International Journal of Applied Engineering Research ISSN 0973-4562 Volume 15, Number 7 (2020) pp. 682-689


# Investigation on Mechanical Properties of Microwave Welded Al6061-Graphite Metal Matrix Composites

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**Abstract**

In the present work, Al6061-Graphite metal matrix composites (MMC) were welded successfully in bulk form using multimode microwave oven at frequency of 2.45 GHz and power of 900W. The microwave hybrid heating principle is applied using charcoal as susceptor material for welding process. The interfacial material used for welding process is Al6061 powder. The Al6061-Gr MMCs are prepared with stir casting process by varying the graphite content by 0%, 3%, 6% and 9% by wt%. The joints were characterized by measuring the ultimate tensile strength, percentage of elongation, Rockwell hardness and the impact strength. These results are compared with the un-welded base composites. The average ultimate tensile strength of microwave welded Al6061-Gr composite is 102.5MPa which is 60.91% of the average tensile strength of base composites and the average percentage of elongation of welded composite is found to be 4.42% and that of base composite is 6.025%. The average Rockwell hardness of microwave welded composites is found to be 59.5 RHB and that of base composites is 53.75 RHB. The hardness at the weld interface observed is more than the base composite and fused regions. The average impact strength of welded composites is found to be 90% of base composites.

**Keywords:** Microwave welding, Microwave hybrid heating, Al6061-Gr MMCs, Mechanical properties.

## 1. INTRODUCTION

The metal matrix composite (MMCs) materials possesses superior properties than the pure metal. The Aluminum based MMCs have received increasing attention in recent decades as engineering materials. The introduction of a ceramic material into a metal matrix produces a composite material that results in an attractive combination of physical and mechanical properties which cannot be obtained with monolithic alloys. These are light-weight materials having wide-spread use in the automobile and aerospace industries due to their better properties, such as lightweight, high strength, high modulus, wear resistance and low coefficient of thermal expansion. The Al6061 alloy series is a preferred matrix material to prepare MMCs due to its better formability characteristics, corrosion resistance, good weld ability and moderate strength [1]. The graphite as reinforced material possesses the properties such as low friction, low wear rate and improved tribological behavior. The composites with graphite as reinforced material are used to make journal bearings which perform better than conventional bearing alloys. The pistons made of graphite reinforced composites instead of other conventional materials results in a saving on fuel and lubricating oil. The graphite in the form of particles has a wide range of applications in composite materials such as engine bearings, pistons, piston rings and cylinder liners etc. [1]. The welding of metal matrix composites can be done using different conventional techniques like conventional welding, soldering and brazing. These methods have several disadvantages like settling of heavier particles in the bottom of the weld pool, formation of inter metallic compounds between the matrix and the reinforcement, solidification shrinkage, voids, cracks, less penetration depth, hot cracking, work hardening effect, precipitation distortion in the joint etc. The mechanical strength of the joint is reduced due to these defects. The conventional welding processes are not cost effective as they require huge setup and equipment [2]. Due to these reasons, it is necessary and must for the researchers to find an alternative and cost-effective welding process to meet the industry demand with improved material properties.

Recently, microwave welding has emerged as a new processing technique for all types of metallic materials including ceramics and composites. Microwave material processing has many advantages over the conventional processing techniques such as selective heating, volumetric heating, less processing time resulting in large energy saving and providing fine microstructure and improved mechanical properties. Microwaves are electromagnetic waves with wavelengths varying from 1mm to 1m and corresponding frequencies between 300 MHz and 300 GHz. In microwave processing, the microwave energy is transferred directly to the material through molecular interaction with the electromagnetic field. Thus, there is energy conversion rather than energy transfer, which generally occurs in conventional processing of materials. The metallic materials are difficult to get processed with microwave because of higher reflection because of low skin depth. But the metallic materials can be processed in powder form by making metallic powder particle size equal to skin depth. The microwave processed products have shown better density, uniform microstructure and better mechanical properties than the conventional methods [3]. The advantages of microwave processing are as shown in figure 1.

