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Characterization of the nugget zone between Aluminum and 304 Stainless Steel Laser Welded

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ABSTRACT
Dissimilar lap joints of AA1050 aluminum alloy sheet and 304 stainless steel (SS) sheet were produced using pulsed laser welding. The effect of welding parameters on the microstructure of the interface and mechanical properties was investigated. The experimental results revealed that maximum shear strength 45MPa obtained when applied 8.3J as a pulse energy with 7.5 ms as pulse width and 8Hz as a frequency. All joints failed at the interface between the two metals and defects were present in the joint. Two phases as intermetallic compounds were identified at the aluminumand 304 SS joint, two of them, namely Al Fe and $Al_{13}Fe_4$, were observed at bothaluminumandstainless steel fracture surfaces. Tensileresidual stresses showed a maximum value at the interface with narrow affectedfor aluminum to stainless steel joints.

KEYWORDS: Dissimilar joint, Laser welding, Intermetallic compounds, Residual stresses, Aluminum-to-304 stainless steel joint

INTRODUCTION

Laser welding has two approaches mechanism,keyhole approach and conduction approach depending on the processing environments. Keyhole approach is extensively used in industrial due to the high penetration depth, high rate of production and narrow heat affected zone formed. The disadvantage of keyhole welding can be unstable of laser beam andmore spattering and causes porosity due to gasesdissolution in weld metalat high temperature and other defects. In contrast,the conduction regime, is more stable, less fluctuating, more controlling for heat distribution supplied to workpiece. Due to low density of power source in conduction regime compare with keyhole regime, the problems for evaporating some alloying elements that have low melting temperature are reduced. Reaching to evaporation temperature produce several problems such as high levels of porosity and blowholes. The disadvantage of conduction mode are low penetration depth and less heat of laser beam absorbed. Cost ofconduction laser welding is lower than keyhole laser welding, because it does not require high qualitypower beam [1-3].Pulsed laser welding is usually used for welds of smallcomponents such as microwave fields, computer accessories, communications devices,and batteries, aerospace, medical applications.

Difference in physical and chemicalproperties of two materials to be welded, such as thermalexpansion coefficient, and melting temperature, leads to many problems occurs. The major goal of any joining process is to achieve a readable joint. Most of processes for aluminum to steel joining require raising both materials to a temperature considerably higher than room temperature. This is true for laser process and other processes.

Mismatch in properties of materials to be welded such as thermal expansion and formation brittle compounds during welding process lead to very large stresses at the interface and in over cases can cause the joint to crack during cool down from the welding temperature[1–5].Most of the beam in keyhole laser welding is absorbed and deep penetration can produce, but in conduction the coupling efficiency of laser beam islow due to smallerabsorbed heat f laser beam to the material.Some researchersfound that the absorption of the laser beam in conduction mode is nearby15 % when laser welding stainless steel while in keyhole regime it reaches to 65% [6]. Laser welding is applied in both similar and dissimilar materials. Several researchers have been reported the joining of similar materials likealuminum [7-10]and stainless steel [11-13].Joining of dissimilar materials by conduction laser welding is in [13-15] are reported. Aluminum to stainless steel weld is one of the most combination of materials used as a structural materials. Due to theproblemsfor joining aluminum to steel or aluminum to stainless steel,numerousstudies using resistance spot welding [16,17],fusion welding [18,19], brazing [20] and solid state welding have been made [21,22,23]. Laserwelding is one of the new joining technologies for joining aluminum to stainless steel. Limited success investigates using keyhole welding in order to join aluminum to steel were made [24-26]. Conversely, investigates using conduction laser welding have indicatedmagnificentresults [27,28]. The benefit of using conduction laser welding in this purpose is associatedto the stability of the process that allows a good control of the temperature distribution in the interface area between the aluminum and the steel [28].Fan Jetal showed that the long cooling time is a major factor to increase the thickness of intermetallic compounds between aluminum and steel [29].

This paper investigates the joint properties and metallurgicalcharacteristics of dissimilar laser welds between AA1050aluminum alloy and 304 stainless steel.The study focused on interface microstructure characterization bymeans of optical microscopy, SEM, EDS, X-ray diffraction analysis and measured the residual stresses across the weld line on the upper sheet (stainless steel).

2. Experimental procedure:

Aluminum AA1050 (Al) and 304 Stainless steel (SS)were welded by pulsed Nd-YAG laser system (Lumonics JK702) with a maximum average power 400W and 1.064µm focal length as shown in Figure 1. Aluminum sheet (80×30×0.5) mm and stainless steel sheet (80×30×1)mm were used in this present study. Overlap designed for shear test dissimilar joints (see Figure2). Aluminum sample of AA 1050-half hard (Fe, 0.4 wt. %; Mg, 0.1wt. %;Si, 0.1wt. %;Mn, 0.1wt.% Al, balance) and 304 stainless steel (C 0.08 wt. % ; Cr18wt.%;Ni, 8wt.%; Mn, 1.5wt.%; Fe, balance) were used for the welding trialsAs illustrated in Tables 1 shows the full set of welding parameters considered in this works for Al/stainless steel after trial and error processes to choose the stable parameters. Prior to laser welding, the specimens grinding with silicon carbide emery papers 1000 grade then cleaned with acetone. Special fixture was made to support the sheets as shown in Figure 1.Argon shielding gas (5L/min) was used during welding process to protect the weld zone from atmosphere. After laser welding, the samples cut along cross-section, grinding and polishing for metallurgical examinations.

