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# Comparison of the Microstructure and Mechanical Properties of As-Cast A356/SiC MMC Processed by ARB and CAR Methods

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**Accumulative roll bonding (ARB) and continual annealing and roll-bonding (CAR) processes were used in this study for improving the microstructure and mechanical properties of the A356/10 vol.% SiC metal matrix composite (MMC) produced by semi-solid metal processing (SSM). The results showed that using the ARB and CAR processes led to the following points: (a) the uniformity of the silicon and silicon carbide in the aluminum matrix improved, (b) the Si particles became finer and more spheroidal in appearance, (c) the porosity disappeared, (d) the bonding quality between the reinforcement and the matrix improved, (e) the particle-free zone disappeared, and therefore (f) the tensile strength (TS), elongation, and formability index of the MMC samples improved. However, it was found that the CAR process is a better method for improvement of microstructure and mechanical properties of as-cast MMC compared to ARB process.**

**Keywords** joining, mechanical testing, metal matrix composites, rolling

## 1. Introduction

The increasing demand for lightweight and high-performance materials for automotive and aerospace applications has led to the development of several processing techniques for the synthesis of metal matrix composites (MMCs). The processes available in the literature can be broadly grouped into three categories including liquid metallurgy route, powder metallurgy, and spray forming. Each of those processes has its own advantages and limitations. Amongst those processes, semi-solid metal processing (SSM) produces a non-dendritic and a more uniform microstructure across the sample. However, through that process, porosity, non-uniform distribution, and coarse and acicular-shaped silicon particles remain in the produced materials. These factors decrease the mechanical properties of alloys or composites produced by any production routes (Table 1) (Ref 1-8). Although the secondary processess, such as compressing, extrusion, rolling, and severe plastic deformation methods have been employed to improve the microstructure and mechanical properties of various SSMed alloys, as far as the present authors are concerned, no secondary processing has so far been carried out on the SSMed MMC. To overcome the aforementioned problems, the present authors used accumulative roll bonding (ARB) and continual annealing and roll-bonding (CAR) processes. These processes were previously used for manufacturing $Al/Al_2O_3$ (Ref 9-12) and $Cu/Al_2O_3$ (Ref 13) MMCs. The produced MMCs had high uniformity, strong bonding, and high strength. Up to now, these processes have not been used as a secondary process for as-cast MMC. Thus, multiplicity of applications of MMCs prompted the present study aimed at investigating the effects of ARB and CAR processes on microstructure and mechanical properties of MMCs. The present study focuses on the A356/10 vol.% SiC MMC produced by SSM, ARB, and CAR processes.

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## 2. Experimental Procedure

A356/10 vol.% SiC composites were produced by semi-solid method using A356 alloy as well as SiC particles with average sizes of $<5$ μm as starting materials. The liquidus temperature of A356 alloy was calculated as 616 °C, the relatively large semi-solid interval of this alloy makes it suitable for semi-solid metal processing (569-616 °C). The composition of A356 alloy is shown in Table 2. Also, the Al-Si phase diagram is presented in Fig. 1 (Ref 14). The alloy was melted in a graphite crucible using a resistance furnace. The temperature of the alloy was first raised to about 700 °C. In order to have a uniform temperature condition, the melt was kept at the preset temperature for approximately 2 min. The molten metal was stirred at 500 rpm using an impeller fabricated from graphite and driven by a variable DC motor, and then injection of the reinforcements started. Upon the completion of the injection, the slurry was continuously cooled at an average rate of 4.2 °C/min to the semi-solid temperature range of the matrix alloy, and then was bottom poured into a steel die after reaching 607 °C (corresponding to 0.2 solid fractions of primary particles according to Scheil equation). In this stage, for investigation of as-cast properties, some samples were selected. Then, in order to produce the composite by ARB and CAR processes, first, the as-cast MMC was solution-treated

