Fracture Analysis of Microwave Induced Al6061 Joints

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Abstract

Increase in applications of aluminum alloys in all sectors of industry tends to develop new technologies for joining of aluminum without affecting the properties of metal. In present work joining of aluminum 6061 has been done by using the newly developed the microwave welding technique. Microwave Joining of aluminum has been successfully achieved without formation of cracks, burn through and distortions defects, which are otherwise very difficult to control. A domestic microwave working at 2450MHz frequency and at 900w power load was used for joining. For joining process aluminum powder with 99.9% purity and 5µm in size was used as bonding agent between two metal pieces. Structural and mechanical properties of the joined samples were observed through different testing techniques like Vicker's harness test, porosity and tensile, SEM and EDS. The observed result for microhardness shows 87±8 Hv. The fractured sample during tensile testing shows an ultimate tensile strength of 142MPa with 14% elongation.

Keywords- *Aluminum 6061, Microwave heating, SEM, UTS*

I. INTRODUCTION

Welding of pure aluminum is difficult as compared to the welding of other metals like steel, iron etc. Formation of oxides during aluminum welding is the main problem. But due to low weight, high strength and non corrosive properties of aluminum now a day the heavy metals like steel, iron used in industries or automobile sector are replaced with aluminum and its alloys. Therefore development of new technologies are required for joining of aluminum, which causes minimum effect on mechanical, chemical and metallurgical properties of metal. Microwave energy can be effectively used for metal processing. In microwave processing the fundamental of heating is totally opposite to traditional heating process. In conventional heating process the heat is conducted from the surface of the to the inner core of the metal, but in microwave heating the heat is introduced due to the penetration of the electromagnetic waves inside the material therefore heating is uniform throughout the material [1], [2], [3], [4]. Heating through microwaves depends upon the absorbing (dielectric) properties of the materials [5]. Due to good absorbing properties ceramic, polymers and composites are found to be effectively and efficiently processed by microwaves as reported by many authors [6], [7]. Due to the reflection of the microwaves at ambient temperature metals are very difficult to process through microwaves [8]. As a solution of this problem it was reported that metals could be processed through microwaves by processing the metals in powder form [9], [10]. Sintering of metal powders using microwave energy has been investigated by several researchers since last decade [11], [12]. Later on microwave processing technique has been effectively used for joining of materials. But this joining process was limited to the ceramics only. First effort to microwave joining of bulk metals was achieved by Siores et al. [13]. Recently, joining of metals in bulk form using microwave energy has been successfully reported. Same author also reported joining of dissimilar metals using domestic microwave oven [14], [15], [16], [17]. Joining of mild steel plates through microwave energy using SiC as susceptor has been also reported [18]. It is clear from the literature that limited work has been reported in the area of joining of metals through microwave energy. In this research work study of joining Al6061 through microwave energy has been reported.

II. MATERIAL SELECTION

High strength-to-weight ratio of aluminum (Al) alloys has attracted the interest of automobiles, defense and aerospace industry. In this research work Al6061 was selected as the base metal to join through microwave induced heating. TABLE I represents the mechanical properties of Al6061 and TABLE II represents the chemical composition of Al6061.

TABLE I
MECHANICAL PROPERTIES OF ALUMINUM 6061

Yield Strength	Ultimate Tensile Strength	(%) Elongation	Shear Strength	Vicker's Hardness
254 MPa	309 MPa	12%	205MPa	108 HV

TABLE II
CHEMICAL COMPOSITION OF ALUMINUM 6061

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.70	0.35	0.28	0.04	1.0	0.16	0.04	0.05	Remaining