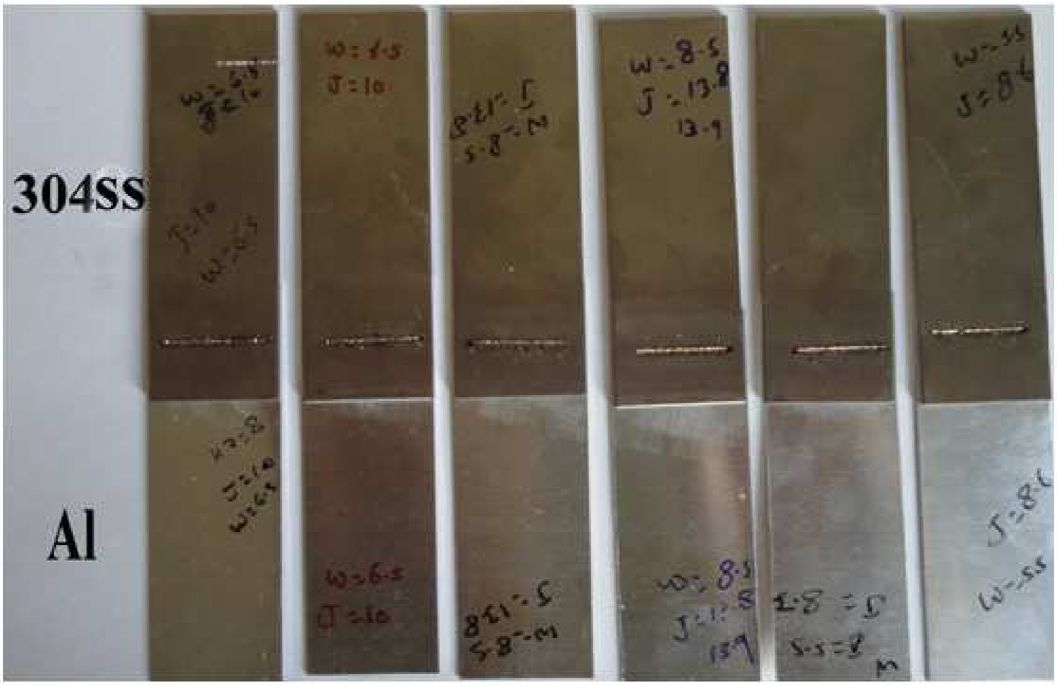


Fig. 1: Aluminum to 304stainless steel overlap joints

Optical microscopy and backscattered scanning electron microscopy (SEM) with EDS and X-ray diffraction techniques were used to analyze the weld joints. Optical microscopy was applied to analysis theweld shape and the interface morphology, while the other techniques were used to generally analysis the diffusion elements across the interfaces between aluminum and stainless steel sides and to identify the intermetallic compounds at the weld interface. For optical microscopy, Al-304SS joints were etched joints in Keller's Reagent (1 mL HF, 1.5 mL HCl, 2.5 mL HNO_3 and 95 mL H_2O) for (15-20 sec) and washed in water, then in stream of warm air.