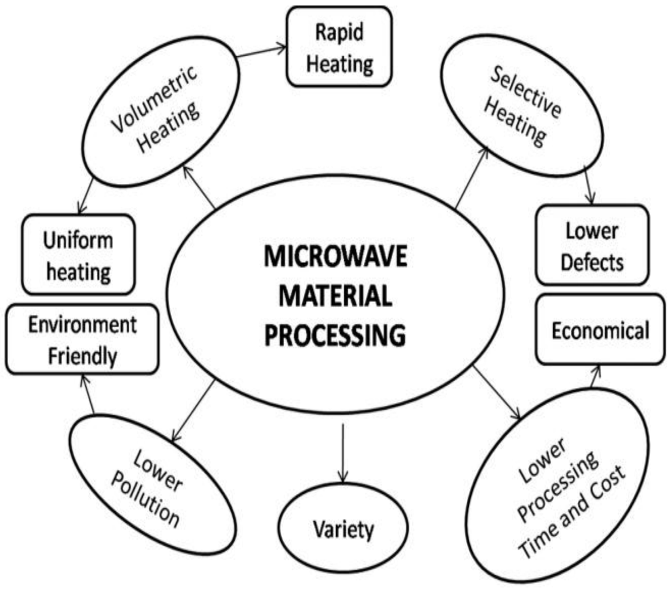


**Figure 1:** Advantages of microwave processing [4]

Due its unique characteristics, many researchers have given significant attention to the microwave processing and the research has been carried out on metals such as ferrous, copper, tungsten, limited studies on aluminium and aluminium based composites. In the early stage of research, the ceramics are sintered through microwave technique as ceramics absorbs the microwaves easily. It is then found that the microwave sintering has more advantage than the conventional sintering [5]. In the year 1999, Roy et al. [6] were successfully able to sinter the metallic powders using microwaves. This work leads to the future of metallic material processing through microwave.

It was reported that microwaves were successfully employed in the welding of copper and mild steel in the bulk form using microwave energy. These developments led researchers [7-10] to work on welding of other different bulk metallic materials and reported lesser energy consumptions and fewer defects with improved properties. Aravindan and Krishnamurthy [11] were carried out the successful joint formation of sintered alumina and 30% zirconia ceramic composite with microwave hybrid heating using 2.54 GHz frequency. Yarlagadda et al. [12] have studied the characterization of ceramic joints through microwave heating and analyzed the flexural strength, grain size, composition with porosity properties. M.S. Srinath et al. [13] have reported the microwave welding of bulk copper by using copper powder as interface material. Bansal et al. [14] have microwave joined the bulk stainless steel (SS-316) and investigated the micro structural and hardness properties. The figure 2 shows the flow of heat transfer in conventional and microwave heating processes.

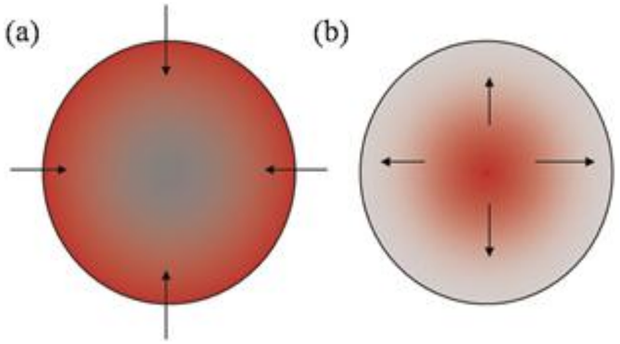


**Figure 2:** (a) conventional heating from outer to inner surface and (b) microwave heating from inner to outer surface **[4]**

From the available literature, it is found that the microwave energy is used to weld only few metals and very less reports on the microwave processing of composites. In the present work, the objective is to weld Al6061-Gr MMCs with varied graphite content (0%, 3%, 6% and 9% by wt%) using the principle of microwave hybrid heating. The mechanical properties of both microwave welded and base composites were investigated and the results were corelated.

## 2. EXPERIMENTATION

The experiments were conducted using domestic microwave oven with 2.45GHz frequency and 900W power. The welding of MMCs using microwave energy is difficult 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 and a number of trials were carried out.

