Experimental investigations on effect of surface treatment of aluminum based metal matrix composites using laser

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Abstract: Laser sintering is one of the most widely used methods for fabricating advanced materials such as metal matrix composites (MMC). It offers a great deal of flexibilities to deal with complex shapes. Laser sintering is also a critical method to deal with constituents of metal matrix composites with higher melting point and hardness. In the present work, an attempt is made to present an experimental study wherein Al-MMC is fabricated first with the powder metallurgy route. Then surfaces of MMC are treated with laser. The effect of laser treatment on hardness and wear property is investigated. The treatment of laser on the surface of MMC resulted in increased hardness as compared to untreated MMC, and the wear resistance is found better along with the increased percentage of reinforcement particles. The work also presents a study on the application of laser to process Metal Matrix Composite. It gives an idea of different associated process parameters like laser power, scanning speed, and their effect on MMC.

Keywords- Laser, Metal Matrix Composite (MMC), Laser Power, Scanning speed, Hardness

1. INTRODUCTION

This paper reviews the processing of Metal Matrix composites using laser and presents an experimental study on surface treatment of Aluminium based metal matrix composites fabricated through powder metallurgy route. With the use of a laser, it is possible to sinter the metal matrix composite. It is also possible to examine the dissolution of reinforcement in the matrix material. Selective Laser Sintering (SLS) one of the Laser-based techniques to produce MMCs. The conventional methods of processing the MMCs may be hindered by the complexity of shapes and geometry and the mechanical properties of the constituent. Hence Selective Laser Sintering (SLS) or Direct Metal Laser Sintering (DMLS) technique can address complex geometry. When it comes to producing pore and crack-free surfaces, DMLS can play a vital role in obtaining the same. It is worth noting that SLS can facilitate Liquid Phase Sintering (LPS); among the different available rapid prototyping SLS and DMLS are the emerging techniques as they can be extended to process the metals in powder form very well. It can be said that in situ, ceramics based MMC can be produced very quickly with SLS.

Since laser has excellent potential and capabilities of the process, all kinds of metals, Laser-based techniques enjoy MMC fabrication plenty of flexibilities as far as materials and shapes are concerned and do offer abundant scope of near net shape fabrication of MMC in complex shapes. A focused laser beam is used in SLS to fuse or melt the mixture of powders of matrix material and reinforcement. Many researchers have suggested selective laser melting(SLM) as one of the complex
metallurgical processes that may require an extensive understanding of parameters such as scanning speed, scanning strategy, and powders' properties. [1] This technique has been found superior to some conventional methods like stir casting, wherein the segregation of matrix material and reinforcement is a critical issue. Subsequent processes like machining is always required to get the needed shape with accuracy. Presence of hard particle sometimes make machining difficult, and tool wear is significant. Material like titanium is difficult to process with this approach. Selective Laser Melting(SLM) is found to be better with the potential to offer the advantages of both the processes, i.e., casting and powder metallurgy. For materials such as tungsten and their carbide selective laser sintering found to utmost effective.

Kumar et al. [2] reported various Rapid Prototyping Technologies, which can be used to prepare or fabricate composites. They suggested that laser is one of the most suitable among the newer technique, especially for MMCs. Another variant of SLS was proposed as Laser Engineered Net Shaping (LENS), where instead of powder, wires of base material can be used. The following are some other suggested methods, which are available for the making of composites.

1. Laminated Object Manufacturing(LOM)
2. Fiber-reinforced composite in LOM
3. Stereolithographic
4. Fused deposition modeling
5. Ultrasonic consolidation.

Direct metal laser sintering is being one of the popular techniques, where MMC can be fabricated by exposing laser on a layer of powder and repeating the process again and again. However, this process requires a dedicated powder distribution system along with a basic CNC setup. Since material in powder form sometimes become sensitive hence proper shielding environment is also needed. Power layer thickness, laser power, hatch distance, and scanning speed becomes the governing variable. [3-4] Obadele et al. (5) experimentally found that the quality of mixing is significant even when processing MMC through laser. It is also equally applicable for other processes like powder metallurgy in which blending/mixing of the power is also an essential activity. According to them, to obtain homogenous mixing of powders, the following factors must be considered.

