Effect of Post Welded Heat Treatment on Tungsten Inert Gas Welded Al6061-SiC Composites

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***Abstract*—Metal matrix composites (MMCs) of aluminum alloys (6061) reinforced with silicon carbide (SiC) were prepared with 8 and 10 wt.% of SiC through a stir casting process, with an average size of 25 μm. The composites of identical compositions were welded using single-pass tungsten inert gas (TIG) welding, using an ER5356-grade filler material. The hardness and tensile strength of the weld zone in the as-welded condition were measured. The samples were then subjected to age-hardening treatment at two different temperatures (100 and 200 ℃) and different holding times. The peak hardness values were recorded under both temperature conditions. The tensile strength for every different condition was also measured and compared with the values of the as-welded condition. The results indicated that age-hardening treatment had a significant influence on the improvement of the hardness and the tensile strength of the samples. The microstructure of the fractured surface in the as-welded and age-hardened specimens was observed under a scanning electron microscope (SEM), and the failure modes were analyzed. The pattern of the failure showed a mix of both brittle and ductile nature. The microstructure of the as-welded samples showed a relative distribution of SiC in the matrix. The distribution was not uniform throughout the matrix and seemed to have preferably distributed around the grain boundaries. The microstructures observed through the SEM could not bring out the fine precipitates that could have resulted from age hardening because of its limited resolution. However, the presence of precipitates was verified through X-ray diffraction studies.**

***Index Terms*—tungsten inert gas welding, metal matrix composites, age hardening treatment, scanning electron microscopy, energy dispersive spectroscopy.**

I. Introduction

Al-based metal matrix composites (MMCs) have a wide range of applications (e.g., aerospace and automobile industries) [1–3], owing to their high specific strength; rigidity; enhanced resistance to wear, fatigue, and creep; high elastic modulus; and good dimensional stability compared with unreinforced alloys [4–7]. These qualities make them a promising structural material for many industries. Owing to the inert nature of silicon carbide (SiC) in the liquid aluminum phase and its ability to strengthen the matrix in the solid state, it is widely accepted as a reinforcement in many MMCs [8]. SiC can be used as a reinforcement in the form of particulates, whiskers, or fibers to improve the properties of the composite [9–12]. When embedded in MMCs, SiC certainly improves the overall strength of the composite, along with corrosion and wear resistance. Aluminum MMCs reinforced with SiC particles also show up to 20% improvement in yield strength, a lower coefficient of thermal expansion, and a higher modulus of elasticity than the corresponding unreinforced matrix alloy systems [13–16].

In order to expand the range of engineering applications of MMC products, research on new technologies of welding is currently being explored. Researchers in the past have focused on a variety of joining techniques applied to Al-based MMCs, which include fusion welding (metal inert gas (MIG), tungsten inert gas (TIG), electron beam (EB), laser beam (LB), and plasma) and solid-state bonding (friction stir welding (FSW), diffusion bonding, adhesive bonding, and brazing) [17–20]. However, in conventional fusion welding methods, due to the differences in the physical properties between the matrix and the reinforcement, problems such as porosity, slag, and agglomeration of SiC particles tend to appear in the weld metal structures. At elevated temperatures, the chemical reaction (1) between the metal matrix and the reinforcement phase due to the prolonged contact leads to the production of a harmful brittle phase (Al_4C_3) that degrades the quality of the weld [21].

$$3SiC + 4Al = Al_4C_3 + 3Si \quad (1)$$

At temperatures above 1000 ℃, the driving force for the reaction is large enough and the formation of Al_4C_3 cannot be avoided [22]. However, there are speculations that the TIG welding results in a relatively shorter time and lower temperatures, thus reducing the degradation of the SiC particles. These interfacial reactions may affect the composition of the solidified melt, leading to the modification of the microstructure and mechanical strength. Furthermore, the microsegregation of the reinforcement phases is likely to occur mainly in the interdendritic regions during the solidification process at an elevated temperature. These are some challenges in the traditional fusion welding techniques of the MMC weld with regard to SiC reinforcement with a lower silicon

Manuscript received January 9, 2018; revised April 1, 2018.

doi: 10.18178/ijmerr.7.4.331-337

content [23]. However, with TIG and MIG fusion welding, the aforementioned problems are less pronounced [18].