### 2.1 Material selection

The stir casting method which is more economical compared to other methods is chosen for the preparation of Al6061-Gr MMCs. The MMCs were prepared with Al6061 alloy as matrix material and graphite as reinforcement with a particle size of 100µm. The Al6061 based powder is used as an interfacial material and charcoal as a susceptor material for the welding process. The charcoal is a good absorber of microwave energy at room temperature and it provides the conventional mode of heat transfer. The physical properties and chemical composition of Al6061 alloy is given in table 1 and 2 respectively [15].

**Table 1:** Physical properties of Al6061 alloy

| | |
|---|---|
| Melting Point | 585˚C |
| Modulus of Elasticity | 70-80 GPa |
| Poisson’s Ratio | 0.33 |
| Density | 2.7 g/cm3 |
| Thermal Conductivity | 173 W/Mk |

**Table 2**: Chemical composition of Al6061 alloy by wt %

| Element | Percentage |
|---|---|
| Mg | 0.9 |
| Si | 0.6 |
| Fe | 0.5 |
| Cu | 0.32 |
| Zn | 0.2 |
| Ti | 0.12 |
| Mn | 0.12 |
| Cr | 0.3 |
| Al | Balance |

The physical properties of graphite are given in table 3 [16].

**Table 3:** Physical properties of graphite

| | |
|---|---|
| Melting Point | 3915˚C |
| Density | 2.09 g/cm$^3$ |
| Coefficient of thermal expansion | 2-4 µm/m˚C |
| Poisson's Ratio | 0.14 |
| Young's modulus | 10 GPa |

### 2.2 Welding process

The Al6061-Gr composite specimens were mechanically polished with emery paper degreased with acetone to remove dust and any kind of impurities. The specimens were placed with butt configuration and kept 1mm apart. The slurry was prepared by mixing Al6061 powder with epoxy resin and hardener. The prepared slurry was applied uniformly between the interfaces of composite specimens and used to bind the interface material with specimens. Then the specimens were covered with graphite sheet. The graphite sheet acts as a separator between the specimens to be welded and the susceptor. It also avoids the direct contact between specimens and microwaves. The charcoal powder was poured near the weld region to provide the initial coupling of microwaves with composite specimens. The whole assembly was kept inside the microwave oven. The charcoal powder began to couple with microwaves as the exposure started and got heated to increase the temperature rapidly at the weld region. This heat is transferred to the interface layer Al6061 by conventional mode of heat transfer through graphite sheet. As the temperature increased, the epoxy resin got heated and evaporated. The Al6061 powder particles directly absorb microwaves at higher temperatures and got melted. At this stage, only the thin interface layers of composite specimens got melted and fused with the molten particles of Al6061. The composite specimens were exposed to microwaves up to 720secs (12mins). After cooling at atmospheric conditions, the homogenous and dense weld joint is formed with complete melting of the interfacial Al6061 powder. The schematic diagram of experimental microwave welding of Al6061-Gr composite is shown in figure 3. The processing parameters of microwave used in the welding of Al6061-Gr MMCs are shown in table 4. Based on the trials, the exposure time was determined.

**Table 4:** Microwave processing parameters

| | |
|---|---|
| Microwave frequency | 2.45 GHz |
| Exposure power | 900 W |
| Base Material | Al6061-Gr MMC |
| Interfacial material | Al6061 powder |
| Susceptor material | Charcoal powder |
| Exposure time | 12mins (720s) |

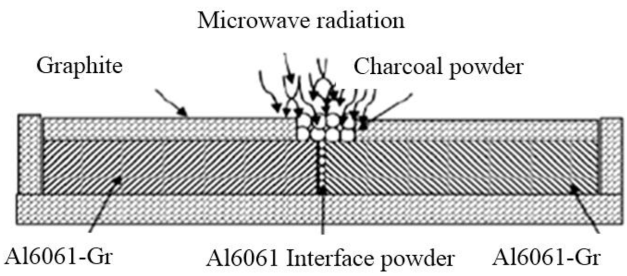


**Figure 3:** Schematic microwave welding of Al6061-Gr MMC

## 3. RESULTS AND DISCUSSION

In the present work, Al6061-Gr composites were welded successfully by exposing them to microwave radiations for 720s (12mins) at 2.45 GHz frequency in a multimode microwave system. All the specimens were prepared as per ASTM standards and the mechanical tests were performed for both base and microwave welded composites. The test results are discussed with appropriate illustrations in the following paragraphs.

