Experimental investigation on characterization of microwave welded Al6061-Gr-SiC hybrid metal matrix composites

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Abstract – In the present work, experimental microwave welding of Al6061-6%Gr-SiC hybrid metal matrix composites (MMC) in bulk form has been carried out. The principle of microwave hybrid heating was applied with domestic microwave having the frequency of 2.45GHz and 900W power. The interface powder Al6061 and susceptor as charcoal powder were used for the welding process. The stir casting process was used to prepare Al6061-6%Gr-SiC hybrid MMCs by varying SiC content by 3%, 6% and 9% and keeping 6% graphite constant by wt%. The composite weld joints were characterized by scanning electron microscope (SEM) equipped with energy dispersive spectrum (EDS) and mechanically through tensile test, Rockwell hardness test and impact test. The microstructure study showed the good metallurgical bonding between the interface and base composites without any visible cracks. The SEM-EDS study revealed the formation of various carbides and inter metallics at the weld interface. The average ultimate tensile strength of the joint was found to be 135MPa with 4.3% elongation. The average Rockwell hardness at the weld joint observed was 61.5HRB. The average impact strength of welded composite was 1.62J/mm².

Keywords: Al6061-Gr-SiC MMCs, Microwave, Welding, Microstructure, Tensile strength, Hardness, Impact strength, Susceptor.

1. Introduction

Metal matrix composites are fast replacing conventional metallic alloys in aerospace, automobile, defence, marine and sports industries due to their excellent combination of properties. Among the alloys, aluminium alloys are the most utilized metallic alloys as matrix material both in research and industry. The aluminium alloys are used in light weight applications due to their properties such as low density and high strength to weight ratio [1]. The major advantages of aluminium based MMCs are the reduction in overall weight, lower fuel consumption and emissions in automobiles. The hybrid composites possess better microstructural and mechanical properties than the single reinforced composites. Aluminium matrix composites reinforced with silicon carbide (SiC) and graphite (Gr) have attracted a considerable attention due to their better mechanical properties and excellent wear resistance. Hence proper volumetric or weight shares of graphite and SiC reinforcements is required in order to get optimum mechanical and tribological properties [2]. Some of the applications of aluminium based composites in automobile industry are pistons, connecting rods, engine cylinders, brake systems and many more. These MMCs are also finding applications in aerospace and space industries [3]. The growth in the field of
engineering and technologies led the industries to find new and improved methods that can be used for processing of wide range of materials like metals, non-metals, ceramics and composites. The developed new methods should have the characteristic of lower energy consumption and higher production rates.

The welding process plays a very significant role in the manufacturing industries. The reasons for welding are: 1) achieve large size of components and geometric complexity which is difficult to obtain by casting, forging or other methods, 2) adding material where it is required and 3) material optimization and many more. The commonly used welding processes are soldering, brazing, friction stir welding, electron beam welding, laser welding etc. But these welding techniques have their own disadvantages like higher power and processing time, costlier set up, operator safety and poor characteristics of the joint. The welding of composites is complex process due to the possible chemical reaction between matrix and reinforcement at higher temperatures, low weld efficiency and settlement of impurities. So, for the industries a more versatile, faster and cleaner process is required that not only improves the production rate but also the microstructural and mechanical properties. The microwave welding of materials is not only an alternative to high energy consumption heating techniques, but also it can meet the needs of the modern industrial applications [4].

In the past, the microwaves were used widely in the field of food processing. Later further research revealed the use of microwave energy in material processing. It is not only a green manufacturing process, but also significantly faster at relatively low investment with selective and volumetric heating capability and improved microstructure. The frequencies of microwaves vary from 300MHz to 300GHz with wavelengths from 1mm to 1m. The microwave energy is produced by the interaction of electric field and magnetic field. The interaction of electromagnetic waves with molecules produces volumetric heating and the energy is directly transferred to the material. In conventional method, the heat is generated from the external sources but in microwave heating, it is generated internally within the material and gets transmitted outward [5].