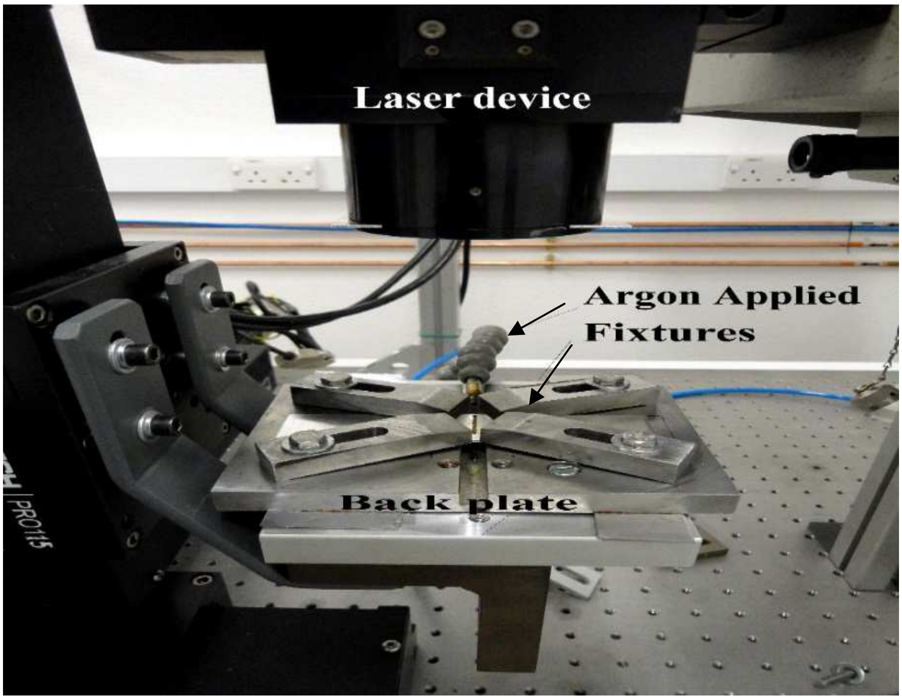


Fig. 2: Laser welding devise with fixtures samples

Residual stresses are measured using a Proto Manufacturing iXRD-portable laboratory X-ray diffraction machine Fig. 3. The sample is placed on a motorized platform that can move in X, Y, Z and Ω (rotary) directions. The X-ray beam is aligned to the surface of the sample with a visible pointing beam. Measurements were taken in the transverse direction to the weld line up to 10mm away from each side of the weld line.

Fig. 3: Residual stresses measurements

The full set of welding parameters considered in this works for Al-304SS illustrated in Table 1.The stable welding process achieved after trial and error to choose these parameters.

Table 1: Laser parameter set up for Al-304 SS welding

Test No.	Pulse Energy J	Pulse Width ms	Frequency Hz	Linear Speed mm/min
1	7	7.5	8	200
2	8.3	7.5	8	200
3	9	7.5	8	200
4	10	7.5	8	200
5	11	7.5	8	200
6	12	7.5	8	200

RESULTS AND DISCUSSION

1-Shear Test:

For Al-304SS joints, ultimate shear stress was found at low pulse energy and it reached a maximum value of45MPa at pulse energy of 8.3 Jwith 200 mm/min, Table 2 shows the average value over 4 samples for each test. All samples fractured after shear test at the interface between aluminum and 304SS of the joints. This means that the weld strength islower than the base metal. Some voids or other defects were observed at the interface. Fractures occurredat the interface may be caused by the defects and formation the brittle intermetallic compounds.

Table 2: Shear test results

Test No.	Shear Stress MPa
1	44
2	45.35
3	35
4	30.4
5	35.5
6	35

2- Residual stresses:

Figure4 shows the maximum residual stress of 80 MPa obtained from aluminium-304SS joint. This stress was tensile in nature and occurred close to the weld line. This stress expanded about 1.5mm from the weld line toward aluminum and 304 SS. It is important to realize that this small value of tensile residual stress small exceeds in aluminum side and the distance of applied tensile stresses is shorter beyond the weld line. The low pulse duration time (7.5ms) and short time for total cycling welding is the main reason for narrowing this distance. Compressive stress observed at 1.5 mm away from the weld line in both materials and extended to the end of the limited distance (10mm) for testing.

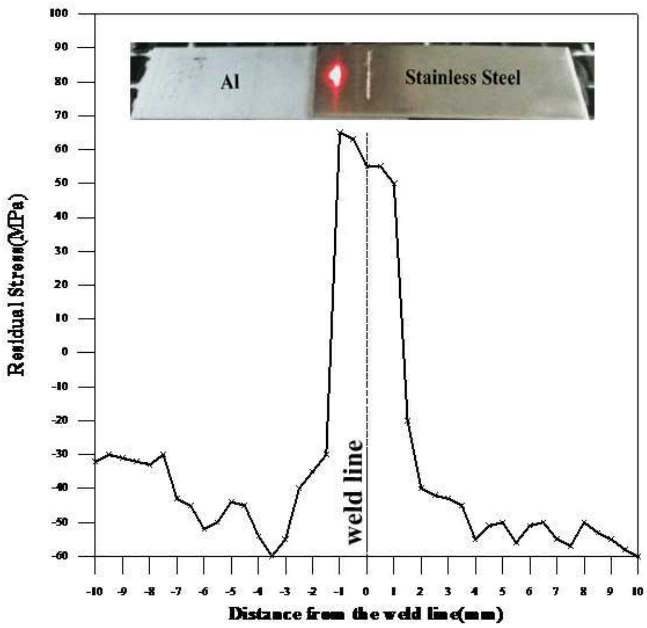


Fig. 4: Transverse residual stresses measurements for Al-304SSJoint**.**

Actual experiments reveal that the fracture path is through the interface between aluminum and stainless steel due to the poor bonding between aluminum and 304 SS. Lower values of shear stresses near the weld line may confirm that there is another reason for the weakness of bonding between aluminum and 304 SS. Formation of brittle compounds at the interface prevented a reliable joint and reduced the strength of the interface.

3- Characteristics of Al-304SS joints:

Figure 5 shows the microstructure of the weld zone of Al-304 SS. Weld nugget observed as irregular shape and incomplete penetration in aluminum sheet thickness (lower sheet). Low penetration due to conduction heat and low absorption of heat while more reflection it at the surface of 304 SS.