### 3.1 Observations from tensile test

The tensile test is carried out for both base and microwave welded MMCs using 60 tones capacity universal testing machine. The specimens were prepared as per ASTM E-08 standards. The dimensions used for the test specimen is shown in figure 4. The width and gauge length of the specimen were 20mm and 50mm respectively

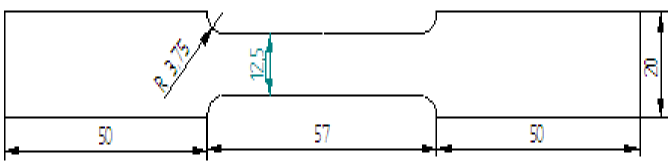


**Figure 4:** Tensile test specimen dimensions (mm)

The figure 5 shows the base composite tensile specimens. The figure 6 and figure 7 shows the tensile composite specimens of before and after microwave weld.

**Figure 5:** Tensile specimens of base MMCs


**Figure 6:** Tensile specimens before microwave weld

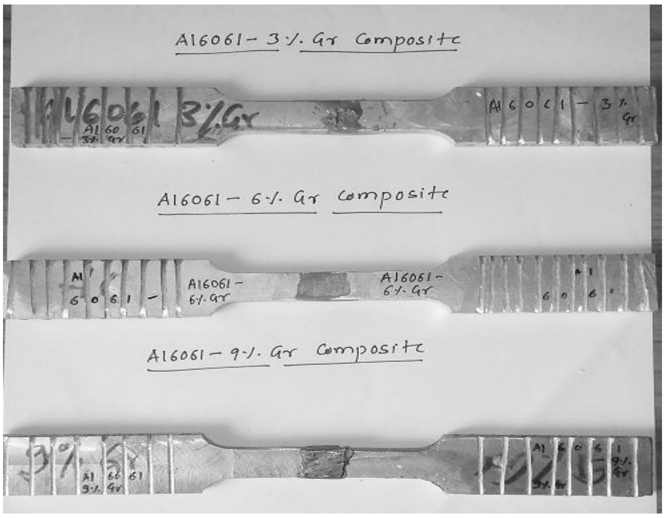


**Figure 7:** Tensile specimens after microwave weld

From the test results, the ultimate tensile strength and the percentage of elongation were determined for base and microwave welded composites and presented in the table 5.

**Table 5:** Tensile test results

| Specimen | Base composites | | Microwave welded MMCs | |
|---|---|---|---|---|
| | UTS MPa | % Elongation | UTS MPa | % Elongation |
| Al6061 alloy | 135 | 4.5 | 80 | 2.8 |
| Al6061+3% Gr | 171 | 6.2 | 98 | 3.5 |
| Al6061+6% Gr | 180 | 7.5 | 112 | 4.8 |
| Al6061+9% Gr | 188 | 8.0 | 115 | 6.6 |

The average ultimate tensile strength of base composites is 168.5 MPa and that of microwave welded joint is 101.25 MPa. The average ultimate tensile strength of welded joint is 60.91% of base composites strength. The average percentage elongation of the weld joints is 4.4% and that of base composites is 6.5%.