**Table 1 Mechanical properties of A356 alloy and A356/SiC composite produced by conventional routes**

| Production route | Material | Hardness, VHN | Yield strength, MPa | Ultimate strength, MPa | Elongation, % |
|---|---|---|---|---|---|
| Semi-solid processing | A356 | $55 \pm 5$ | $90 \pm 10$ | $100 \pm 10$ | $5 \pm 2$ |
| | A356/10 vol.% SiC | $65 \pm 5$ | $100 \pm 10$ | $110 \pm 10$ | $2 \pm 1$ |
| Powder metallurgy | A356 | $60 \pm 5$ | $110 \pm 10$ | $140 \pm 10$ | $5 \pm 2$ |
| | A356/10 vol.% SiC | $70 \pm 5$ | $130 \pm 10$ | $150 \pm 10$ | $2 \pm 1$ |
| Stir casting | A356 | $45 \pm 5$ | $80 \pm 10$ | $90 \pm 10$ | $3 \pm 1$ |
| | A356/10 vol.% SiC | $50 \pm 5$ | $85 \pm 10$ | $95 \pm 10$ | $2 \pm 1$ |

**Table 2 Chemical composition of A356 alloy (in wt.%)**

| Al | Si | Fe | Cu | Mn | Mg | Zn | Ti | Others |
|---|---|---|---|---|---|---|---|---|
| 91.89 | 7.28 | 0.31 | 0.11 | 0.01 | 0.33 | 0.04 | 0.01 | 0.02 |