The welding of metallic materials in bulk form using microwave energy is challenging as the most of the metals reflect microwaves at room temperature. The unique characteristics led many researchers to carry out microwave welding of bulk metals such as stainless steel, aluminium, copper, iron, tungsten etc. with significant importance. M. S. Srinath et al. [6] have reported the welding of dissimilar materials such as mild steel (MS) with stainless steel (SS) through microwave energy technique which resulted in good metallurgical bond and lesser defects. Gupta and Kumar [7] have studied the microwave welding of stainless-steel using nickel metallic powder as sandwich layer. The joint showed no visible cracks and strong interfacial bond with uniform microstructure was observed. Badiger et al. [8] have joined Inconel-625 alloy using microwave energy technique and studied the microstructural and mechanical properties of the joint. Bansal et al. [9] have microwave welded stainless steel (SS-316) using nickel-based powder as interfacial material and studied joint microstructural and mechanical properties. Further many other researchers were encouraged to weld bulk metallic materials using microwave energy and reported better microstructure with lesser defects [10] [11] [12].

The available literature showed that the microwave energy is used successfully to weld bulk metals with very fewer reports on the microwave welding of hybrid MMCs. The aim of the present investigation is to weld Al6061-6%Gr-SiC hybrid MMCs by using the principle of microwave hybrid heating and study their microstructural and mechanical properties.

2 Experimentation

The welding of MMCs using microwave energy is very challenging as they do not allow the microwaves to penetrate inside the bulk composites and get reflected at room temperature. This can be overcome by using the principle of microwave hybrid heating with proper susceptor medium. The susceptor transfers the heat to the bulk composites by absorbing microwave energy and a number of trials were carried out. Al6061 based powder was used as filler material between the welding surfaces. The present study showed the successful welding of Al6061-6%Gr-SiC hybrid composites using microwave energy technique. The experiments were conducted using the domestic multimode microwave oven (Make: Samsung) with 2.45GHz frequency and 900W power. The mechanical properties of the joints were
studied by performing tensile, Rockwell hardness and Charpy impact tests. All the specimens were prepared as per ASTM standards for the experiment.

2.1 Material selection

The stir casting method was used for the preparation of Al6061-6%Gr-SiC hybrid MMCs. In the preparation of hybrid MMCs, the commercially available Al6061 alloy billets as matrix material, the reinforcements SiC with a particle size of 40µm and graphite with particle size of 100µm were used. The reinforcement SiC was varied with 3%, 6%, 9% and graphite at 6% constant by weight percentage. This produced a very hard and strong composite. It has characteristics like low density, high strength and thermal conductivity etc. [13]. The chemical composition of Al6061 alloy and Al6061 interfacial powder are given in table 1. The physical properties of Al6061 alloy, reinforcements SiC and graphite are given in table 2. In the present experiment, charcoal powder as susceptor and commercially available Al6061 based powder with 97.9% purity having average particle size of 30µm as an interfacial material was used for microwave welding. During microwave hybrid heating (MHH), the conventional mode of heat transfer was provided by the charcoal powder since it is a good absorber of microwave energy.

| Element | Al6061 alloy (%) | Al6061 Powder (%) |
|---------|------------------|-------------------|
| Mg      | 0.9              | 0.85              |
| Si      | 0.6              | 0.39              |
| Fe      | 0.5              | 0.35              |
| Cu      | 0.32             | 0.28              |
| Zn      | 0.2              | 0.15              |
| Ti      | 0.12             | 0.10              |
| Mn      | 0.12             | 0.12              |
| Cr      | 0.3              | 0.28              |
| Al      | Balance          | Balance           |

| Physical properties | Al6061 alloy | SiC | Graphite |
|---------------------|--------------|-----|----------|
| Tensile strength MPa| 115 (T)      | 3900 (C) | 20-200 (T) |
| Melting point °C    | 650          | 2200-2700 | 3915     |
| Hardness (HB500)    | 30           | 2800 | 1.7mohs scale |
| Density g/cm³       | 2.7          | 3.1  | 2.09     |
| Poisson’s Ratio     | 0.33         | 0.14 | 0.14     |