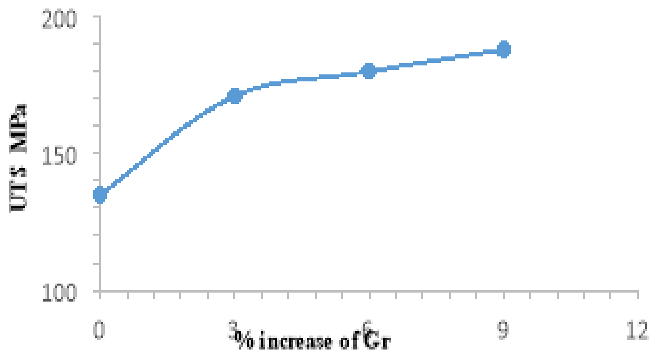


**Figure 8:** UTS of base Al6061-Gr MMCs

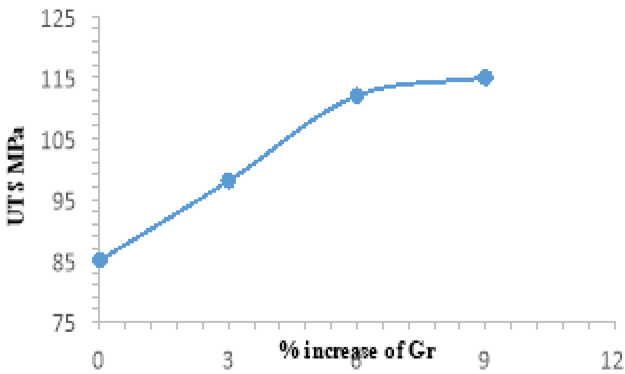


**Figure 9:** UTS of microwave welded Al6061-Gr MMCs

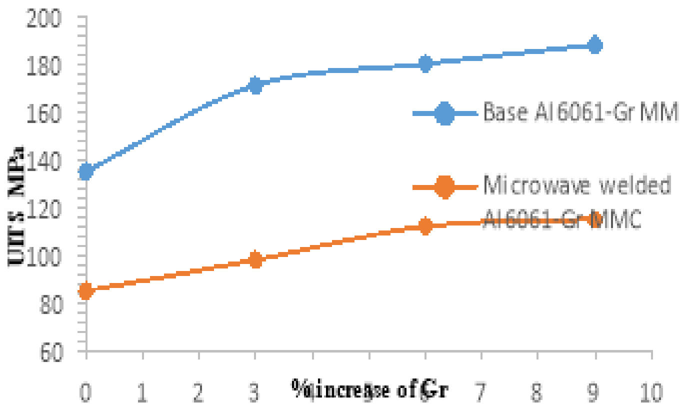


**Figure 10:** UTS of base and welded Al6061-Gr MMCs

The figure 8 and figure 9 indicates the increase of ultimate tensile strength for both base and joint composites as the content of graphite is increased. The strength comparison for both is shown by the figure 10. The graphite particles act as barriers to dislocations in the microstructure. These results show the successful welding of composites using microwave energy.

### 3.2 Observations from Rockwell hardness test

Hardness is the ability of the material to resist the wear and abrasion. The hardness specimens were prepared as per ASTM E-28 standards having the dimensions of 30x30x6mm. It is measured at different locations of weld interface, fused zone and base composite surface and their average value is taken for study. For the testing, 2.5mm diameter steel indenter with a load of 100 kgf is forced on the surfaces of base and joint specimens and removed. The figure 11 and figure 12 shows the base and microwave welded hardness specimens respectively. The test results are represented in the table 6.