III. JOINING PROCESS

In this research work joining of aluminum 6061 through a green, time saving and cost effective process was introduced. Heat required for melting and joining was generated by conversion of electromagnetic energy in to heat energy. A domestic multimode microwave of 1kw load at a fixed frequency of 2.45GHz was used as heat source. For joining of Al 6061, aluminum powder 99.9% in purity and 5µm in size was used as bonding agent. But it was difficult to place aluminum in between the metal piece in powder form. To avoid this slurry was prepared by mixing aluminum powder with epoxy resin. This slurry was filled in the gap between the metal pieces. Microwaves produces spark when they are interacted with metals owing to the very low penetration depth, so they get reflected from the surface. But from the literature it was observed that the penetration depth of the microwaves for metals can be increased by making metals microwave absorbing or placing a microwave absorbing material at the surface of the metal. To avoid reflection of the microwaves, metal pieces were place in refractory brick. In this research work charcoal powder was used as absorbing material. Charcoal get interacted with microwaves and heated up very fast. This generated heat is then transferred to the prepared slurry at the interface zone. To avoid the mixing of charcoal powder with slurry a thin graphite sheet was used as separator. This transferred heat increases the temperature of metal powder used as bonding agent upto elevated temperature, beyond which the metals starts coupling with the microwave and there was sudden increase in the temperate of the metal powder. Which results in melting of metal powder and on cooling a uniform joint was formed. Fig.1 (a) and (b) shows the view of join while microwave processing and formed joint after processing. Argon gas was used shielding gas to avoid the formation of oxides during microwave processing.

Fig 1: View of microwave processed joint (a) while processing (b) formed joint

IV. TESTING AND RESULTS

A. Hardness and Porosity measurement

Vicker's microharness tester was used to measure the harness of the joint. The microhardness was measures at different locations of the joint zone along with the base metal. Average of three readings was recorded. Microhardness of the microwave processed joint was measured using a load of 10 g for 30 s. Fig. 2 presents the indentation image at the joint zone. At the weld region average joint microhardness was observed to be 87±8 Hv, and at the joint interface was observed 92±5. The higher hardness value nearer the interface zone was due to the present of hard phases, which results in shear failure of the joint during tensile testing. Further, growth of columnar microstructure nearer to the fusion boundary and presence of hard intermetallic do contribute towards this improvement in joint microhardness. TABLE III represents the hardness test results at different locations. The average micro hardness on the either sides of the base material was measured to be ~ 81 Hv and 84 Hv, which are reasonably close. Measurement of porosity is very important task for any weld specimen. In this research work porosity of the joint was measured by using least count method. The observed porosity of the joint recoded to be 1.38% at the center of the joint and 1.67% at the interface zone. Higher value of porosity may be due to the inclusion of gasses produced on burring of epoxy resin used for making slurry.

TABLE III
HARDNESS TEST RESULTS

Parameters	**Joint zone**	**Interface zone**
Vickers' microhardness	87±8	92±5
Porosity	1.38%	1.67%

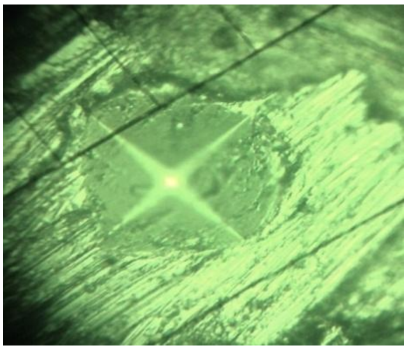

Fig 2: Indentation image for Vicker's hardness at joint zone

B. SEM Analysis

Scanning Electron Microscopy was used to analyze the microstructure of the joint. Fig. 3 shows the SEM micrograph of the joint zone. It is evident from the SEM micrograph that there was total melting of the metal powder at the joint zone due to the volumetric heating. A well fused joint and properly merged with the metal pieces can be clearly seen. Fig. 4 shows the enlarged view of the joint zone. A well defined and elongated grain structure of microstructure was observed.