2.2 Microwave Welding

Prior to the welding, Al6061-6%Gr-SiC hybrid MMC specimens were polished mechanically with emery paper of different grades and cleaned with acetone to remove dust and impurities. The welding thickness of approximately 1mm to 2mm was maintained with butt joint configuration. The interfacial powder Al6061 was mixed with epoxy resin and hardener to prepare paste like slurry. The paste was applied uniformly between the composite specimen interfaces. The epoxy resin binds the interface material with specimens. Then the graphite sheets of approximately 0.5mm thickness were used to cover the specimens. These graphite sheets avoid the intermixing between the charcoal susceptor with specimens and prevents the specimens from direct exposure to microwaves. The initial coupling of microwaves with composite specimens was provided by charcoal powder and poured near the weld region. The microwave oven was switched on with required power and exposure time after the covered specimen kept inside. As the microwave exposure started, the charcoal powder began to couple with microwaves and increases the temperature rapidly at the weld region. The figure 1 shows the schematic diagram of experimental microwave welding of Al6061-6%Gr-SiC hybrid MMCs. The table 3 gives the microwave processing parameters used in the experiment.
Microwave frequency | Multimode -2.45 GHz
---|---
Exposure power | 900 W
Base Material | Al6061-6%Gr-SiC MMC
Interfacial material | Al6061 based powder
Susceptor material | Charcoal powder
Exposure time | 12mins (720s)

**Table 3.** Microwave processing parameters.

The graphite sheets transfer this heat by conventional mode of heat transfer to the interface layer Al6061 powder. The epoxy resin got evaporated at higher temperature without affecting the weld strength. During this period, microwaves were absorbed by Al6061 powder particles directly and wetting takes place at the joint region. The molten particles of Al6061 fuse with the melted thin interface layers of composite specimens. The microwave welding of composite specimens was carried out with exposure time of 720secs (12mins). Before conducting the final experiment, the trails were carried out and the exposure time was determined. After the process, the entire specimen assembly was taken out from the oven and kept for cooling at atmospheric conditions. On cooling, the homogenous and dense joint was formed between specimens with complete melting of the interfacial layer.

2.3 Characterization of joints

The microstructure study of the joints was carried out through scanning electron microscopy (SEM) equipped with energy dispersive spectrum (EDS) (Make: JEOL JSM, Model: JSM-IT500LA, Japan). Prior to the SEM-EDS characterization test, the specimens were polished mechanically with series of abrasive papers of different grades ranging from 200 to 2000 grades and finally polished by velvet cloth. The Keller’s’ reagent was used to etch the polished specimen to reveal the microstructure. For the mechanical property evaluation, the ultimate tensile strength and percentage elongation were determined using the universal testing machine at room temperature, the hardness measurements were carried out using Rockwell hardness tester and the Charpy impact test was used to determine the impact strength.

3 Results and discussion

In the present work, Al6061-6%Gr-SiC hybrid composites were welded successfully by exposing them to microwave radiations for 720s (12mins) at 2.45 GHz frequency and power of 900W in a multimode domestic microwave oven. The characterization results were discussed with appropriate illustrations in the following paragraphs.

3.1 SEM-EDS observations

The figures 2-5 illustrates the SEM microstructure of hybrid composite joints. The images show the good metallurgical bond between interface material and hybrid composites with complete melting of Al6061 based powder particles.