- Mixing time
- Type of mixer
- Particle size
- Particle shape
- Binder or any other media

It is a matter of the fact that one or two mechanisms accomplish the mixing of powder, and these are convection, shear, and diffusion, respectively. A mixing device may incorporate any one or combination of the above mechanism. If the particles of powders are subject to forces during mixing, then the resultant particle may be sub-micron size or nano size. If these smaller particles can be embedded in the pores of a bigger particle, then porosity in the MMC can be minimized and can impact density obtained.

2. MIXING TECHNIQUES FOR POWDERS

Shen et al. [6] did the blending of powders using a ball mill in their experimental work. They used a vacuum ball mill rotated at 150 rpm for 60 minutes. Since it was a ball – mill, the ratio of ball to powder kept as 5:1. In another experimental study [7], the researchers used a double cone blender to mix the powders. They used different fill ratios like 1.68, 3.39, and 6.8 concerning the blender's total volume. It is to note that the weight ratio of the matrix to the reinforcement was kept constant. The blending of powders was carried at a slow speed of 48 rpm in the range of 1 - 43 minutes, and samples were taken from the blender. They observed that the rate of mixing is significantly increased as the fill ratio is decreased. Hence, it is advisable to have a large volume of mixing chamber, which is used for
the mixing of powders [7]. It was also suggested that evaluating the standard deviation of the mixing process and optimum mixing time could be evaluated. Obadele et al.[5] used a Turbula mixture, a sound laboratory mixer, and imparts pulsating motion to the powders. They advocated that the Turbula mixture can give motion to the powder, which is a combination of rotation, translation, and inversion. The rotation speed of the mixing device affects the degree of homogeneity of the powder mix. As the speed, increases mixing can become more homogenous at the expense of mixing time. However, beyond a particular high-speed, homogeneity of powder mix is not improved. The specific value or range of speed can be determined by carrying out experiments with a specific device of mixing type. In one experimental studies related to laser cladding, Chong et al.[8] used a ball mill with different fill ratios to mix Mo and Tic powder uniformly. They also used a liquid media polyvinyl alcohol as a binding agent.

3. MATRIX MATERIAL & REINFORCEMENT

Vaucher et al. (9) reported that titanium, aluminium could be used as a matrix material, which can be reinforced by silicon carbide, diamond, and graphite. As far as particle size is concerned, powders were used with particle size ranging from 15 μm to 150 μm. A combination of AlMg12/SiC was used in their study.

Titanium with SiC was also selected for the experimental purpose for the following reasons.
1. There is availability of past data for sintering
2. Recent research
3. Relatively lower explosion sensitivity compared to aluminum.

In the experimental study, SiC was found embedded in the matrix of titanium.

4. SCANNING SPEED OF LASER

Srinivasa et al. [7] used the 180-watt CO2 laser to prepare specimens at the scanning speed range of 50-125 mm/s, respectively. Layer thickness was kept 50 μm. In their study, it was found that the sintered surface of MMC was better and uniform than that of which was obtained at a scanning speed of 125 mm/s. Un- melted powder found at some portion. It indicated that less time could be available for heating and melting of powder mix in case of higher laser speed. The effect of ambiance was also studied; it was revealed that there is a definite effect on the density of matrix material when sintered in a nitrogen atmosphere. Density was found increased as compared to sintering done in an ambiance atmosphere. In their work, Ghosh et al. [7] found that scanning speed does affect the properties of MMC, and they used three different scanning speeds 2000, 4000, and 6000 mm/s. Obadele et al. [2] did experiments for processing of powder with a laser with a scanning speed of 0.4, 0.6, and 0.8 and 1 m/min in their experimental investigation.