Previously, Al-Mg-Si alloys with SiC reinforcement subjected to thermal aging showed promising results in terms of an increase in strength and hardness. This is attributed to the formation of the precipitate phase [24–27]. The addition of Mg leads to possible precipitation of a Mg_2Si phase. The addition of ternary alloying elements such as Mg in the weld, followed by aging, can also significantly improve the strength, although there are is significant literature to date reporting on the improvement in the strength of Al-SiC MMC welded joints subjected to thermal aging. The presence of precipitates leads to increased hardness and accelerates with the aging temperature. Due to the incompatibility in the coefficient of thermal expansion, which results because of cooling from the temperature of solutionizing and the difference in lattice structures between the reinforced SiC and the aluminum alloy matrix results in a higher dislocation density close to the interfaces and buildup of residual stresses [28]. In addition, the evaporation of the magnesium particles during welding can help improve the quality of the weld, as magnesium is considered to be a deoxidizer [29].

The present study brings out some important observations on the microstructures of the as-welded and aged specimens and relating the microstructural phenomena to explain the mechanical behavior of these welded joints. To date, there are no significant works evident in the literature reporting on the enhancement of the mechanical properties of welded joints by age hardening, particularly emphasizing the microstructural aspects. An attempt has therefore been made to bring out characteristic microstructural changes as a result of age-hardening treatment, thereby correlating these to the observed mechanical behavior. Such investigation will form a baseline study for manufacturers and engineers to understand the problems associated with the fabrication and in-use application of the welds.

II. Experimental

A. Materials and Methods

In the present work, the samples were prepared from composites made of Al6061 reinforced with 8 and 10 wt.% of particulate SiC (99.9% purity) and with an average size of 25 μm. The composites used in this study were prepared through a stir casting process [30]. Powders of SiC were preheated at a temperature of around 550 ℃ for 2 h before the casting process for removing moisture and impurities. The aluminum melt was prepared by heating to 700 ℃ within a bottom-pouring furnace. A graphite stirrer was placed under the liquid melt and rotated at a speed of 500 rpm in an argon atmosphere to make sure that the SiC gets homogenously distributed in the liquid matrix. The molten slurry was poured into steel molds. Mg of 1% weight fraction was added to the melt to increase the wettability of the interface between the matrix and the reinforcements.

The resulting composites of both 8 and 10 wt.% SiC were cut and machined into several rectangular pieces of 120 mm long by 6 mm wide, and the samples were laterally butt-welded using a TIG setup. The specimens were prepared as per the BIS standard with a 3 mm thickness, having a groove angle of 65 °. Welding was carried out on 0, 8, and 10 wt.% SiC composites under a welding current of 220 A, a speed of 140 mm/min, and a gas flow rate of 14 L/min. The samples were first solutionized at 558 ℃ for 2 h, followed by quenching in water at room temperature. All the solutionized specimens were aged at 100 and 200 ℃ for different holding times to measure the peak-age-hardening condition. Specimens were further sectioned from the welded pieces for hardness and tensile tests and metallographic analysis.

B. Characterization of Samples

Samples subjected to hardness tests were flattened at the weld zone and checked for hardness using a Brinell hardness testing machine with multiple indentations taken in the important regions. The hardness profiles across the weld nugget, the heat affected zone (HAZ), and partly base material were measured under a load of 250 kgf using a steel ball indenter of diameter 5 mm for 20 s. Indents with a spacing of 2 mm were used to avoid the strain hardening effect imposed by neighboring indents. The hardness tests were conducted on both as-welded and age-hardened samples at 100 and 200 ℃ under different holding times.