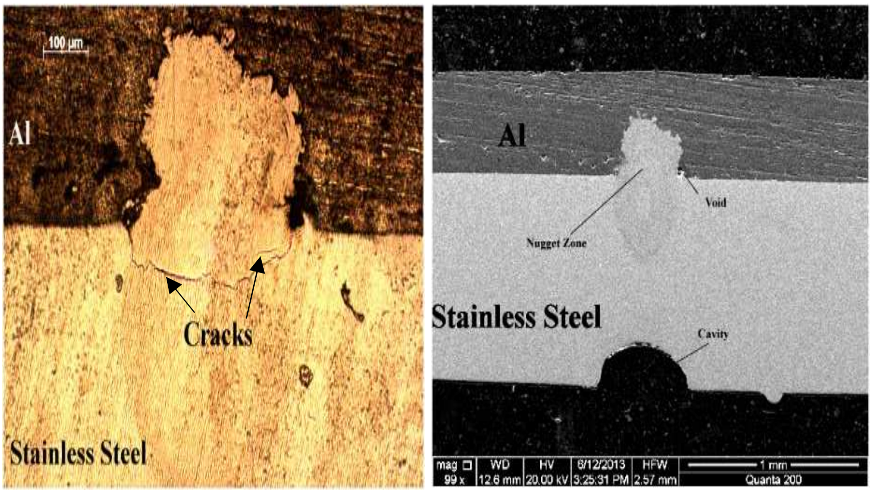


Fig. 5: Microstructure of Al-304 SSjoints by(a)optical microscopy(b)SEM

Undercut defective observed at the top of solidified weld pool due to the slow cooling gravity has exerted a vertical pull causing this defect. Some voids and cracks initiated from the edges and propagate as a concave to the center of the nugget zone.

The x-ray diffraction (XRD) analysis of the weld nugget detected an$Fe_{13}Al_4$, andFeAlintermetallic compounds at the surfaces fractures by shear test in both aluminum and 304SS sides as shown in Figure 6 (a) and Figure 6 (b) respectively. These intermetallic compounds play a main role for decreasing the strength and the toughness of the formed structure at interface between aluminum and 304SS.These lead to form unstable interface between aluminum and stainless steel. At high temperature of laser welding, compounds promote the brittleness of when the thickness of the compounds layer increased at the grains boundaries. Crakes generated due to brittle intermetallic compounds formation.

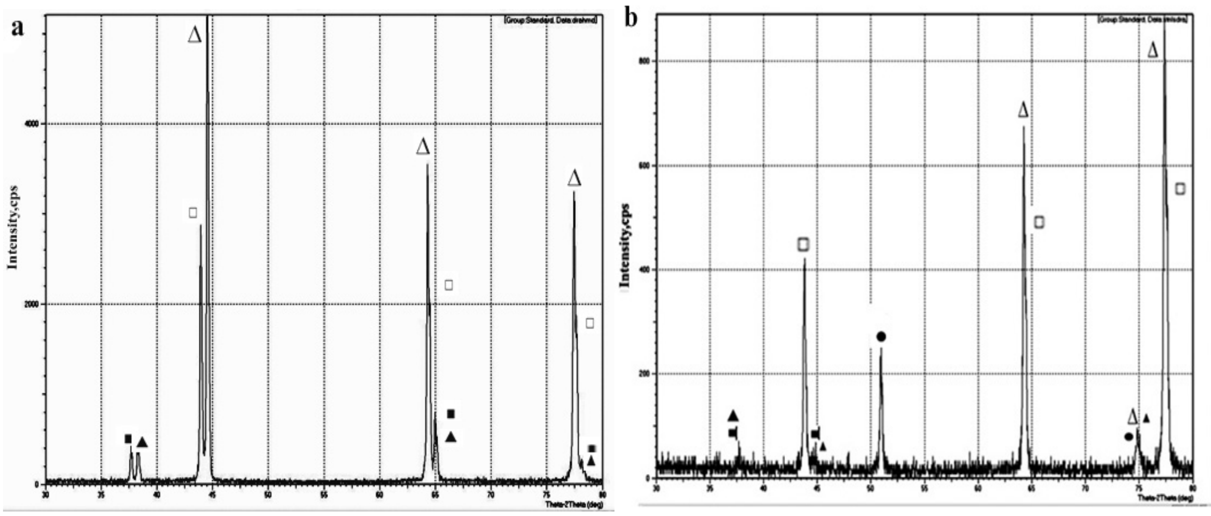


Fig. 6: XRD Patterns of fracture surfaces of Al-304SS Joint: (a) Al side and (b) 304SS side: ΔAl, □Fe, ■Al Fe, ▲Al_{13} Fe_4 respectively

Energy dispersive spectroscopy EDS with scanning electron microscopy SEM used to analysis the structure and measure the weight composition of nugget zone at the different positions. Figure7 shows a gradients of diffusion elements (Al, Fe, C, Cr) in the marked of line-scan. It was found a sharp concentration gradient of aluminum element at the end of nugget zone. Carbon and chromium elements shows fast diffusion from stainless steel towards aluminum base metal while iron element remain at nugget zone. Nickel spectrum not detected in the line-scan. Carbon has high affinity to react with chromium and formation brittle chromium carbides during welding process. Presence of these carbides reduce the toughness of the joint.

