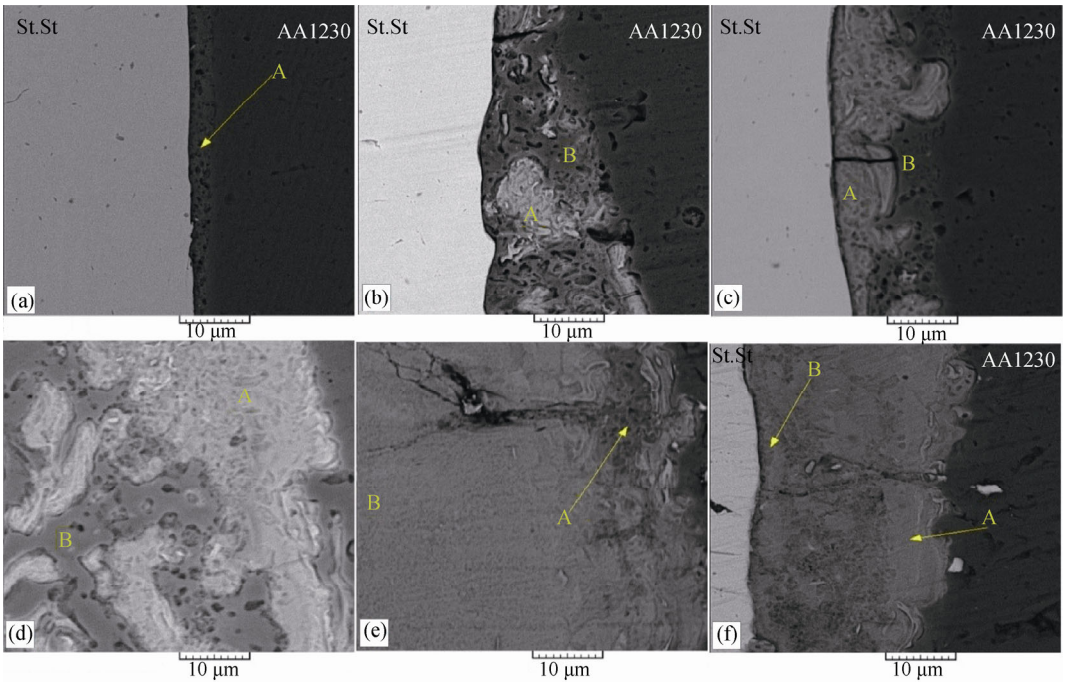

Fig. 6. SEM images of intermetallic compounds in the interfaces of the samples before heat treatment (St.St. represents stainless steel; A and B indicate different regions in the interfaces of the samples for EDS analysis): (a) AS1; (b) AS2; (c) AS3; (d) AS4; (e) AS5; (f) AS6.