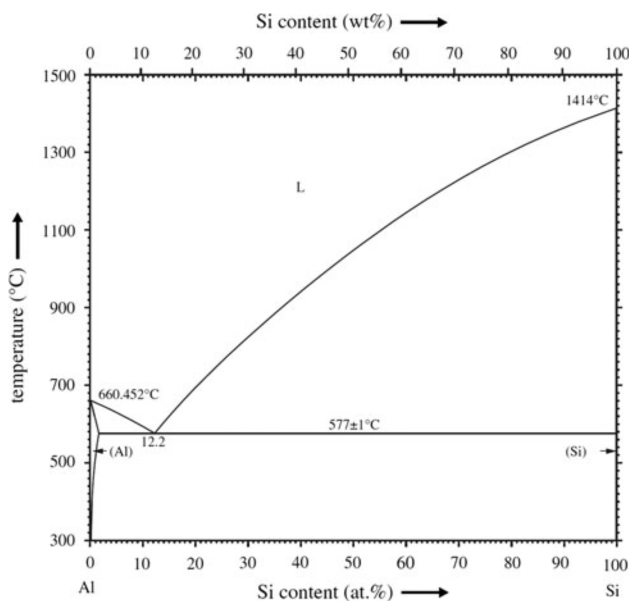


**Fig. 1** The Al-Si phase diagram (Ref 14)

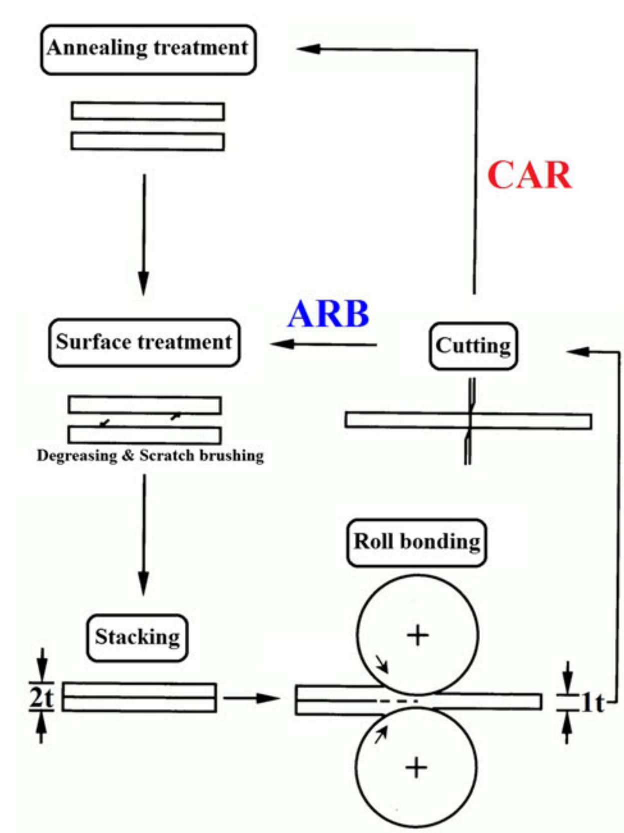


**Fig. 2** Schematic illustration of ARB and CAR processes

at 500 °C for 6 h. Then, samples of 100-mm length, 40-mm width, and 4-mm height were machined. The initial rolling process was carried out with a specific amount of reduction equal to ~60%, for transforming the samples to sheets. The samples' dimensions were 250 mm × 40 mm × 1.5 mm, after roll bodings were performed in ARB and CAR processes. Next, those samples were annealed at 500 °C for 6 h. Two strips were degreased in acetone bath and scratch brushed with a stainless steel wire brush 0.26 mm in diameter. After surface preparation, the two strips were stacked over each other and fastened at both ends by steel wires. The roll-bonding process was carried out with no lubrication, using a laboratory rolling mill with a loading capacity of 20 tons. An important point is that the roll-bonding process in both ARB and CAR methods was performed with a specific amount of reduction equal to 50% (corresponding to a von Mises equivalent strain $\varepsilon_{vM}$ of 0.8 per cycle). Then, the roll-bonded strips were cut in half (and annealed again for CAR process). The same procedure was repeated up to ten cycles at room temperature. The schematic illustration of ARB and CAR processes is shown in Fig. 2.

The microstructures of the as-cast, ARBed, and CARed MMC strips were evaluated using scanning electron microscopy (SEM) PHILIPS XL30. The microstructures were observed along all planes RD-ND, RD-TD, and TD-ND (RD: rolling direction, TD: transverse direction, ND: normal direction). Also, the tensile test samples were machined from the rolled strips according to the ASTM E8M standard, and were oriented along the rolling direction. The gauge width and length of the tensile test samples were 6 and 25 mm, respectively. The tensile tests were conducted at room temperature on a Hounsfield H50KS testing machine at an initial strain rate of $1.67 \times 10^{-4}$ $s^{-1}$. Total elongation of the samples was measured as the difference in gauge length before and after testing.

## 3. Results and Discussion

Microstructures of as-cast, ARBed, and CARed MMCs at all planes (RD-ND, RD-TD, and TD-ND) are presented in