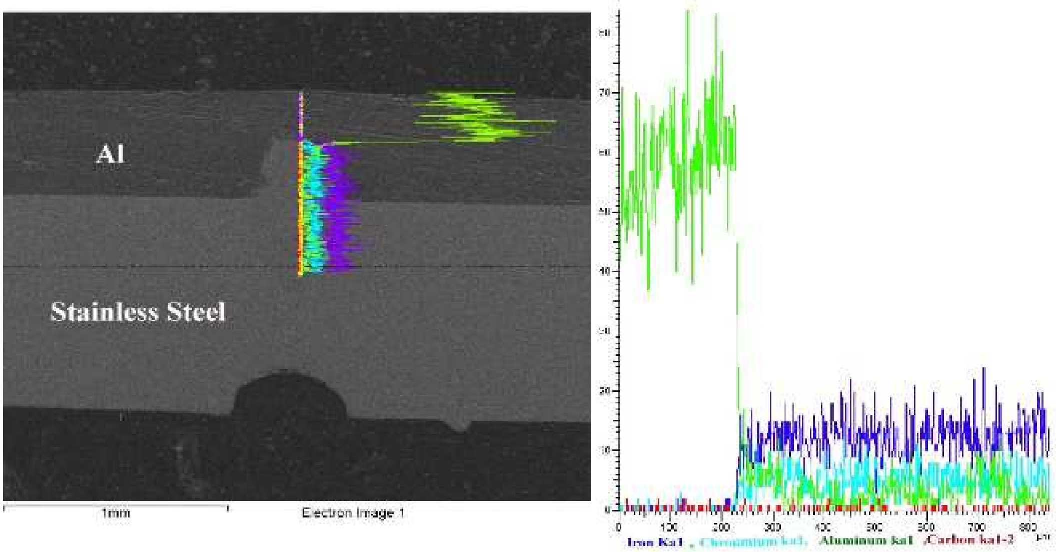


Fig. 7: Line-Scan by EDS with SEM analysis the elements across the nugget zone

In the Figure 8, EDS analysis the weight composition at the spot spectrum in the middle nugget zone. This composition contain 18%wtCr, 8%Ni, 60%Fe and 17%Al approximately.

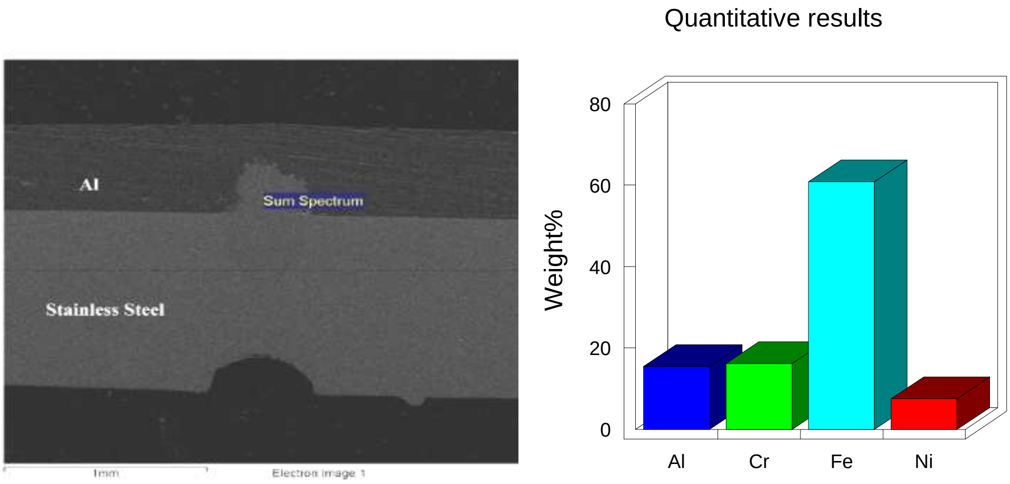


Fig. 8: Composition weight of marked Al, Cr, Fe, Ni elements in spot of center of nugget zone

Figure 9 shows the quantitative results of the weight compositions of elements(Al, Cr, Fe, and Ni) elements across the interface at the right hand. Al wt. % content in the marked spot spectrum is less than in the center of the nugget. Reduced in Al wt. % at the interface due to far away from the Al base metal. It observed increases in Fe composition wt. % due to close the 304SS base metal.

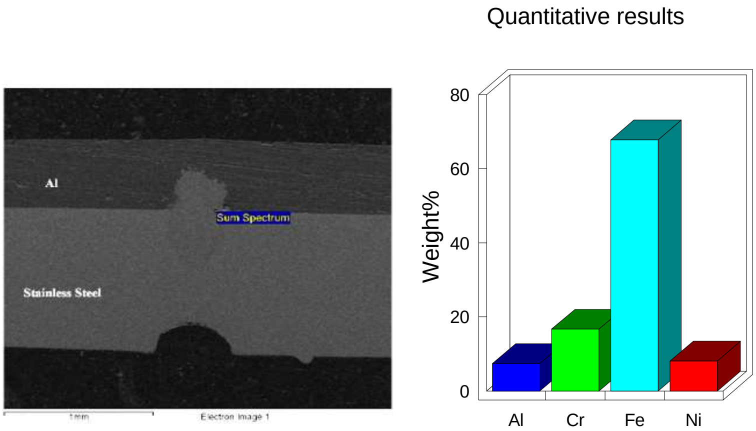


Fig. 9: Composition weight of marked Al, Cr, Fe, Ni elements in spot atright hand of nugget zone

Figure 10 shows the composition of the spot at the center of the interface. It observed decreases in amount of Al at this position and small amount of Mn appear.