The tensile specimens were sectioned as per the ASTM E8M standards (see Fig. 1). The tensile axis remains perpendicular to the welded cross section. The tests were conducted using a digital tensometer under normal ambient condition at a crosshead speed of 10 mm/min, and the tensile properties of each joint were evaluated using three tensile specimens cut from the same joint. It must be noted that the tensile test was carried out on the as-welded and only the peak-aged samples of both 8 and 10 wt.% composition by taking the average of three measured values.

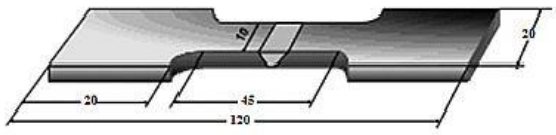


Figure 1. Dimensions of the tensile test specimen of the MMC welded joint prepared as per the ASTM E8M standards used in the present investigation.

For the metallographic analysis, sections were prepared such that the plane of the microscopic examination contains the weld metal region and the HAZ. The cross sections of the metallographic specimens were polished with diamond suspensions, followed by etching using standard Keller's reagent (150 mL of water, 3 mL of nitric acid, 6 mL of hydrochloric acid, and 6 mL of hydrofluoric acid) at 0 ℃ for about 10 s.

All the microstructural examinations were conducted using a Zeiss EVO 18 (Special Edition) scanning electron microscope (SEM) equipped with an Oxford Instruments

energy-dispersive spectrometer (EDS) for compositional analysis. Imaging was carried out at an acceleration voltage of 20 keV. For X-ray composition analysis, the voltage was brought down to 10 keV for better resolution.

III. Results and Discussion

The distribution of hardness at the weld zone for 0, 8, and 10 wt.% of SiC composites aged at 100 and 200 ℃ is plotted against the aging time [see Figs. 2(a)–2(c)]

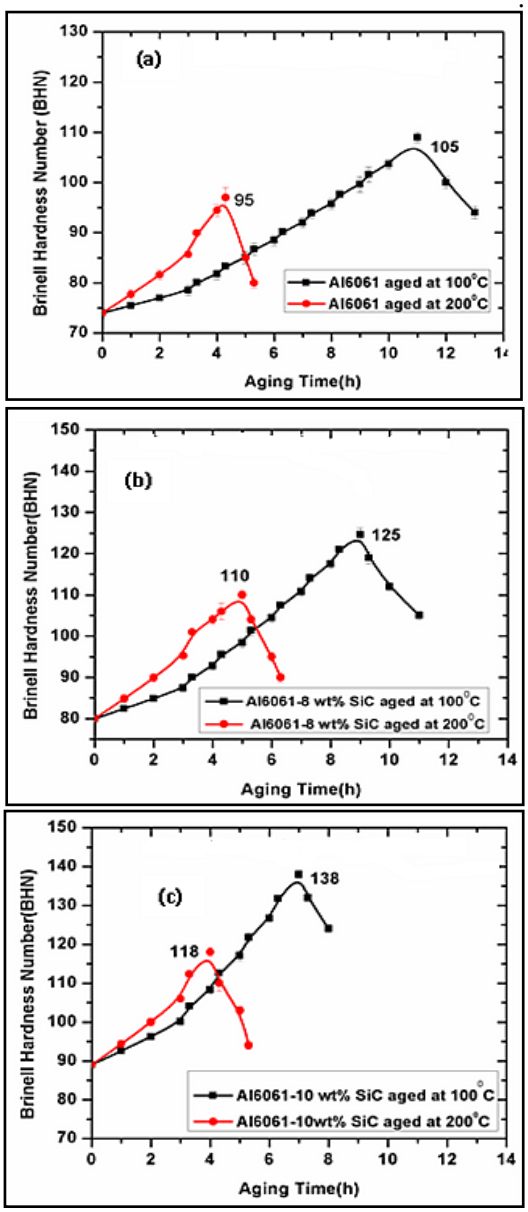


Figure 2. Hardness plotted against different aging times carried out at 100 and 200 ℃ for (a) Al6061 alloy, (b) Al6061-8% SiC, and (c) Al6061-10% SiC welded composites. The peak hardness values corresponding to different aging times and temperatures at all compositions were determined. Error bars represent the typical accuracy of the estimated hardness within 3% of the mean values.