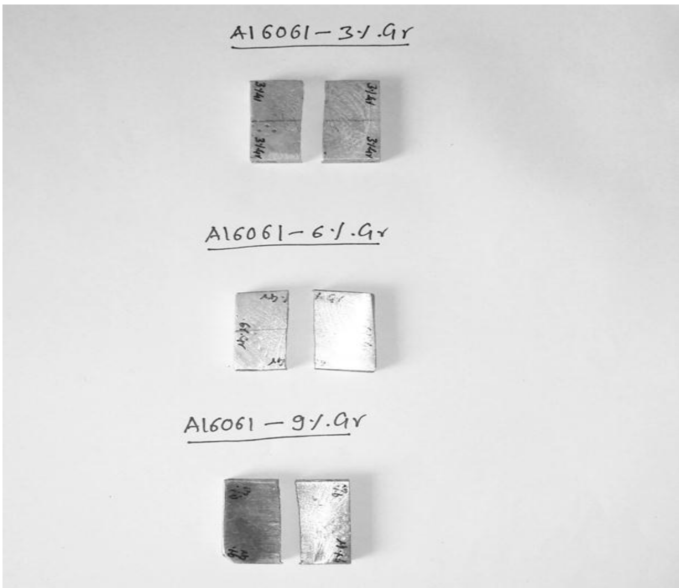


**Figure 11:** Base MMC hardness specimens

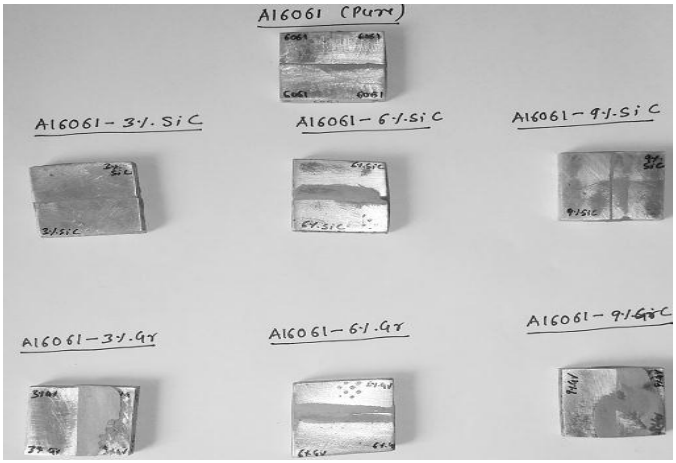


**Figure 12:** Microwave welded MMCs

**Table 6:** Hardness test results

| Specimen | Rockwell Hardness (RHB) | |
|---|---|---|
| | Base composites | Microwave welded MMC |
| Al6061 alloy | 53 | 56 |
| Al6061+ 3% Gr | 58 | 65 |
| Al6061+ 6% Gr | 54 | 62 |
| Al6061+ 9% Gr | 50 | 55 |

The average hardness of base composites is 53.75 RHB and that of microwave welded is 59.5 RHB. The maximum hardness is observed at the weld interface than the base composite surface and weld zone regions due to the presence of various carbides and inter metallic compounds. Also, the fast heating rate which prevents softening of aluminum and the absorption of carbon from graphite sheet improves the hardness. The figure 13 and figure 14 shows the decrease of hardness value for both base and microwave welded Al6061-Gr MMCs as the content of graphite is increased.