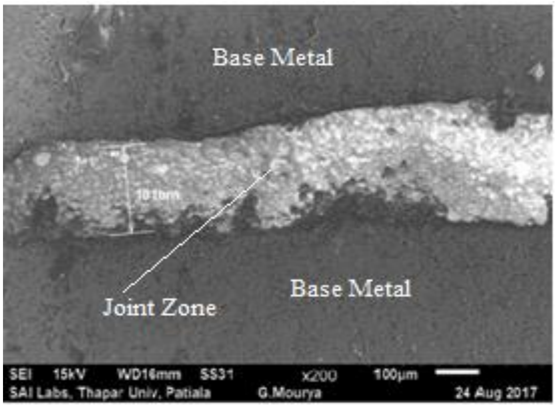

Fig 3: SEM image of Aluminum 6061 joint developed through microwave processing.

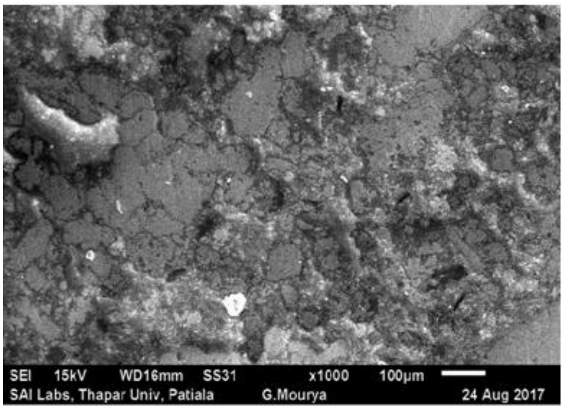

Fig 4: SEM image of joint zone at higher magnification

C. Tensile Strength

To analyze the strength of the joint tensile strength test was performed on developed microwave induced joints. The tensile test was conducted on Universal testing machine at a uniform strain rate 2.63×10^{-4}mm/s specimens were prepared according to ASTM standard as shown in Fig. 5.

Fig 5: View of tensile test specimen

The test results for fracture sample are shown in TABLE IV. It was observed while testing that the microwave jointed sample failed at the joint area only. Fig. 6 presents the stress-strain characteristics of microwave processed aluminum joints while subjected to tensile loading. Initially upon loading pont A the material behaves plastically. Further, increase in the loading could lead to strain hardening in the joint zone which continuous till (point C) stress reaches to ultimate tensile strength of 142MPa. Loading beyond this limit resulted in sudden failure of the joint. It was analyzed from the stress-strain curve that the failure of the joint was in mix mode of failure. Complete fusion of the powder particle and susceptible metallurgical bonding was evidenced from the significant elevation obtained during tensile testing of the processed joint.

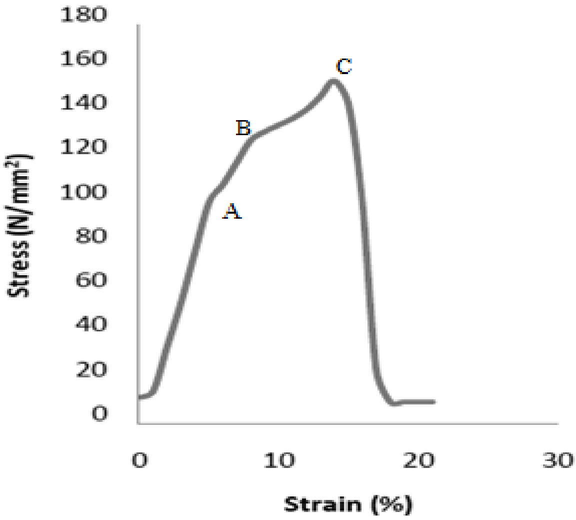

Fig 6: Stress Strain curve of fractured aluminum joint during tensile loading

Further, the characterization of fracture sample during tensile testing was done using scanning electron microscope. Fig. 7 represents the SEM micrograph of a fracture joint. It was analyzed from the topography of fracture sample, that at the joint interface mixed mode of failure was occur. Evidence of both ductile and brittle mode of failure in the joint zone could be clearly seen. Ductile failure of the joint under tensile loading was evidenced from the presence of concave depressions on the fracture surface, characterized by microscope. However, due to the presence of hard phases like aluminum iron silicon and Al_3Ni_2, this plastic flow could not continue and the shearing occurs. This leads to both ductile as well as brittle mode of failure at the joint interface. These hard particles do not allow the material to flow elastically during tensile loading and does sharing action occurs at the joint zone. This sharing finally leads to occurrence of failure of the material at the joint area. The dominance of brittle failure in the joint zone could be in the area where total melting of the powder particle takes place in the sandwich layer and subsequent resolidification during microwave irradiation.