A minimum of five different hardness measurements were performed for every different condition within the weld pool region, and the mean hardness values are plotted. This standard deviation is indicated with a suitable error bar. Table I presents the peak hardness values achieved in as-welded and differently aged samples. As clearly shown in the table, the hardness has improved appreciably with the addition of reinforcements. The aging time is equally critical in deciding the strength of the welded material. The peak hardness shows an increase for all samples with increasing wt.% of SiC aged at 100 ℃; however, aging at 200 ℃ leads to softening. Table II presents the tensile strength data for different conditions of aged composites and the base alloy. The test was carried out on the as-welded and peak-aged samples by taking the average of three measured values. This clearly depicts that there is an increase in the ultimate tensile strength (UTS) with the addition of reinforcements as opposed to pure alloys in the as-welded condition. The observed trends of UTS with varying conditions of aging are similar to the estimated hardness. Fig. 3 is a plot of the hardness against the UTS. Due to the lower number of data points available, it was difficult to make any speculation if the measured hardness and UTS truly follow a linear trend. Previous researches have reported different empirical relationships between hardness and tensile strength. There is a generally well-known rule of thumb relating hardness to linear variations in the UTS, studied for a large range of pure metal alloys. However, there are studies that contradict the linearity between the hardness and the UTS. It is noted that hardness is not an intrinsic property of a material. Rather, the hardness value depends more on the technique and the attributes of the material (e.g., strain hardening, microstructure) than on the fundamental physical properties of the material. The nature of this microstructure dependence is usually explained through different grain structures and orientations. Sometimes, hardness measured on the surface and the bulk may have different defects (both micro and macro), and hence the relationship between the tensile strength and hardness may not be predictable at certain situations.

TABLE I. Peak Hardness Values at 100 and 200 ℃: (a) Al6061 Alloy, (b) Al6061-8% SiC, and (c) Al6061-10% SiC Welded Composites. The Hardness Values for Nonaged Specimens are Also Reported for the Readers' Reference. The Hardness Values Correspond to the Observed Peaks in the Plot Shown in Fig. 1.

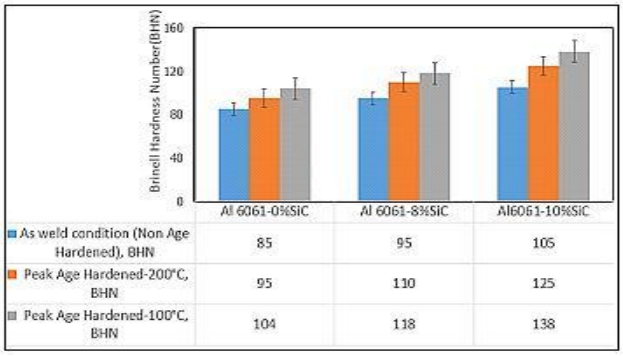
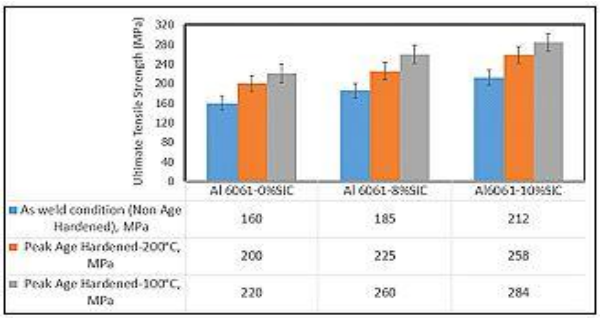


TABLE II. TENSILE STRENGTH VALUES AT 100 AND 200 ℃ UNDER PEAK-AGE-HARDENED CONDITIONS FOR THE (A) AL6061 ALLOY, (B) AL6061-8% SIC, AND (C) AL6061-10% SIC WELDED COMPOSITES.