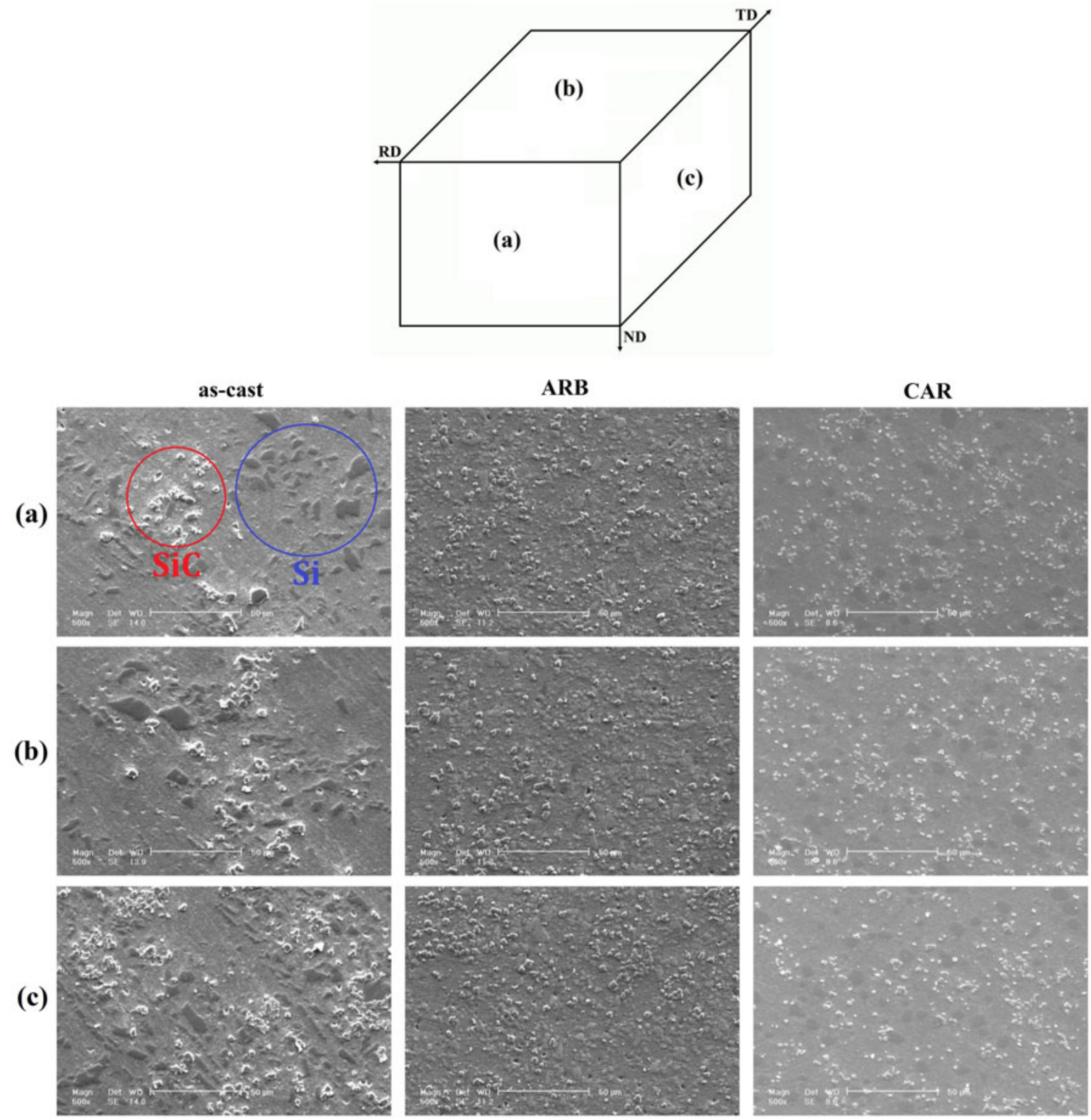


**Fig. 3** SEM images of microstructure at all planes of as-cast, ARBed, and CARed composites

Fig. 3. It is clear that for as-cast composite the distribution of the silicon and silicon carbide in the aluminum matrix is non-uniform, and there are many clusters of Si and SiC particles. Also, the silicon particles are coarse and acicular-shaped in appearance and there is porosity, in particular, in the SiC clusters. Bonding quality between the SiC particles and the matrix is weak and there are large particle-free zones in the matrix. For ARBed sample, the uniformity of the Si and SiC improved, and the number of clusters decreased. In addition, Si particles became finer and more spheroidal in appearance and the porosity disappeared. The quality of Al/SiC interfaces improved and the particle-free zones disappeared. Finally, for CARed MMC, the distribution of the silicon and silicon carbide in the aluminum matrix became completely uniform. The size of Si particles did not change compared to ARBed sample but was finer than that of as-cast composite. Also, the shape of silicon particles became completely spheroid, and there was no porosity in the aluminum matrix. The bonding quality of interfaces was strong, and there were no particle-free zones. According to the above results, it can be concluded that the microstructure of the composite produced by CAR process is better that that of as-cast and ARBed MMCs.

Tensile strength (TS)-elongation curves of the as-cast, ARBed, and CARed A356/10 vol.% SiC MMCs are shown in Fig. 4. As seen, the TSs of the ARBed and CARed composites are, respectively, 3.31 and 1.59 times higher than those obtained for the as-cast sample. On other hand, the MMC processed by ARB has higher TS (348 MPa) compared to the CARed sample (167 MPa), registering 108% improvement. Also, it can be seen that the composite after the tenth cycle of CAR process has a much higher elongation value compared to the as-cast and the ARBed samples, registering 1542 and 253% increase, respectively. In order to better understand these results, it is essential to introduce the strengthening factors which affect TS and elongation of the produced MMCs.

