Green Design of Novel Metal Matrix Composites

R Singh¹, N Singh¹, I Farina², I Mascolo³, M De Piano³, A Amendola³, F Fraternali³*

¹Department of Production Engineering, Guru Nanak Dev Engineering College, Ludhiana (India)
²University of Naples “Pathenope”, Naples (Italy)
³Department of Civil Engineering, University of Salerno (Italy)

Abstract. In the present research work investigations have been made for surface hardness of Al-SiC metal matrix composite (MMC) prepared by combining fused deposition modelling (FDM), vacuum moulding (VM) and stir casting process. This combination resulted into novel method for preparation of MMC as green process in single step with significant reduction in time. The input process parameters (namely: SiC particle size, proportion of SiC, vacuum pressure and VM sand grin size) were studied at three levels using Taguchi L9 orthogonal array to find out there effect on surface hardne ss of casted specimens. Microstructure analysis was conducted to support hardness data.

1. Introduction
MMC is engineered combination of the metal or metal alloy and hard particle/ceramic which are reinforced to base metal to get essential properties [1]. It is used to make engine blocks which helps to reduce weight of engine and also improved fuel efficiency [2]. MMCs are functional materials and provide an alternative to conventional monolithic alloys. The use of Al based matrix as functional materials resulted into improvement of physical and mechanical properties (such as: high specific modulus, strength, thermal stability etc.) [3]. Besides, Al based matrix performs better in different conditions such as, higher speed and different load which is beneficial for different fields [4, 5]. Several methods (like: stir casting, infiltration, powder metallurgy and spray forming etc.) are used to prepare Al-SiC MMC [6, 7]. The base matrix phase for the present study selected was Al6063, and particles of SiC. In this work, Acrylonitrile-Butadiene-Styrene (ABS) material based pattern was prepared on FDM. This pattern was used for VM assisted stir casting to produce of Al-SiC MMC. FDM is one of the commercial additive manufacturing processes which reduce cycle times, material costs etc. [8-11]. In FDM process, parts are fabricated by extruding a molten ABS material through a heated nozzle in a prescribed pattern onto a platform where material is deposited; it cools, solidifies and bonds with the adjoining material [12, 13]. The previous studies highlights that VM process gives better mechanical properties [14-16]. It was due to the solidification time which can be controlled by controlling the permeability in the mould. Increasing the permeability decreases the solidification time which in turn results in less hardness. In order to increase the hardness, the permeability in the mould has to be less, due to which the heat transfer rate from the cavity-mould interface to the outer of the mould reduces. This could be achieved by increasing the vacuum pressure and by using the sand of fine grit size. High vacuum pressure and finer sand grains increases the mould strength because of tightly packing of sand grains [17, 18]. Tightening the mould could bring more sand into the box and thus increases the time to solidify. This means that increasing the quantity of sand in the mould, reduces the heat transfer rate from the mould. Increasing the sand amount can also be done by providing correct degree of vibration which helps in uniform distribution of sand and completely fills all the corners of the mould. The various steps of VM process shows in figure 1. For this research
work, standard geometry of circular disc was taken 50mm diameter and thickness was 10mm. Small holes were made in the FDM pattern for the suction of vacuum to provide proper sticking of plastic film. In stir casting stage, electrical stirrer was used to mix SiC abrasive particles in molten Al. The slurry was heated to a liquid state and then automatic electrically mixing was carried out for 10 min at a normal stirring rate of 500 rpm. The furnace temperature was controlled up to 700°C ± 20°C. VM process specimens were casted by Al-6063 alloy.

![Figure 1. Steps in VM process.](image)

2. Experimentation

Based upon pilot experimentation, table 1 shows different parameters and their levels for final experimentation. Further table 2 shows control log for experimentation as per Taguchi L9 OA. Based upon table 2, table 3 shows observations for surface hardness. It has been observed that keeping the vacuum pressure below 300mm of Hg results in distorted mould cavity on pouring molten metal during casting. However, when the pressure was above 400 mm of Hg it results in tearing of plastic film which drops the pressure of the mould well below 200mm of Hg hence results in distorted cavity. So the 3 levels for vacuum pressure were selected between 300-400mm of Hg pressure. Three particle size of SiC i.e. single particle size (SPS) 100µm, dual particle size (DPS) 100µm+120µm and triple particle size (TPS) 100µm+120µm+150µm are used as reinforcement.

| (A) Particle size | (B) Vacuum pressure (mm of Hg) | (C) Sand grain size AFS No | (D) Percentage Of SiC |
|-------------------|-------------------------------|---------------------------|-----------------------|
| 1 SPS             | 300                           | 50                        | 5%                    |
| 2 DPS             | 350                           | 60                        | 7.5%                  |
| 3 TPS             | 400                           | 70                        | 10%                   |