All hybrid composite joints are dense and homogenous as illustrated in SEM images. The uniform heating has resulted in homogenous joint. The well bonded microstructure between interface layer and bulk composite results in more efficient joint. The weld zone contains more Al6061 powder particles than the reinforcements SiC and graphite. The SEM images of composite joints with different content of reinforcements show fewer voids and absence of cracks. In figure 4, it is observed that Al₂O₃ and graphite particles have tendency to segregate and cluster at inter-dendritic regions. The images also show the unreacted carbons particles in the joint area [8-9][16].
The EDS analysis of Al6061-6%Gr-SiC composite joints is carried out at different positions and are shown in figures 6-8. The EDS figures indicate the aluminium as major constituent element with other elements such as oxygen, carbon and sulphur (S). The presence of carbon is appeared due to diffusion from graphite sheet or decomposition of SiC reinforcement at higher temperature. The carbon and oxygen elements in EDS analysis confirms the presence of reaction products aluminium carbide and aluminium oxide. The molten aluminium reacted with carbon to form aluminium carbide (Al4C3) phase at higher temperature. Many researchers have observed that the formation of aluminium carbide is unavoidable in welding of Al-based composites using different methods [17-20].
3.2 Observations from tensile test

The universal testing machine (Make: Testwell Instruments, Model: TUTE60T, India) of capacity of 60 tonnes was used to evaluate the tensile properties of microwave welded hybrid MMCs. The specimens were prepared as per ASTM E-8 standards having the gauge length of 50mm and width of 12.5mm as shown in figure 9. The microwave welded tensile specimens are shown in figure 10. The table 4 summarizes the recorded ultimate tensile strength and percentage of elongation of Al6061-6%Gr-SiC hybrid composites.

Table 4. Tensile test results.

| Composites         | UTS (MPa) | % Elong. |
|--------------------|-----------|----------|
| Al6061             | 85        | 2.8      |
| Al6061-6%Gr-3%SiC  | 115       | 6.8      |
| Al6061-6%Gr-6%SiC  | 145       | 4.4      |
| Al6061-6%Gr-9%SiC  | 195       | 3.2      |

From the table 4, the ultimate tensile strength of Al6061 alloy joint was found to be 85MPa with 2.8% elongation. For the Al6061-6%Gr-3%SiC MMC joint, the ultimate tensile strength was found to be 115MPa with 6.8% elongation. For the Al6061-6%Gr-6%SiC MMC joint, the ultimate tensile strength was recorded as 145MPa with 4.4% elongation and for Al6061-6%Gr-9%SiC MMC, the ultimate tensile
strength was found to be 195 MPa with 3.4% elongation. The average ultimate tensile strength of microwave welded hybrid MMC joint was 135 MPa with average elongation 4.3%. From the test results, it is observed that as the content of SiC is increased, the ultimate tensile strength also increased for the welded joints. This is due to the strong metallurgical bond between bulk composites and interfacial Al6061 layer along with plastic deformation resistance of harder SiC particles. The elongated grains and few semi-molten Al6061 particles as observed in SEM images also enhanced the strength. The reduction in elongation or ductility is due to the brittleness of SiC particles and presence of aluminium carbide phases in the weld region. Similar observations were made by other researchers [18-21]. The figure 11 indicates the variation of ultimate tensile strength for welded composites as the content of SiC is increased.

![Figure 11. Ultimate tensile strength of welded Al6061-6%Gr-SiC MMCs.](image)

3.3 Observations from Rockwell hardness test

The Rockwell hardness test (TRAB-2010-263, Testwell Instruments, India) was carried out on welded hybrid MMCs using steel ball indenter of diameter (1/16) inch and load of 100 kgf. The specimens were prepared as per ASTM E28 standards as shown in figure 12. The hardness was measured on the base composite, weld interface and weld zone. For the analysis, the average hardness value was calculated. The table 5 summarizes the hardness test results.