	Al 6061-0%SiC	Al 6061-8%SiC	Al6061-10%SiC
As weld condition (Non Age Hardened), MPa	160	185	212
Peak Age Hardened-200°C, MPa	200	225	258
Peak Age Hardened-100°C, MPa	220	260	284

SEM micrographs of the fractured section of the tensile specimens of both as-welded and peak-aged (100 ℃) composites with 8% SiC are presented in Figs. 4(a)–4(c). As apparent in the images, the overall fracture is of a mixed mode in nature. The dimples and river-like pattern observed in the micrographs are possible signatures of the failure mode being a combination of ductile–brittle (mixed) fractures. An important observation made in this study on microcrack formation is illustrated in Fig. 5. Microcracks are clearly brought out at a higher magnification around an SiC particle. The EDS spectra obtained at 10 keV are in support of the particle being SiC. During deformation under a tensile loading condition, strain localization could have likely occurred due to dislocation pile-up around the SiC particle. Although nothing is speculative from the micrograph images in the present study, it was decided to include all possible observations carried out in the course of this research.

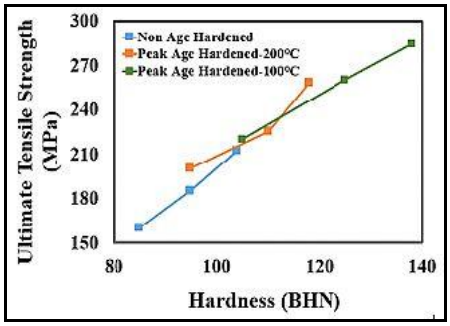
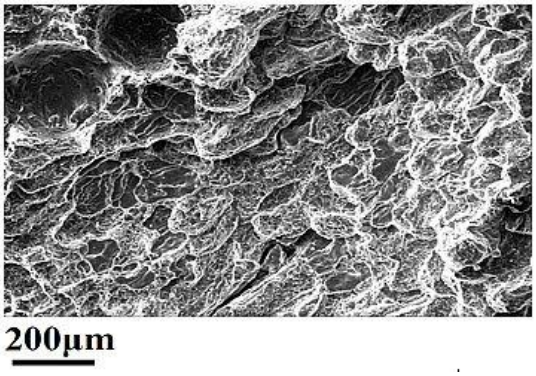


Figure 3. Tensile strength plotted against hardness for all the compositions and conditions for aging. The tensile strength shows a near-linear correlation with hardness with a limited number of data points.



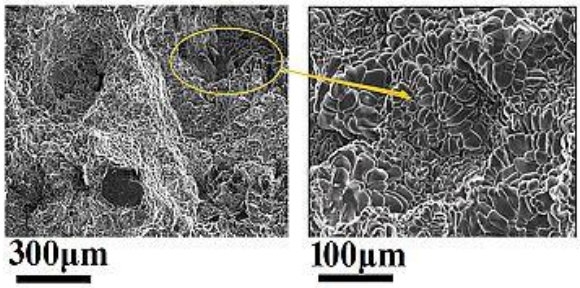


Figure 4. SEM microstructure of the fractured surface of (a) as-welded Al6061-10% SiC and (b) composites aged at 100 ℃. (c) A higher-magnification image of the encircled region in (b).The morphology of the fractured sections of both samples exhibits a dimple and river-like pattern, a possible signature of mixed-mode failure.