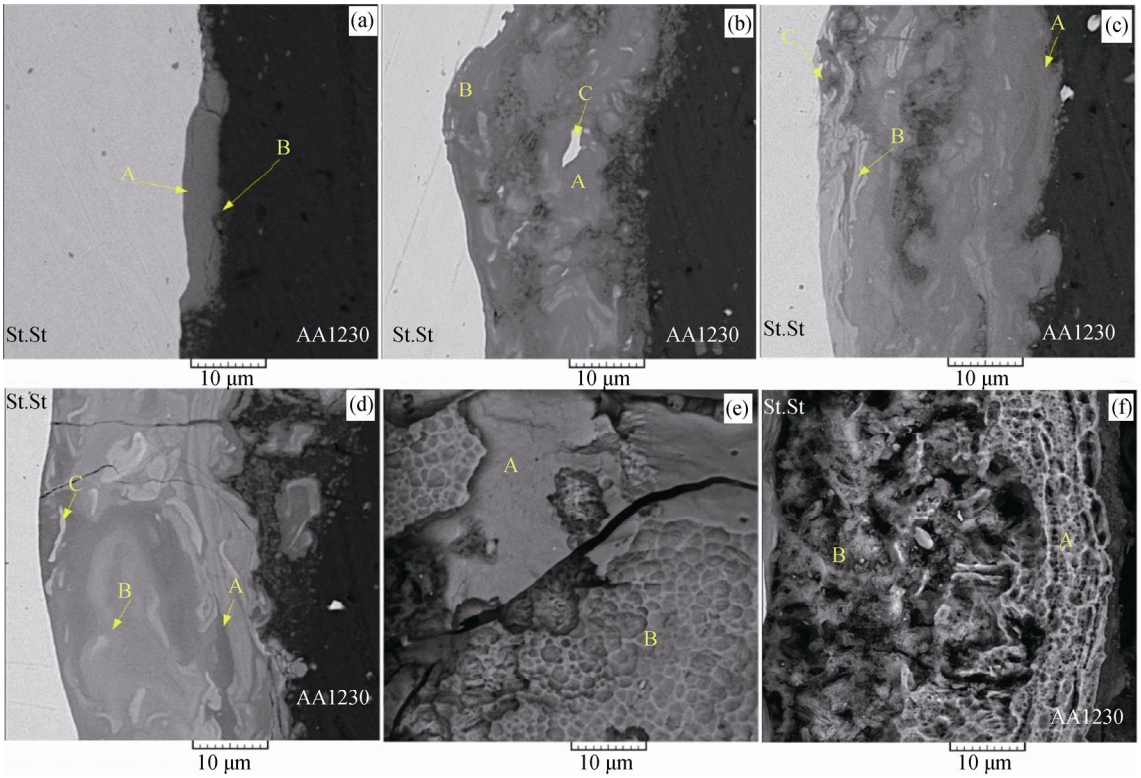

Fig. 7. SEM images of intermetallic compounds in the interfaces of the samples after heat treatment (St.St. represents stainless steel; A, B, and C indicate different regions in the interfaces of the samples for EDS analysis): (a) AS1; (b) AS2; (c) AS3; (d) AS4; (e) AS5; (f) AS6.

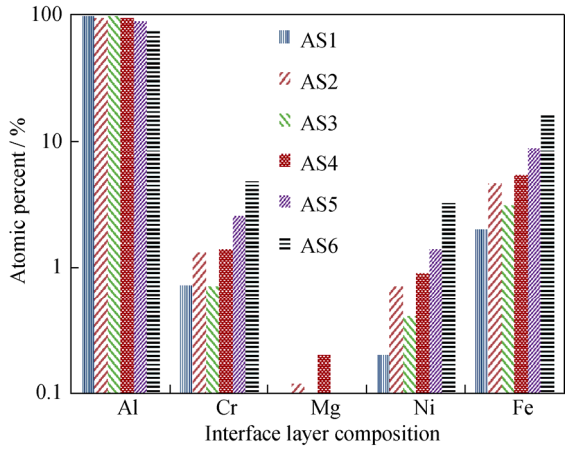

Fig. 8. Variations in the composition of the interface layers of the samples before heat treatment.

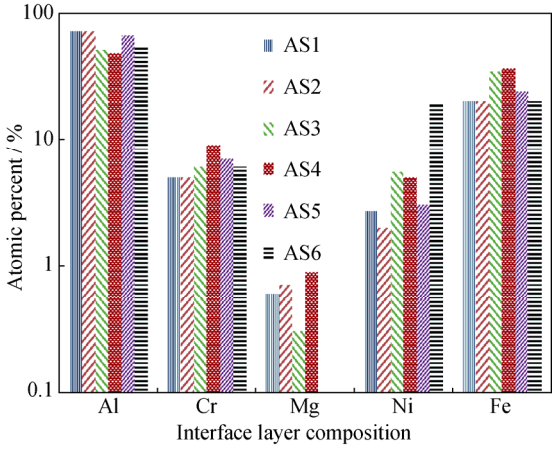

Fig. 9. Variations in the composition of the interface layers of the samples after heat treatment.

According to the literature, the internal heat is generated by the high pressure of shock waves, intense plastic deformation, and adiabatic heat status. Because of the trapped vortex in the front of waves, some waves are generated by the conversion of kinetic energy to heat energy from impact or the adiabatic heat from the gases trapped between the plates. According to the different densities and wave propagation speeds of the two metals, the shapes of the waves are not completely symmetric. As well, the lower thermal conductivity of Al compared with that of steel causes intermetallic compounds to concentrate in the Al side of the wave during solidification. The amounts of these regions in the interface, especially in the vicinity of the vortex, increase by increasing the stand-off distance because of the increases in pressure, impact energy, and, finally, temperature. Akbari *et al.* reported that heat treatment after explosive bonding of

steel to Al causes the penetration mechanism to become more active and results in the formation or increase in thickness of the intermetallic layer [25].

After heat treatment, Cr, Ni, and Fe penetrated into the intermetallic compounds, and the thickness of the layers increased, mainly because the grid structure developed a high density of linear and point defects. These defects could increase the penetration of Cr, Ni, and Fe by providing penetration paths. The activation energy of penetration increases with increasing temperature, and the width of the region would increase. Changes in the intermetallic layers are influenced by the extent of the base element penetration, residual stresses due to welding, which results in creation of strain in the penetrating region, the strain generated by physical–thermal incompatibility of the materials during heat treatment, and softening of the base metal due to the complete degradation of structural defects [25–26].