![Figure 12. Hardness specimen of composite joint](image)

| Composites                  | Rockwell Hardness HRB |
|-----------------------------|------------------------|
| Al6061                      | 56                     |
| Al6061+6%Gr+3%SiC           | 59                     |
| Al6061+6%Gr+6%SiC           | 64                     |
| Al6061+6%Gr+9%SiC           | 67                     |

From the table 5, it is observed that the hardness value increases as the content of SiC increases for the welded composites. The average hardness value on the base composite was found to be 55HRB and on the weld interface 61.50HRB. The higher hardness on the weld interface is due to the presence of aluminium oxides, aluminium carbides and free carbon which make it harder than the base composite. It is observed that the hardness value decreased while traversing from weld interface to the weld zone, due to lesser harder particles in the weld zone [7-8][22-23][25] The variation of Rockwell hardness for the welded hybrid MMC joints with increase of SiC content is shown in figure 13.
Figure 13. Hardness of welded Al6061-Gr-SiC MMC joints.

3.4 Observations from Charpy impact test

The Charpy impact test (Make: Testwell Instruments, India) was carried out on microwave welded Al6061-6%Gr-SiC composites. The specimens were prepared as per ASTM E23 standards with 45° V-notch as shown in figure 14. The impact test was carried out on two specimens and the average value was taken for the study. The table 6 represents the experimental impact test results of welded composites.

| Composites                  | Impact strength (J/mm²) |
|-----------------------------|-------------------------|
| Al6061                      | 1.44                    |
| Al6061+6%Gr+3%SiC           | 1.60                    |
| Al6061+6%Gr+6%SiC           | 1.70                    |
| Al6061+6%Gr+9%SiC           | 1.75                    |

From the table 6, the average impact strength of welded composites was found to be 1.53J/mm². It is observed that the impact strength of welded Al60061-6%Gr-SiC MMCs was increased as the content of SiC increased. The more load carrying capacity of SiC particles, good fusion of interface Al6061 layer with composites and good metallurgical bond enhanced the overall impact strength of weld joint [8-9]. The combination of hard SiC particles and soft aluminium matrix improves the impact property of composites up to 6% SiC. For the Al6061-6%-9%SiC MMC joint, there was no drastic increase in the impact strength due to more porosity [22]. The figure 15 shows the variation of impact strength for welded Al60061-6%Gr-SiC MMCs with increase of SiC content [24].
Figure 15. Impact strength of welded Al6061-6%Gr-SiC MMCs.

4. Conclusions

The microwave welding of bulk composites is challenging as microwaves get reflected at room temperature. The present investigation shows that the microwave welding of composites can be an alternative joining method which is fast and eco-friendly. The following are the conclusions drawn from the present investigation.

1. The microwave welding of Al6061-6%Gr-SiC hybrid composites varying SiC by 3%, 6% and 9% with keeping graphite constant at 6% was carried out successfully using Al6061 powder as interface material.
2. The SEM images of composite joints showed homogenous and dense weld joint without any visible cracks due to the complete melting of interface material. The increase in porosity of the joint was observed with increase of SiC content from 6 to 9%.
3. The EDS analysis of joints indicate the presence of aluminium, carbon, oxygen and other elements. The oxygen and carbon react with aluminium at higher temperature to form aluminium oxide and aluminium carbide phases respectively. The images showed the presence of unreacted carbon in the joint area.
4. The average ultimate tensile strength of microwave welded Al6061-6%Gr-SiC hybrid composites was found to be 135MPa with 4.3% elongation. For the welded composites, the tensile strength increases as percentage of SiC increases due to the hardness of SiC particles and the ductility of weld zone.
5. The average Rockwell hardness of weld joint was found to be 55HRB. The presence of harder aluminium carbide, aluminium oxide and SiC particles at the weld interface made it harder than the base composites.
6. The average impact strength of microwave weld was found to be 1.53J/mm². The impact strength is improved as the content of SiC increased.

The quality of weld joints can be improved further by investigating the microwave hybrid heating process parameters.

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