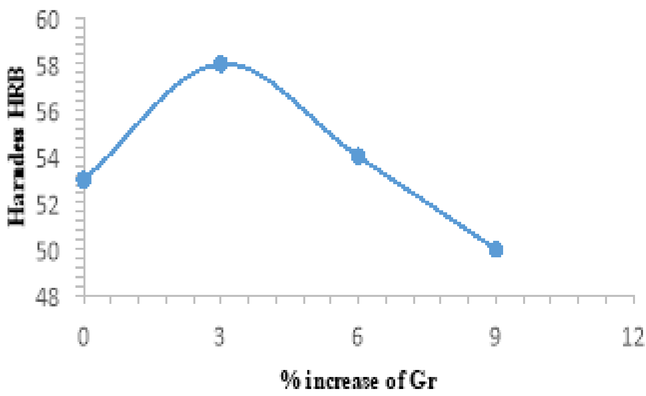


**Figure 13:** Hardness of base Al6061-Gr MMCs

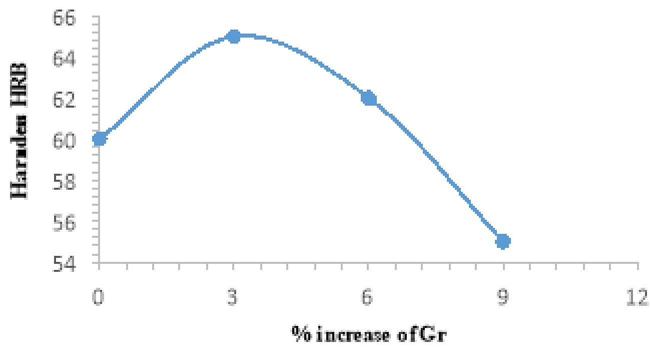


**Figure 14:** Hardness of welded Al6061-Gr MMCs

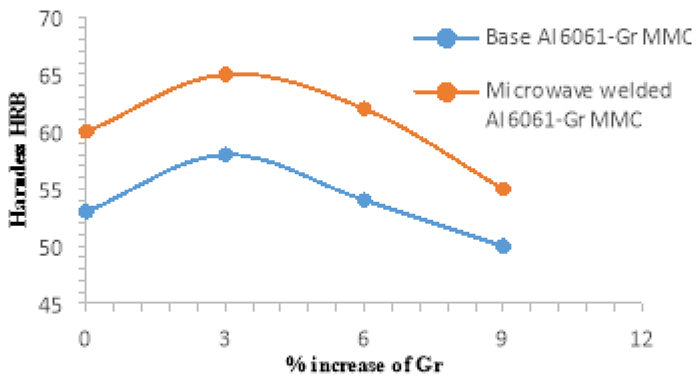


**Figure 15:** Hardness of base and welded Al6061-Gr MMC

The comparison between hardness of base and microwave welded Al60061-Gr MMCs is shown by the figure 15.

### 3.3 Observations from charpy impact test

The impact strength is the capacity of a material to withstand blows without fracture. The specimens were prepared as per ASTM E-23 standards for V notched bar. The dimension used for charpy specimen is 55x10x5mm with $45^0$ V-notch angle. The figures 16 and 17 show the test specimens of base and microwave welded Al6061-Gr MMCs respectively. The experimental test results of base and microwave welded composites is presented in table 7.

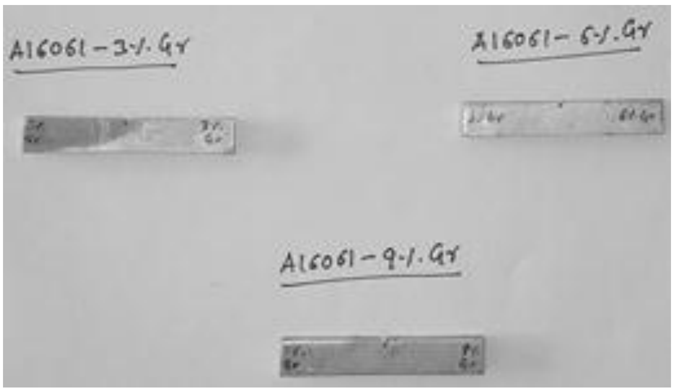

**Figure 16:** Charpy specimens of base MMCs

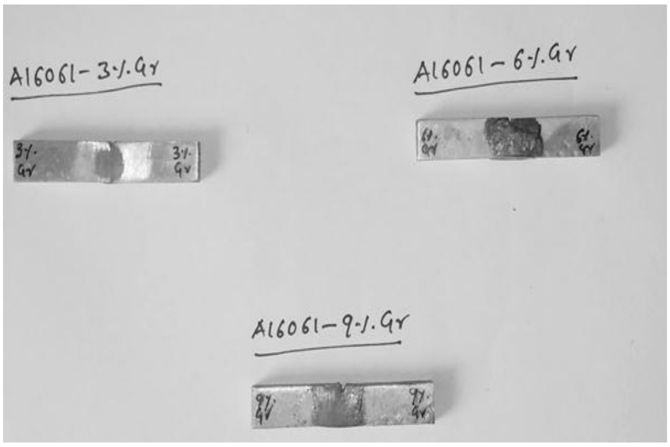

**Figure 17:** Charpy specimens of microwave weld MMCs

**Table 7:** Impact test results

| Specimen | Impact strength (J/mm$^2$) | |
|---|---|---|
| | Base composites | Microwave welded MMC |
| Al6061 | 1.62 | 1.44 |
| Al6061+ 3% Gr | 1.69 | 1.48 |
| Al6061+ 6% Gr | 1.76 | 1.59 |
| Al6061+ 9% Gr | 1.80 | 1.62 |

From the test results, it is observed that the average impact strength of base composites is 1.71J/mm$^2$ and that of microwave weld is 1.53J/mm$^2$. The impact strength of microwave welded composite is 89.19% of base composite. The figure 18 and figure 19 shows the increase of impact strength for both base and welded Al60061-Gr MMCs as the content of graphite is increased.