5. LASER POWER AND LAYER THICKNESS

Vaucher et al. [9] found that MMC’s microstructure prepared through SLS depends on laser power. This observation was made after examining the samples through optical microscopy. They showed that in Al- Mg powder, elongated crystal of SiC becomes more important when laser power increases. According to them, it is due to the epitaxial relationship of Al-Mg crystal with SiC. It was observed that upon increasing the laser power, interfacial reactions of SiC and Ti were enhanced; the same was confirmed by the presence of titanium silicides when examined. It was also observed that reactions among the particle could be controlled by controlling the laser power. Ghosh et al. [3] fabricated MMC using three-level laser power, i.e., 600, 800, and 1000 watts. This study was carried out by applying the Taguchi technique to optimize the parameter for the development of MMC. In this experimental study, Subrata et al. worked on aluminum- based MMC, which were sintered at using laser power of 600, 800, and 1000 Watts. They reported that laser power is one of the important factors to sinter the MMC when the layer thickness of the powder mix increases. The higher the laser power,
there are less chances that porosity shall prevail in the MMC samples. Due to high laser power, a better fusion of particles is possible. Based on experimental investigation, they suggested that if layer thickness goes beyond 300 µm, the laser power becomes very critical, as the bottom portion of the layer may not fuse properly. Hence it becomes evident to increase laser power as the layer thickness increases.

In one of the experimental investigations, Gasci et al. [10] used the laser beam of 2.35 KW to treat the MMC to obtain a pore and crack-free surface. Laser was used to cure the MMC at the surface only. MMC was prepared through compaction of powders at 200 MPa and 400 MPa. MMC with 18 layers can be fabricated, while it is relatively easy to produce a single layer MMC using DMLS. Voucher et al. [9] reported that Ti/SiC offers enormous scope for the fabrication of multilayer MMC. Gosh et al. [3] fabricated the MMC in their experimental work with a layer thickness of 200 and 300 µm. It was found that if layer thickness is more than 300 µm, then the bottom part of the powder mix will not be fused by the laser. Hence, it is an indication that 300 µm layer thickness is a limiting thickness, which can be satisfactorily fused in one pass of laser action.

6. MICROSTRUCTURE STUDY

When MMC is sintered through a laser, the laser track is visible on the top surface as the melting of powder is caused by the laser itself, and molten metal gets quickly solidified. If the overlapping of successive scanning is large, then a previously solidified track may try to spread over the next track. Ghosh et al. [3] reported that this could lead to pores or voids. If these voids are not rectified in the subsequent scan, then it may result in porosity. Scanning Electron Microscope (SEM) image showed the presence of pore too, which confirmed the need for rectification of each previous scan by the next scan. SEM micrograph helped in the identification matrix material and reinforcement, which was found in the distributed form. Besides, this micrograph can help to study the bonding of ceramic particles with the matrix material. If the bonding is seen accurately, it becomes easy to predict MMC’s properties, especially the hardness and wear resistance. Obadele et al.[5] studied the morphology of powder of WC-9Co-4Cr and Wc-10Ni powders. They could found that if particles have microspores on their outer surface, then fine particles of reinforcement may get embedded into those pores and can result in MMC with enhanced strength and hardness.

![SEM image of powder showing pores](image)

**Fig 1.** SEM image of powder showing pores [5]

It is also observed that needle-like structure, when formed in laser-treated MMC, ensures the presence of hard ceramic particles blended with base material like aluminum.

7. MECHANICAL PROPERTIES

Microhardness in MMC was found depended on laser energy, cooling rate, and amount of reinforcement particles. It is interesting to note that the layer thickness of powder is one of the
significant factors in the processing of MMC with Laser, but it has little contribution to the hardness of MMC.