In Figs. 8 and 9, analyzes of the metal compositions before and after heat treatment are provided. The results indicate that the layer composition in the vicinity of the Al boundary was not changed noticeably and the Fe_2Al_5 type remained. In the vicinity of the austenitic steel, penetration of Cr, Ni, and Fe could be observed after heat treatment, and the intermetallic compounds changed from the $FeAl_3$ type to the Fe_2Al_5 type.

Fig. 9 shows that increasing the heat treatment duration from 6 to 8 h (AS6) inhibited Al penetration to the steel side relative to that in AS3; however, penetration of other elements increased. Considering the penetration coefficient and the melting point of these elements, increasing the heating duration appears to increase the width of the penetration region.

The effect of heat treatment duration on the intermetallic layers of AS3 and AS6 was investigated at a constant temperature of 450°C. Fig. 9 reveals that AS3, which was treated for 6 h, contained 76at% Al, 3.8at% Cr, and 1.9at% Ni, and the thickness of the intermetallic layer was determined to be in the range of 33.8–86.8 μm. By comparison, AS6, which was treated for 2 h longer in the furnace, contained 54.7at% Al, 6.1at% Cr, and 18.4at% Ni; the thickness of the intermetallic layer of this sample was also determined to be in the range of 47.1–83.9 μm.

In Fig. 10, small, dark cavities can be seen in the bonding region of AS6. A number of empty vacancies combined with each other through increases in temperature. Since atom penetration occurs mainly by the empty vacancies mechanism, increasing the temperature during penetration would disturb the thermal balance and some vacancies could be added to the system to achieve equilibrium. Consequently, vacancies combine with each other and form cavities [25–26].

Small cracks perpendicular to the interface can be seen in the SEM images, similar to reports in previous investigations. Thermal stress and the residual strain field arising from differences in the thermal conductivities of the two metals increase the thickness of the intermetallic layer [26].

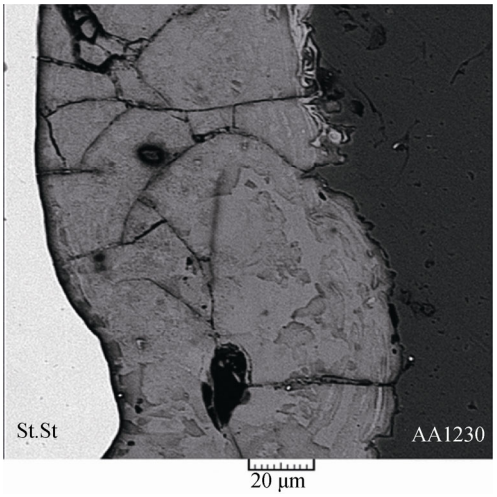

Fig. 10. SEM images of the cracks and cavities on the interface of AS6 (heat treatment for 8 h at 450°C).

3.3. Microhardness test

During explosion welding, the flying and base plates are subjected to intense stress waves resulting from explosion of the explosive material. These waves cause metallurgical variations leading to increased microhardness. Microhardness is a function of the chemical compositions and elemental percentages of the alloys, presence of intermetallic compounds, thermal changes, explosion load, and stand-off distance [25–26].

As can be seen from Fig. 11, test results indicate that prior to heat treatment, increasing the stand-off distance increased the moving speed and the dynamic angle of impact of the flying plate. Under these conditions, the impact kinetic energy increased, intensive plastic deformation occurred in the bonding interface, and shocking hardening developed because explosion waves increased the microhardness of the sample [27].

After heat treatment at 450°C for 6 h, the microhardness of the samples decreased. The microhardness values of the intermetallic compounds in AS1, AS2, AS3, and AS4 were HV 600, HV 666, HV 646, and HV 766, respectively. Increasing the heating temperature relieved the welding-induced residual stress, removed the point and linear

defects formed by transmission of shock waves and decreased the hardness of the samples after heat treatment. However, microhardness of the sample increased by increasing the treatment duration.