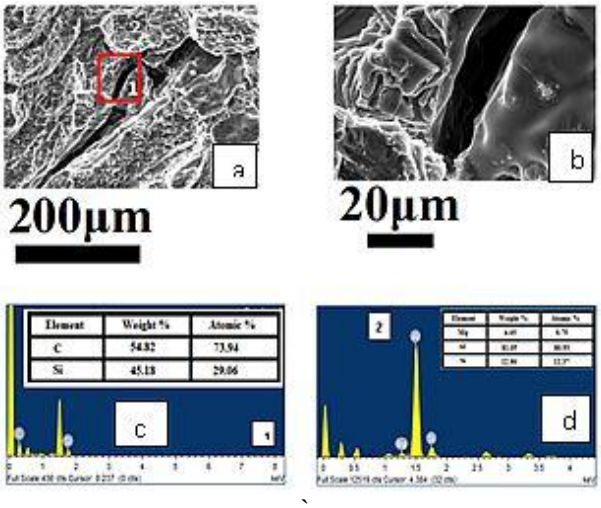


Figure 5. (a) Microcracks around an SiC particle (1) brought for an as-welded 10% SiC specimen. (b) A higher magnification of the crack region in the red box. These microcracks' formation is primary evidence of strain localization around the sharp edges of the hard SiC reinforcements. (c, d) The X-ray spectra identify the relative composition of the elements in both the reinforcement (1) and the matrix (2). Insets in the spectra are the wt.% of the elements.

The observed increase in hardness with an increase in the SiC composition for the as-welded specimens is primarily attributed to the increased presence of SiC in the weld metal region. Some of these SiC particles close to the edge of the base metal could have migrated toward the weld metal through the liquid pool. The microstructures presented in Figs. 6(a) and 6(b) for the 8 wt.% SiC welded specimen show the relative distribution of the SiC in both the HAZ and weld metal pool. These SiC particles introduce misfits with the surrounding alloy matrix that impedes the dislocation movement, leading to strengthening of the weld metal matrix. A close look into the microstructure shows that these SiC particles were likely to have dispersed along the grain boundaries of the matrix. The grain boundaries were not brought out clearly in the microstructures though. A higher-magnification image obtained in the weld metal region in Fig. 6(c) shows a necklace pattern of SiC particles, which could be the footprints of a grain boundary.

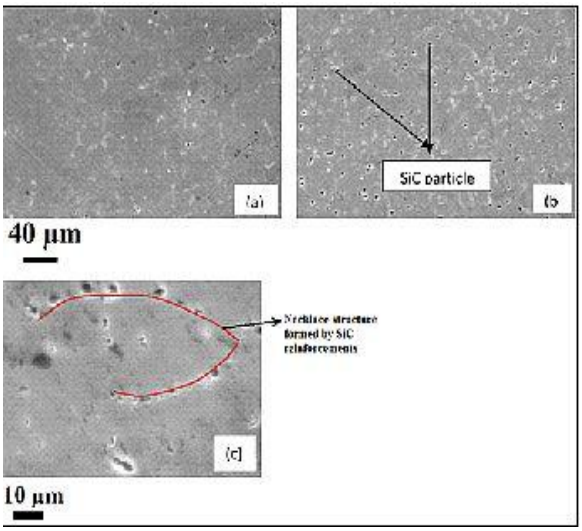


Figure 6. SEM microstructure of the (a) weld metal region and (b) HAZ of 8 wt.% SiC welded composites (non-age-hardened) brought under the same magnification. The relative distribution of SiC particles for both regions shows a much lower presence of reinforcement in the weld metal region. The SiC seen in the weld metal region is a result of the migration of these particles from the base metal region. The strengthening effect observed in the as-welded specimen is largely due to the presence of SiC. (c) Distribution of the SiC particles in a necklace pattern along the grain boundary region. The grain boundaries, however, were not brought out clearly for the matrix through the adopted chemical etching process.

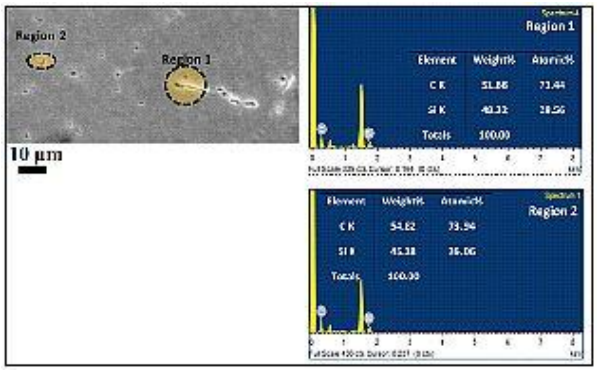


Figure 7. (a) SEM microstructure of Al6061-8% SiC welded composites (non-age-hardened) showing SiC particles distributed in the matrix. The morphologies of these particles range from lenticular to granular/round shape form. These differences in the morphologies arise from the different orientations of these particles in the matrix and the section under which the microstructures are viewed. (b, c) X-ray spectra for the compositional analysis for two different particulates taken in regions 1 and 2, respectively, confirming that these particulates are SiC.