However, lower layer thickness should result in increased microhardness as intense melting of powder is possible. Gaard et al.[11] reported that an increased proportion of ceramic particles in the matrix might result in less porosity if the dendrite structure is obtained. Still, thermal cracking may be present and can grow pore to pore. Hardness in the range of 380 - 850 HV was achieved and was found increasing with the increased percentage of reinforcement particles. It shows that the introduction of hard ceramic particles can improve the hardness of base material. One of the studies suggested that if the particle of small size creates coarse grain after mixing, then density porosity of target material increases; however, dissimilar grain may result in decreased porosity and enhanced density. If layer thickness exceeds a nominal value, then the bottom part of powders may not be used to form MMC. The power of laser beam affects MMC's microstructure, and the quality of surface treatment given to MMC also depends on laser power. Berns et al.[12] investigated wear resistance of MMC, which was produced by super solids liquid phase sintering (SLPS). They reported that hard particle contributes towards increased wear resistance of MMC.

The hardness of sintered MMC was found on dependent on laser power as more energy is available for melting and fusion matrix material ad hard reinforcement particles. The same was confirmed in the experimental investigation of (3). Through the Taguchi technique, they demonstrated that after the composition of MMC, laser power is one of the critical parameters to contribute to the enhancement of laser. Microhardness of MMCs can be seen increasing when the amount of hard particles increases, and rapid heating and cooling takes place due to higher laser energy. Also, 600 HV hardness of MMC was reported in contrast to 2900-3200 HV of boron carbide, which could be further improved by increasing laser power.

8. LASER CLADDING

Another method or approach for preparing Al-MMC is Laser Cladding, which is being a matter of interest of lots of researchers. It is possible to combine molybdenum or titanium carbide on the surface of different alloys of aluminum. Laser cladding can contribute significantly to the alteration of tribological properties. Chong et al.[13] used a continuous laser of 2 KW of NDYAG system. They kept the laser beam Diameter as 3 mm and a coaxial jet of argon gas to protect the melt pool from oxidation and contamination. It was reported by them that a good quality MMC coating over base alloy is very much dependent on the volume of metal, which infiltrates the ceramics particle. If molten metal volume is not sufficient during the cladding process, a rough surface layer may be formed. Energy density was also found correlating with high-quality cladding of TiC on aluminum alloy [14].

Wear behavior of cladded MMC was found to be better than that of base alloy, and also microhardness was found around 5-10 times higher than Aluminium alloys. Thus it can be seen that Laser Cladding can be treated as one of the variants of Laser-based processing of MMC for increase hardness and enhanced wear resistance[15].

9. EXPERIMENTAL PROCEDURE

Four compositions were taken for this experimental study. The silicon carbide content was kept as 12 %, 15 %, 18%, and 20 % by weight into the matrix of pure aluminum. The powder was mixed through to achieve a uniform mixture through a V-Blender. Each time powder was mixed for 12 Hrs. to evaluate the quality of powder mixed, statistical techniques (Russel and Dotter 1984) were applied, and the standard deviation was assessed. It was found satisfactory. Various powder mixes were prepared with the content of Silicon Carbide in the range of 12 % to 20% (w/w).

After that powder mix was compacted using a set of punch and die. The compaction was done on a mechanical press. After that, green compaction compacts were obtained and sintered in a muffle
furnace in the inert atmosphere of argon gas. After sintering, samples were water-cooled and dried overnight.

After sintering, the top surface of a few specimens were applied, a laser with a maximum power of 200- watt. Samples were laser-treated with the laser power of 100, 150, and 200 watts. After using laser, hardness and wear resistance of samples were examined and compared with those untreated samples to see the effect of laser treatment. Wear studies were carried out with pin on the disk set up and wear rate, and loss of mass was recorded. Microstructures of laser-treated and untreated samples were also examined, and an optical micrograph was obtained. All the specimens were also polished with abrasive papers of various grit sizes and using diamond paste. A polishing machine with a rotating mount was used to clean the specimen for microscopic examination.

10. RESULT AND DISCUSSION

10.1 Morphology of powders:
Powders of aluminum and Silicon Carbide were examined. The silicon carbide powder was found of irregular shape with sharp edges, and aluminum powder found composed of spherical shape with smooth edges. The average size of grain in aluminum powder was 1000 grit, and Silicon carbide powder grain size was found around 800 grit.