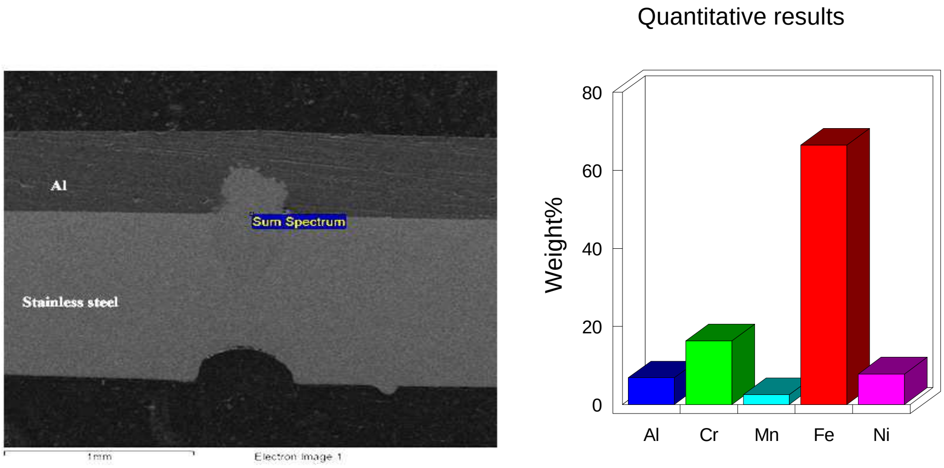


Fig. 10: Composition weight of marked Al, Cr, Fe, Ni elements in spot at center of nugget zone

Figure (11) shows a composition at the left spot. The composition approximate is the same spot scan in the left hand.

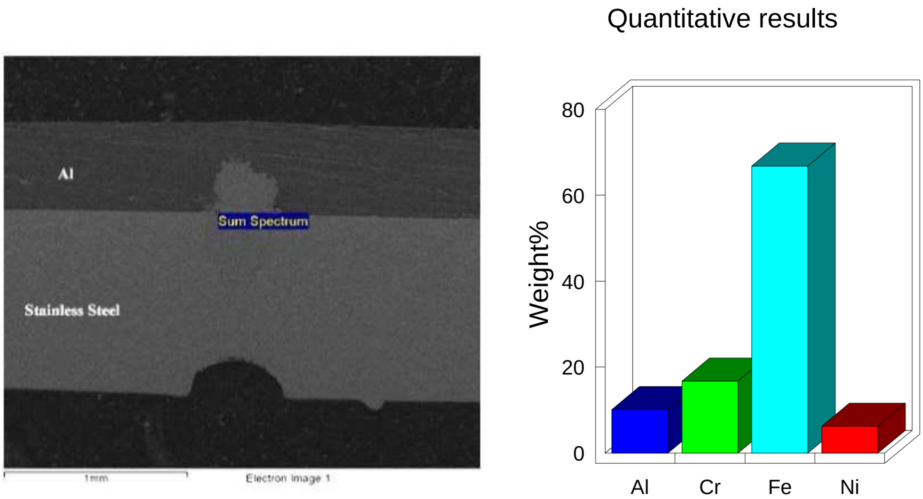
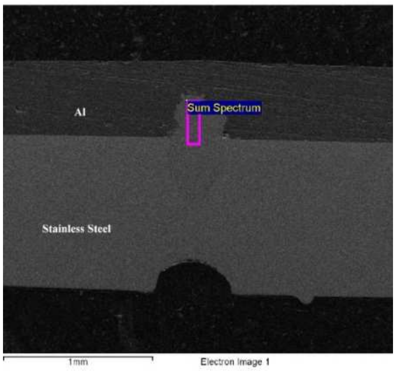


Fig. 11: Composition weight of marked Al, Cr, Fe, Ni elements in spot at left hand of nugget zone

It is seen from the figures above the concentration of iron element is higher than other elements in the each area of the nugget zone and the interface. This means that iron element remain as steady state of concentration during spot welding and the figure12 confirm this result at area-scan at nugget zone. Also the carbon element is not detected at figures above except by line-scan due to very small amount in 304SS.