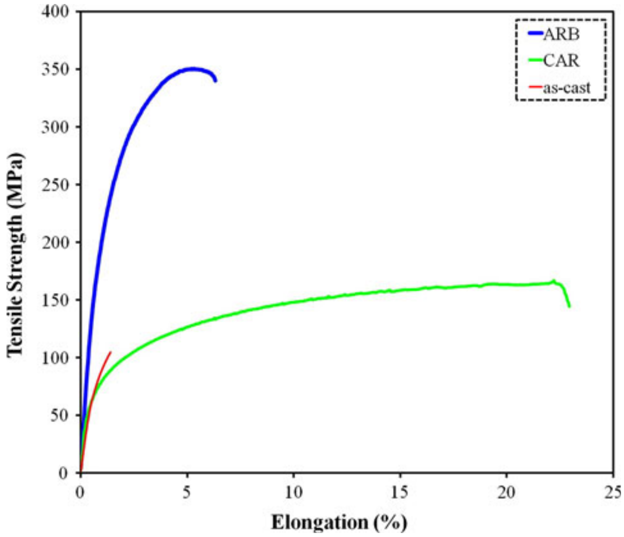


**Fig. 4** Tensile strength and elongation of as-cast, ARBed, and CARed composites

1. *Role of the SiC and Si particles as reinforcement*: Silicon carbide and even silicon particles increase the threshold stress for dislocation glide and cause the generation of additional dislocations around particles, thus decreasing the mobility of dislocations during plastic deformation. These effects lead to increases in the strength and decreases in the ductility of the produced MMCs (effective factor for as-cast, ARBed, and CARed samples).
2. *Uniformity of the SiC and Si particles*: This factor has an important effect on both TS and elongation. When the distribution of the silicon carbide and silicon particles in the aluminum matrix changes to be more uniform and homogeneous, the distance between the Al/SiC and Al/Si interfaces increases. Therefore, during plastic deformation, the cracks which are initiated in the interfaces will propagate and link up with other cracks later, and the TS and elongation values of MMC improve (for ARBed and especially for CARed samples).
3. *Size of the SiC particles*: It has been reported (Ref 15-18) that fine silicon carbide particles can play a role as barriers to the movement of subgrains or grain boundaries, retarding the recovery, recrystallization, and grain growth of the composite microstructure. Therefore, the strength increases for all samples.
4. *Size of Si particles*: This is another factor that affects the strength and elongation of MMCs. During tensile test, coarse Si particles tend to break early, and thus the strength and ductility decrease. Therefore, when the particle size of silicon in aluminum matrix decreases because of the rolling pressure and plastic deformation of matrix, the strength and elongation improve (for ARBed and CARed samples).
5. *Shape of Si particles*: It is well known (Ref 15-18) that spheroid particles increase the TS and elongation compared to less or non-spheroid particles. This can be attributed to lower levels of stress concentration around spheroid particles. Therefore, when the sphericity of silicon particles increases, the mechanical properties of composites improve(for ARBed and especially for CARed samples).
6. *Bonding quality of the Al/SiC interfaces*: In case of the MMCs, fracture mechanism dominated by the crack initiation at the interface propagates through the interface and links up with other cracks and reinforcement/matrix interfaces cause the failure. Thus, the bonding quality plays a vital role for improving the strength and ductility (for ARBed and CARed samples).
7. *Porosity*: the presence of porosity in composites especially around the reinforcement particles leads to a lower TS and elongation (for ARBed and CARed samples).
8. *Mismatch between the coefficients of thermal expansion (CTE)*: The CTE of silicon carbide and aluminum is $4.1 \times 10^{-6}$ and $23.1 \times 10^{-6}\ K^{-1}$, respectively. Therefore, when the MMCs are cooled, silicon carbide particles and aluminum matrix generate dislocations in the sample as a result of heavily built multidirectional thermal stress at the Al/SiC interfaces induced by the large difference of the CTE between the matrix and the reinforcement. Thus, the TS improves, and the ductility decreases (for all samples, in particular, CARed MMC because of annealing treatment between cycles).
9. *Accumulated strain hardening*: It has been expressed (Ref 9, 11, 13) that during ARB process, in the initial cycles, the strain hardening or dislocation strengthening play a main role in increasing the TS, and in remarkably decreasing the elongation,(just for ARBed composite).
10. *Grain refinement*: It is well known (Ref 15-18) that, this factor has notable effect on TS at high ARB cycles. According to previous researches (Ref 9-13), decreasing the grain size results in improving the TS. It is important to note that when the number of ARB cycles increases, the role of work hardening decreases, and gradual evolution of ultra-fine grains plays the main role in strengthening (for ARBed samples only).