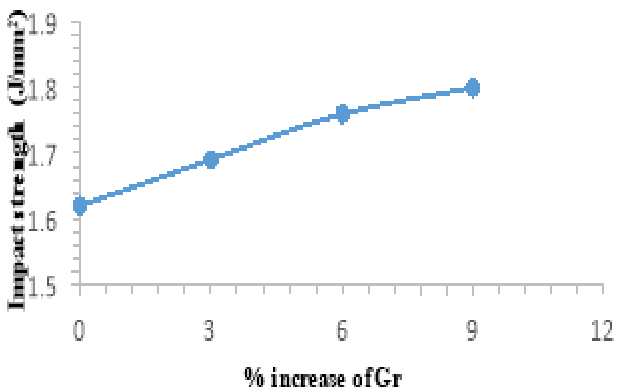


**Figure 18:** Impact strength of base Al6061-Gr MMCs

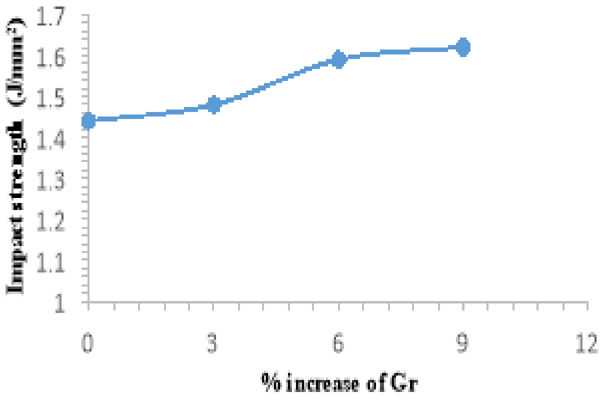


**Figure 19:** Impact strength of welded Al6061-Gr MMCs

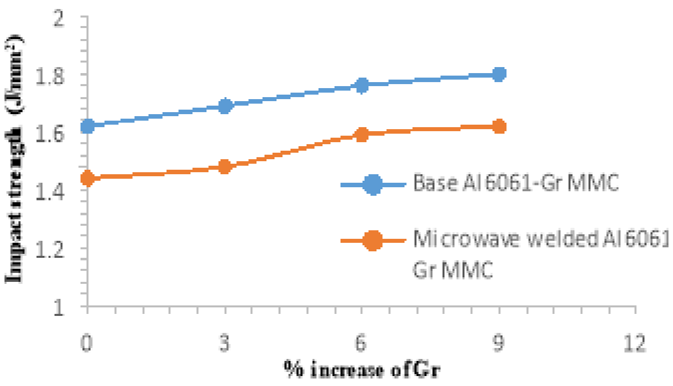


**Figure 20:** Impact strength of base and welded Al6061-Gr MMCs

The presence of various carbides and free carbon absorbed from graphite sheet enhances the impact strength of welded composites. The figure 20 shows the comparison of impact strength between base and microwave welded Al60061-Gr MMCs.

## 4. CONCLUSIONS

The present work establishes that the microwave energy can be used as an alternative method to weld Al6061-Gr MMCs in bulk form economically and at a faster rate. The following are the conclusions drawn on the basis of experimental work.

- The welding of Al6061-Gr MMCs is carried out successfully using the principle of microwave hybrid heating for varied graphite content ( 0%, 3%, 6% and 9%) with Al6061 powder as interface material.
- The homogenous and dense weld joint is formed without any visible cracks by melting the interface material completely. The weld interfaces are clearly visible.
- The average ultimate tensile strength of microwave welded Al6061-Gr composite is 60.91% of base composites with 4.42% elongation.
- The ultimate tensile strength is increased as the content of graphite is increased for both base and microwave welded composites. For microwave welded composites, the improvements in weld strength is due to the formation of various carbides and inter metallic compounds.
- The hardness of base and microwave welded composites decreases as the graphite content increases due to the softness the graphite. It is observed that the hardness increases while traversing from weld center to the weld interface.
- The average hardness of microwave welded Al6061-Gr composite is found to be more than the base composites due to fast heating rate and the presence of carbides.
- The average impact strength of microwave welded Al6061-Gr composite is 89.19% of base composite.

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

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