TABLE IV
ULTIMATE TENSILE TEST RESULTS

Ultimate Tensile Strength (UTS)	142 MPa
(%) Elongation	14.23%

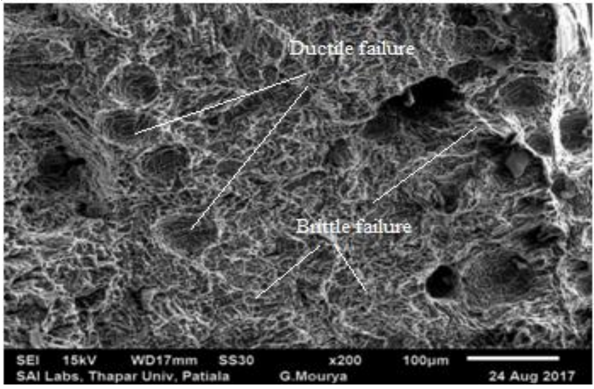

Fig 7: SEM micrograph of typical fractured aluminum joint during tensile loading

D. EDS analysis of fracture joint

Fig. 8 shows a typical EDS spectrum of a fractured specimen understand tensile loading. This higher percentage aluminum along with Fe, Si, Ni, Cu once again confirms the presence of brittleness subjected to tensile loading. The formation of quasi cleavage patterns at the joint zone indicates the failure of the joint in both ductile and brittle mode.

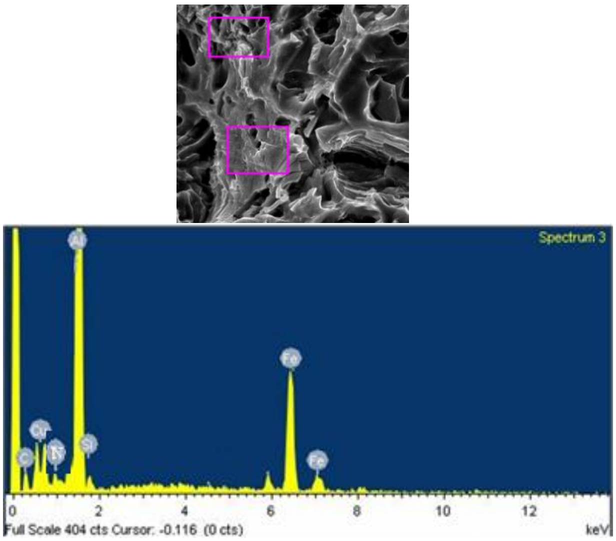

Fig 8: EDS spectra of fractured aluminum joint under tensile loading.

V. CONCLUSSIONS

In the present work a new approach of joining Al6061 through microwave energy has been studied. It is evident from the above observations that Al6061 could be joined efficiently and effectively by using microwave energy. The main conclusions drawn from the present work are:

(1) Microwave energy has been effectively used for joining Al6061.
(2) Aluminum metal powder 99.9% and 5µm in size was used as bonding agent between two metal pieces.
(3) Formation of aluminum iron silicon and Al_3Ni_2 was observed in the microstructure.
(4) Vicker's microhardness recorded to be 87±8 Hv at the joint zone.
(5) Tensile strength was observed to be 142MPa with 14.23% elongation.
(6) The joint partially fails due to ductile failure and partially due to brittle failure. There for a mix mode of failure was observed from the analysis of the fractured surface of the sample.

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