It is obvious that there are many lower strengthening factors for as-cast sample compared with ARBed and CARed samples. Therefore, very weak TS and elongation of as-cast composite is reasonable. On the other hand, the difference between mechanical properties of ARBed and CARed MMCs is mainly related to the second, fifth, eighth, ninth, and tenth factors. Accumulated strain hardening factor (ninth) has amore important effect on high TS and low elongation of ARBed sample compared to CARed composite. The absence of this factor in CARed sample leads to very high elongation. However, the second, fifth, eighth, and tenth factors are very important and effective, too.

The material formability (as formability index), which is a function of the strength and ductility, was determined by calculating the product of the ultimate tensile stress (UTS) and total elongation:

$$\text{Formability Index (MPa\,\%)} = \text{UTS (MPa)} \times \text{El (\%)} \qquad \text{(Eq 1)}$$

The variation of formability index for as-cast, ARBed, and CARed samples are shown in Fig. 5. It is clear that the composite processed by CAR process has a much higher formability index (3841 MPa %) than as-cast (147 MPa %) and ARBed (2262 MPa %) samples, registering 2512 and 70% improvement, respectively. Formability in A356/SiC MMC is mainly controlled by all the aforementioned factors. The elongation value is one of the formability index parameters. As mentioned before, this parameter improves by the spheroidization of Si phase, decreasing of the accumulated strain hardening,

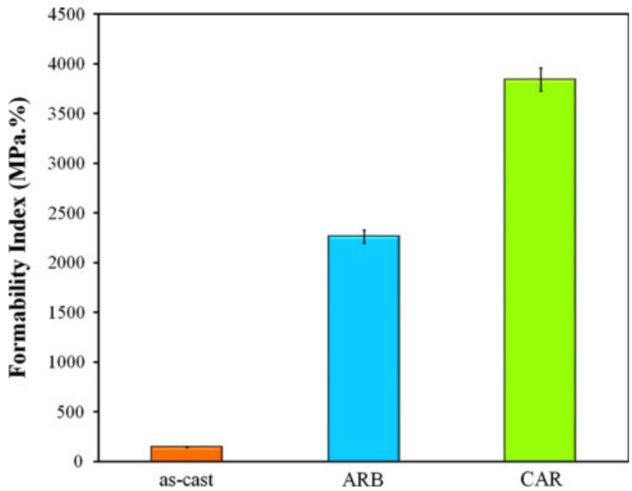


**Fig. 5** Formability index of as-cast, ARBed, and CARed composites

and more uniform distribution of particles. The annealing treatment between cycles in CAR process facilitates the spheroidization of silicon particles, annihilates the accumulated strain hardening, and distributes the particles more uniformly compared to ARB process. In fact, the aforementioned three factors facilitate the plastic deformation around SiC and Si particles, with the decrease in the local stresses around these particles, thereby increasing the formability index. Therefore, it can be concluded that the CAR process is a better method for improving the microstructure and mechanical properties of MMCs compared to ARB process.

## 4. Conclusions

Accumulative roll bonding (ARB) and continual annealing and roll-bonding (CAR) processes were used as a new and very effective technique in this study to manufacture highly uniform and finely dispersed SSMed A356/SiC MMC with high-mechanical properties. The microstructure and mechanical properties of the MMCs were also investigated. The ARB and CAR processes improved the uniformity of silicon and silicon carbide particles in the aluminum matrix. Also, increasing the number of cycles made the Si particles finer and spheroidal in appearance. Furthermore, the particle-free zone and porosity disappeared, and the bonding quality between the reinforcement (SiC) and the matrix (aluminum) improved. The TS of the samples greatly improved by the employment of ARB and CAR processes compared with as-cast sample. However, the CAR process was a better method for improving the microstructure and mechanical properties of as-cast MMC compared to ARB process.

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