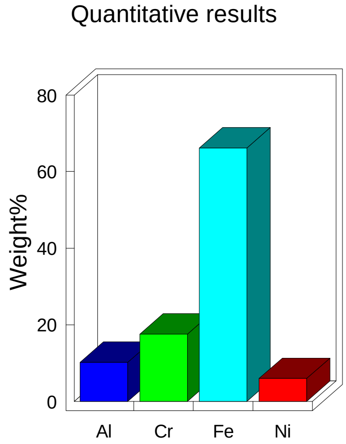
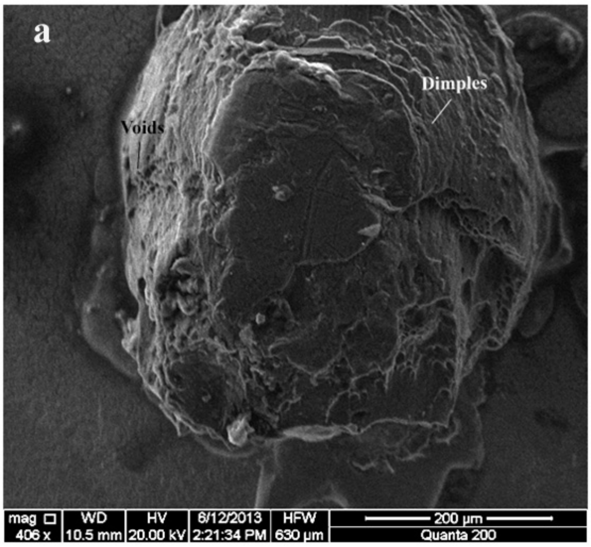


Fig. 12: Analysis of area-scan at nugget zone

Figure 13 shows the fracture surface by SEM of Al-304SS joint after shear tensile test at aluminum side. A cone and arrow of dimples shows at the fracture shape is observed at the pulse weld. The fracture surface is ductile behavior and some voids observed. More intermixing diffusion for elements; Al, Cr, Fe occurs. EDS analysis of the scanned weld area showed 78 wt. % of Al and 17%wt. of Fe and 5wt%Cr (Figure14). The presence of Cr and Fe promote the formation of brittle compounds by chemical reaction with aluminum and carbon.



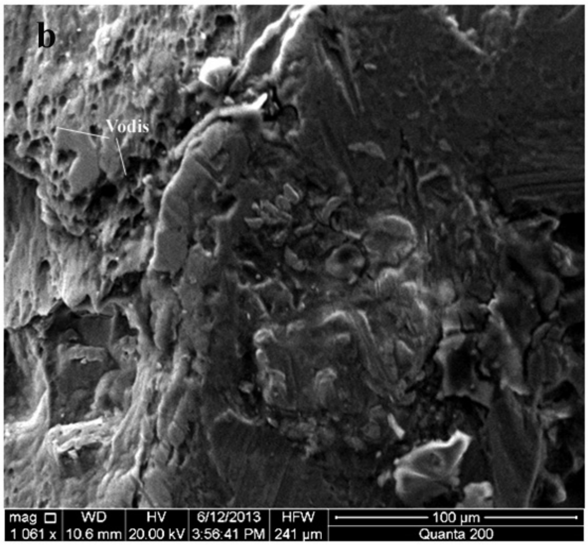


Fig. 13: Fracture surface of Al nugget zone by SEM(a)Low magnification(b)High magnification

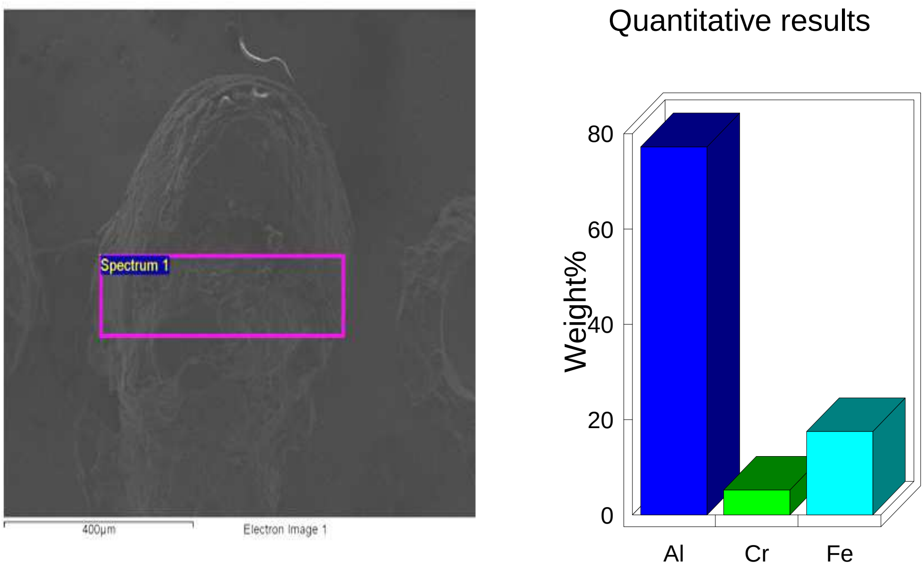


Fig. 14: Analysis of composition of Al nugget zone by EDS

Figure15 shows the fracture surface after shear tensile test on the 304SS side by SEM. It observed that a cup shaped formed in each pulse center with cracks and voids at the circumference of shape pulse. This indicated that more brittle intermetallic compounds formed closed to the 304SS side and a degradation of the bond between aluminum and 304SS.It not observe dimples arrow while a cleavages fractures occurs.