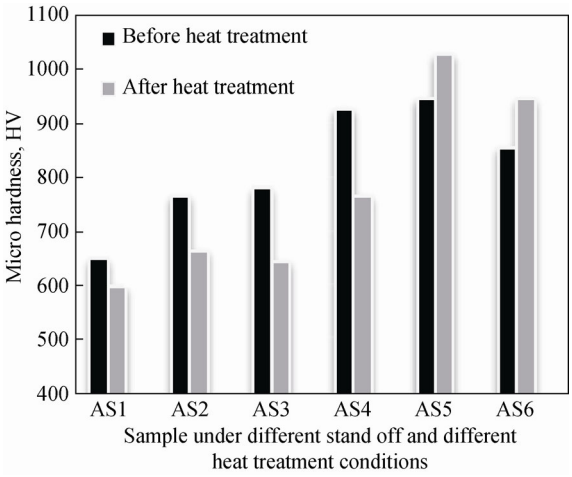

Fig. 11. Results of the microhardness test of intermetallic compounds before and after heat treatment at different temperatures for different durations.

3.4. Shear tensile strength testing

The results of the shear tensile strength test, which are provided in Fig. 12, reveal that the shear tensile strengths of AS1 and AS2 were 103 and 156 MPa, respectively. When the stand-off distance was 1.5 mm (AS2), the domain of the waves increased because of plastic deformation. In Fig. 4, an increase in the waviness of the interface is shown; in this region, a mechanical lock that effectively increased the strength was produced. Fig. 12 demonstrates that increasing the stand-off distance from 2 to 2.5 mm increases the strength from 181 (AS3) to 214.5 MPa (AS4).

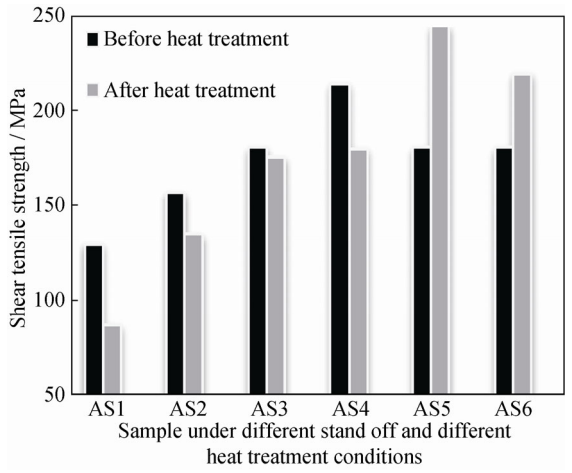

Fig. 12. Results of shear tensile strength tests of steel explosively welded to aluminum before and after heat treatment at different temperatures for different durations.

Performing heat treatment at 450°C for 6 h increased the thickness of the intermetallic layer at the interface of the samples, augmented the stress concentration, and increased cracks and cavities in this region, all of which reduced the shear tensile strength of the sample. All the sample fractures occurred on the Al surface, and no fractures were observed in the interface.

4. Conclusions

In this study, the effect of heat treatment on the intermetallic compounds, strength, and hardness of the interface of austenitic stainless steel 321 explosively bonded to Al 1230 was investigated at different stand-off distances, and the following results were obtained:

(1) Increasing the stand-off distance from 1 to 2.5 mm led to an increase in thickness of the intermetallic layer from 3.5 to 118.5 μm due to the plastic deformation resulting from increases in kinetic energy.

(2) The thickness of the intermetallic layer was increased by heat treatment. A stand-off distance of 2 mm, a treatment duration of 8 h, and a heating temperature of 450°C could lead to an increase in layer thickness from 118.5 to 135.4 μm. Decreasing the heating temperature from 450 to 350°C and applying a treatment duration of 6 h decreased the thickness of the intermetallic layer from 118.5 to 104.5 μm.

(3) Heat treatment at 450°C for 6 h decreased the microhardness of the samples; the maximum change was observed in the sample prepared at a stand-off distance of 2.5 mm, the hardness of which decreased from HV 927 to HV 766. This decrease is attributed to the removal of point and linear defects resulting from the transmission of shock waves, the effect of annealing, and decreases in residual stress brought about by welding.

(4) By increasing the heat treatment duration from 6 to 8 h at a constant temperature of 450°C, the thickness of the intermetallic layer was increased from 118.8 to 135.4 μm and the microhardness of the interface was increased from HV 646 to HV 946. These changes are attributed to the increased penetration of Cr and Ni and decreased penetration of Al during bonding.

(5) Increasing the heating temperature from 350 to 450°C and increasing the treatment duration from 6 to 8 h produced small, dark cavities parallel to the interface. Formation of these cavities is attributed to differences in penetration speed and thermal imbalance of the vacancies.

(6) Increasing the stand-off distance from 1 to 2.5 mm caused more plastic deformation and waviness of the bonding interface and increased the strength from 103.2 to 214.5 MPa.

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