![SEM micrograph of Silicon Carbide powder](image)

Fig 2. SEM micrograph of Silicon Carbide powder [5]

10.2 Measurement of hardness:
The hardness of each sample was measured, and observations are presented in Table 1

| Sr no | Composition of MMC | Untreated MMC | Laser treated MMC | Improvement in hardness |
|-------|--------------------|--------------|------------------|------------------------|
| 1     | Al+12% SiC         | 22           | 24               | 9%                     |
| 2     | Al+15% SiC         | 27           | 30               | 11%                    |
| 3     | Al+18% SiC         | 30           | 34               | 13%                    |
| 4     | Al+20% SiC         | 34           | 37               | 8%                     |

Figure 3 shows the comparison of hardness Al-MMC. It is observed that the hardness of laser-treated MMC samples is higher than those of untreated MMC samples. Definitely, laser treatment enhances the hardness; this may be due to Laser produces intense energy; hence remelting of matrix material followed by subsequent cooling improves the bonding between matrix material and reinforcement. Due to improved bonding, action load may likely get transferred to hard particles, which results in
enhanced hardness.

With the increase of SiC content, the hardness of MMC increases, which is in line with the results of many researchers, and at the same time, laser treatment further improved the same. Hence laser treatment can be seen as one of the post-processing treatment.

![Graph showing hardness vs composition](image)

**Fig 3.** Effect of laser treatment on hardness of Al-MMC

10.3 The effect of laser speed: laser scanning speed was varied during the treatment of Al-MMC samples, and figure 4 shows variation in friction coefficient due to laser scan speed. It was observed that for all compositions of the Al-MMC coefficient of friction decreases as laser scan speed increases, it could be noted that the density of the laser-sintered part may reduce. As a result, the extent of asperity interaction diminishes, which results in a reduction in friction coefficient.

![Graph showing coefficient of friction vs scan speed](image)

**Fig 4.** Effect of laser scan speed on the coefficient of friction

10.4 Wear of MMC

Since porosity is one of the inherent characteristics of powder metallurgy, it is evident that the porous region may act as a source of crack and wear. It may be promoted due to exposure to these regions when such material is put to the service application. Figure 5 shows the wear behavior of Al-MMC. It can be seen that with increased content of SiC in matrix and surface treatment, the volume loss is lower. A hard face in the soft matrix may reduce the wear at the same time; intense bonding created through laser energy. Improvement in hardness was seen, which in turn improves wear resistance; also, the growth in bonding at surface level is one of the other attributes for increased wear resistance.
During laser application on the surface of MMC, laser energy causes a selective melting of the matrix material, which in turn form the melt pool. This melt pool may contain both liquid and solid phases. Since the melting point of SiC is higher than that of aluminium [6], a transition may happen from pushing to engulfment, which can improve the bonding. As a result, it has a direct impact on wear resistance.

![Fig 5. Effect of laser treatment on wear of Al-MMC](image)

Figure 6 shows the wear track on the surface of Al-MMC, fig 6(a) is a micrograph of Al-MMC as fabricated and sintered. In contrast, figure 6(b,c,d) shows the micrograph of Al-MMC after wear test. It is evident that worn out surfaces show a different morphology altogether when examined. Broad and deep scratches were observed on the surface of Al-MMC for a lower content of reinforcement material.

Large plastic deformations combined with large values of the load increases the cracking phenomenon at the sub-surface [16].

![Fig 6. Wear of Al-MMC](image)
11. CONCLUSIONS

In this study, laser treatment on the surface was studied, and its impact on different properties of MMC was experimentally observed. Capabilities and application of laser as one of the newer methods has also been discussed. MMC in Near Net shape and complex geometry can be fabricated by laser efficiently and effectively. Mixing of powder and mixing time is important if the starting material for laser processing is in the powder form. It affects the microstructure and mechanical properties of MMC too. It is possible to improve wear resistance of Al-MMC by doing surface treatment along with th increased content of reinforcement.

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