The different morphologies (round, elongated) pertaining to SiC particles are possibly due to the different orientations of these particles in the matrix material, for which the exact shape was difficult to determine within the given section plane. The X-ray spectra obtained for these particles confirm that these are SiC (see Fig. 7).

With aging, there has been a significant change in the strength. As can be inferred from the plot in Table 2, that lower aging temperature resulted in a 25–28% increase in strength when compared to the as-welded condition. This increase in strength and hardness of the low-temperature aged alloys is a combined effect of the presence of hard reinforcement and the formation of a secondary phase of Mg_2Si in the weld metal region. The presence of Mg_2Si is verified through an X-ray diffraction peak at $2\theta = 30°$ using a Cu-kα radiation (see Fig. 8). Optimum aging increases the number of precipitate particles. The fine and uniform distribution of precipitates at the weld joints that are attained by applying heat treatment along with the good features of the TIG welding method such as spatter-free welding is liable for the increase in hardness. However, higher aging temperatures lead to softening. Overaging induces softness because of the coherency between the precipitates and the alloy matrix, which reduces the lattice strain, and hence the hardness value decreases. The other possibility that could be concurrently occurring during the high-temperature aging is the recovery of dislocations, which relaxes the strain around the precipitates, thus reducing the peak hardness. The rise of temperature causes the aging rate to increase because of the enhanced rate of diffusion of atoms in the matrix.

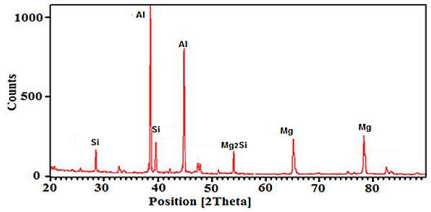


Figure 8. X-ray diffraction plot of intensity Vs 2θ measured in the weld metal region, showing the precipitation of intermetallic Mg_2Si as a result of age hardening for Al6061-10% SiC welded composites.

From the above results, it can be concluded that heat treatment has a profound influence on the hardness of matrix alloys and composites. The higher the aging temperature, the shorter the time required to attain peak hardness with a lower peak hardness value. Although a complete understanding of the pattern of change in the strength of the welded aluminum composites with increasing reinforcement and aging time is speculative, the experimental observations can be considered reliable and appear to be the only reasonable explanation available at this point. The next stage of work will include investigations on other microstructural parameters to be measured in the weld metal zone, such as the nature of the grain boundary, in-grain misorientation, the interface nature of the reinforcement and matrix or the phase boundary nature of the secondary phases, and more importantly the role of the preferred orientation of grains through techniques like electron backscattered diffraction (EBSD).

IV. Conclusions

- Al-SiC MMCs of varying compositions of SiC were welded through the TIG welding process under identical conditions. For all the compositions of SiC in the MMC, the peak-age-hardened condition was attained for a longer holding time at 100 ℃ than at 200 ℃. A 22–24% increase in the peak age hardness was clear for samples aged at 100 ℃. However, higher-

temperature aging led to an increase of 13–19%. The tensile strength for peak-age-hardened specimens at 100 ℃ shows an increase of 25–28%.

- The pattern of fracture for the 8% SiC specimen under both as-welded and peak-age-hardened conditions showed a mixed (brittle and ductile) mode of failure. It is evident that strain localization during deformation could have likely occurred because of dislocation pile-up around the SiC particle.
- The microstructure of the 8 wt.% SiC composite welded region showed that SiC particles have dispersed along the grain boundaries.
- Optimum aging increases the number of precipitate particles with fine and uniform distribution throughout the matrix. Thus, it can be concluded that heat treatment has a profound influence on the strength of the weld.

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