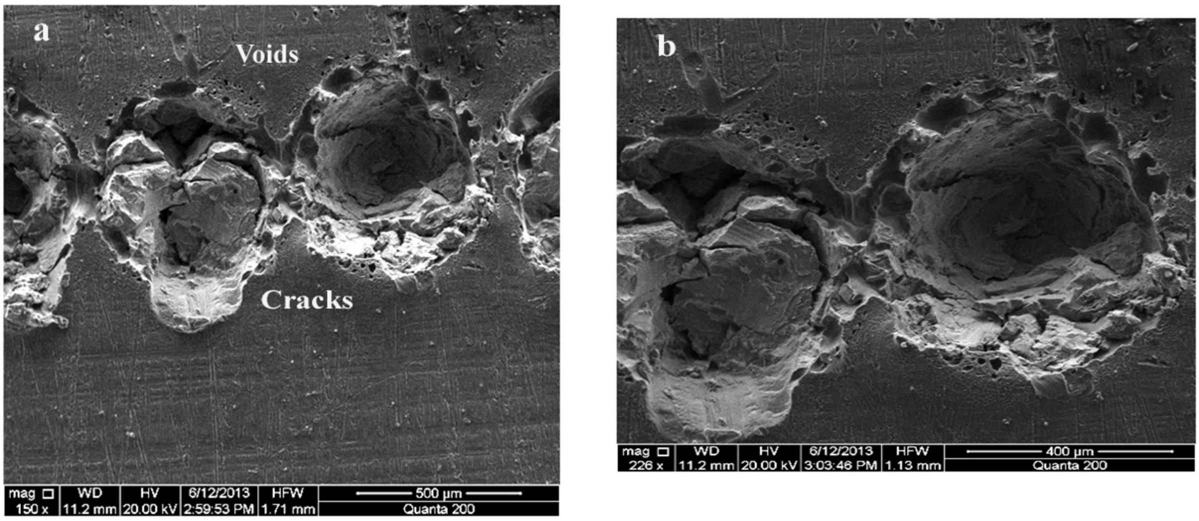
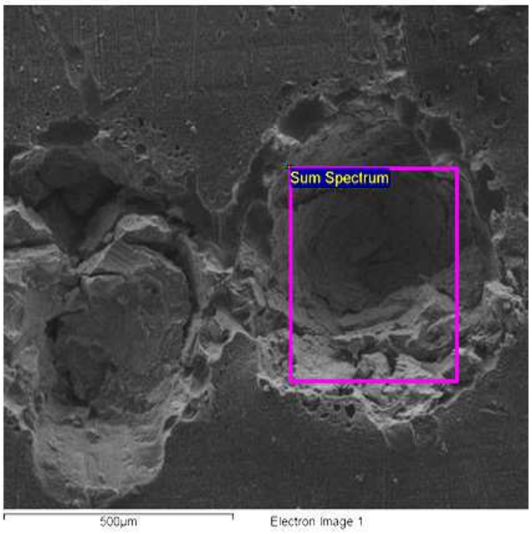


Fig. 15: Fracture surface of 304SS nugget zone by SEM(a)Low magnification (b)High magnification

EDS analysis by area-scan of the fracture surface of 304SS indicated 32wt%Al, 50wt%Fe, 11wt. %Cr and 5wt. %Ni.It was found an increase in wt. % of Cr content due to implantation of some Cr from grain boundary. Also showed more Al content in the fracture surface of 304SS and this result confirms a chemical reaction between aluminum and iron to formation brittle intermetallic compounds (Figure16).



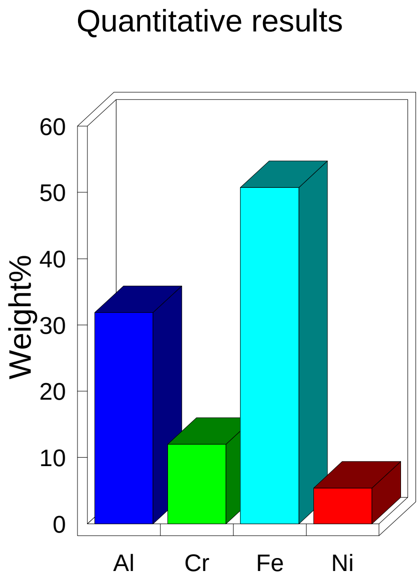


Fig. 16: Analysis of composition of 304SS nugget zone by EDS:

Conclusions:

In this paper dissimilar joints of aluminum and 304 stainless steel welded by pulse laser is investigated. A maximum shear strength of 45MPa obtained for Al-304SS joint under 5L/min flow of Ar gas. The weld parameters in this case are: pulse energy 8.3J, pulse width 7.5ms, frequency and linear speed8Hz and 200 mm/min respectively. All fracture occurred at the interface between Al and 304SSunder tensile shear test. The intermetallic compounds Al Fe and Al_{13} Fe_4, for Al-304SS joint, formed at the surface of the Al and 304SS sheets. Also, the nugget zone of this joint reviled that intermixing of Al and 304SS stainless steel elements are uniformed.

Cracks and voids observed at the interface between Al and 304SS and they are higher observed at the fracture surface of 304SS.Maximum tensile residual stresses observed at the interface of the joint and it is affect at a narrow distance of the joint.

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