The hardness tests on vacuum molded components were performed using Mitutoyo micro hardness tester (Vickers hardness). The surface obtained after casting was cleaned. Based on control log of experimentation (see table 2), three sets of experiments were made as R1, R2 and R3 for measurement of hardness as shown in table 3.
Table 2. Control log for experimentation.

| S. no. | Particle size | Vacuum pressure (mm of Hg) | Grain size AFS No | Percentage of SiC |
|--------|---------------|-----------------------------|-------------------|------------------|
| 1      | SPS           | 300                         | 50                | 5%               |
| 2      | SPS           | 350                         | 60                | 7.5%             |
| 3      | SPS           | 400                         | 70                | 10%              |
| 4      | DPS           | 300                         | 60                | 10%              |
| 5      | DPS           | 350                         | 70                | 5%               |
| 6      | DPS           | 400                         | 50                | 7.5%             |
| 7      | TPS           | 300                         | 70                | 7.5%             |
| 8      | TPS           | 350                         | 50                | 10%              |
| 9      | TPS           | 400                         | 60                | 5%               |

Table 3. Observations of hardness.

| S. no. | Hardness (HV) |
|--------|---------------|
|        | R₁  | R₂  | R₃  |
| 1      | 47.6 | 49.4 | 50.7 |
| 2      | 54.6 | 52.6 | 53.6 |
| 3      | 59.2 | 65.5 | 62.4 |
| 4      | 72.1 | 68.3 | 70.2 |
| 5      | 60.5 | 54.2 | 54.2 |
| 6      | 64.0 | 65.0 | 64.5 |
| 7      | 57.1 | 58.3 | 60.4 |
| 8      | 54.6 | 53.4 | 54.0 |
| 9      | 61.3 | 58.9 | 63.7 |

The best results for hardness were obtained at DPS particle size of SiC with 10% of SiC and 400 mm of Hg vacuum pressure with 60 grit size of sand particle. Particle size of SiC-DPS: It has been observed that hardness of the MMC was best when MMC was prepared using DPS. TPS was found to be the intermediate size among the three particle sizes. Due to this, the amount of DPS added during casting was more than SPS or TPS for the same percentage of addition. This high amount of addition results in more hardness. Percentage of SiC-10%: SiC found to be harder than Al because of which, when added to the Al during casting, hardness of the AMC increases. Which shows that the hardness of the AMC increases with an increase in the percentage of SiC content.

The microstructure images of 9 experiments were taken at 100X as shown in figure 2, which shows SiC abrasive particles present in AMC.

Figure 2. Microstructure images of 9 experiments.
Vacuum pressure—400mm of Hg vacuum pressure increases the compaction ratio of the mould increases and gives tight mould which in turn allows extra sand to come into the moulding box and thus reduces the heat transfer rate. This increases the time required for solidification and gives more hardness and grain size—60: As the mesh number increases, the grain becomes finer. So 60 grain size was the intermediate size among the selected sizes and got closely packed on application of pressure. This reduces the permeability in the sand and also the time required for solidification. If finer sand particles are use then it goes in tiny holes of mould box which block the path of vacuum suction. At optimized parametric conditions (i.e. DPS particle size of SiC with 10% of SiC and 400mm of Hg vacuum pressure with 60 grit size of sand particle) the dimensional measurements were made in order to understand the capability of combined process. It has been observed that the dimensional accuracy/ deviation (expressed as difference between nominal dimension and measured dimension) ‘Δd’ of the castings prepared by combined process are in the range of 0.35-0.39mm with IT grade of castings in range of IT12-13, acceptable as per UNIEN 20286-1 (ISO standard) with process capability index ‘Cp’ of 1.38. Based upon table 3, table 4 shows percentage contribution of input parameters for hardness.

The confirmatory experiments were conducted at suggested settings and the percentage improvement for hardness is 14.71%, which was calculated using the modelling \((F.V - I.V)/I.V \times 100\). These results are valid for 95% confidence level and are in line with the observations made by other investigators.

| Parameter     | Particle size | Vacuum pressure | % SiC | Sand size |
|---------------|---------------|-----------------|-------|----------|
| Hardness      | 34.04%        | 31.04%          | 18.84%| 15.56%   |

3. Conclusions
Improvement in hardness has been observed by combining of VM process, FDM and stir casting. The results suggest that particle size of SiC, vacuum pressure, sand grain size and percentage of SiC significantly affects the hardness. The improvement in hardness is found to be 14.71%. The best parameter setting for hardness is: particle size of Sic-DPS, vacuum pressure-400mm/Hg, sand grain size-60 and percentage of SiC-10% respectively. The hardness was also justified by comparing microstructure images. This study may be further carried out with more number of input parameters and their levels. We address studies on the employment of the analyzed materials for the fabrication and testing of innovative materials and structures at different scales to future work [19-59].

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