Reusing marble dust as reinforcement material for better mechanical performance: studies on compositing aluminum matrix

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Abstract
The present paper addresses the effects of the preheating of reinforcement particles on the performance of an aluminium metal composite. Waste marble dust particles were used as reinforcements in the Al 6063 aluminium matrix. The aluminium composites were fabricated by preheating the marbles particles at and 200 °C, 100 °C and at room temperature with the help of friction stir processing technique. Tensile strength, micro-hardness, wear and friction behavior of the fabricated materials were compared with aluminium marble dust composite fabricated with room temperature heated marble dust. It was observed that the aluminium marble dust composite processed with 200 °C preheated marble dust resulted in maximum tensile strength and micro-hardness as compared to the composite fabricated with room temperature heated marble dust. Improvement of 52% in tensile strength and 29% in micro-hardness as compared to the composite with room temperature preheated marble dust. The wear and friction properties for the Al-MD composite were also enhanced with the introduction of preheated marble dust in the aluminium matrix. There was an improvement of 25% in the specific wear rate and 23% in the coefficient of friction for the fabricated aluminium marble dust composite as compared to the composite with room temperature preheated marble dust.

1. Introduction
Metal matrix composites are used as a material for automobile. Aerospace and the other number of applications [Prasad and Shoba (2015)]. High hardness, strength, and wear resistance are some of the important properties of the composite materials for which these materials are successfully used in many industrial applications. Ceramic particles like Al2O3, TiC, SiC, MgO, Zircon, B4C and whiskers/ fibers are generally used as reinforcement in the metal matrix to improve mechanical and tribological properties.

The selection of reinforcement parameters such as the amount of reinforcement, size, and shape of particles and mixing of reinforcement particles in the metal matrix greatly affects the performance of the composite materials [Mishra et al (2015)]. The cost and processing of the reinforcement particles also play an important role in the selection of reinforcements and the ever-increasing demand for minimum cost reinforcement gives rise to the usage of industrial and agro wastes as a potential reinforcement in the metal matrix. With this the focus of the current researchers has been shifting towards the usage of agro and industrial wastes.

Flyash, rice husk ash, bamboo leaf ash, rock dust particles are some of the waste reinforcements which has been successfully used to fabricate the AMC [Prakash et al (2016), Sharma et al (2017)]. Out of these industrial and agro wastes, waste marble dust contributed to major environmental problems due to the generation of different stages of mining and related operations. The generation of marble waste starts from mining and lasts for the development of finished products. Leaving the waste particles in environment directly might cause environmental problems. Hence, many researchers are working on how to use this waste material in an effective
way [Aliabdo et al (2014)]. A brief review of the usage of waste marble dust in different applications is presented here.

Kumar et al (2018) used the marble dust powder as a possible reinforcement in the AlCuNi alloy. The marble dust was varied in the proportion of 3, 4, 9 and 12% in the matrix material. It was reported by authors that, lower amounts of marble dust particles improved the tensile strength and hardness of the aluminium composite. With higher percentages (12%), the marble dust particles tend to agglomerate which in result decreased the mechanical properties. Ramesh et al (2013) used the quarry dust particles to fabricate an AMC with the help of a stir casting method. Quarry dust in weight percentages of 5, 7.5 and 10 was used and the prepared composite was investigated to determine the effects of quarry dust particles on the mechanical properties. Increased strength, hardness and wear resistance was reported by the authors with the addition of quarry dust particles.

Rajak et al (2019) proposed a copper–marble dust composite as a bearing material. Different Copper composites with marble dust (1.5, 3.4.5 and 6 wt%) particles were prepared using the stir casting in a vacuum. It was reported by authors that, marble dust enhanced the mechanical properties of the copper composite. The marble dust particles reduced the porosity in the composite and improved the bond strength between the matrix materials. Alaneme et al (2018) manufactured Al–Mg–Si alloy from two-step stir casting method with groundnut shell ash and SiC to examine microstructural and mechanical properties, the author showed that ultimate tensile strength (UTS) and fracture toughness of the composite increased but hardness and strength decreased

Apart from the fabrication of aluminium composites, marble dust has been successfully used as an additive for the constructional bricks and concrete materials. With the addition of marble dust, mechanical, chemical and physical properties of the bricks get improved (Bilgin et al (2012)) and marble dust can replace the clay in the bricks (Marras et al (2010)). For concretes structures, marble particles enhanced the compressive strength and reduced the porosity of concrete (Demirel (2010)). Aliabdo et al (2014) used the marble dust as a possible constituent of the cement and concrete construction. It is reported that the introduction of marble dust in the cement does not affect the initial and final setting time of the cement. The scanning electron microscope images also confirm the similarity in size for the marble dust and cement particles. The marble dust also helped in improving the compressive and tensile strength of the cement and concrete. For the best results, Aruntaş et al (2010) suggested using 10 wt% marble dust in cement preparation.

To utilize the benefits of two or more reinforcing agents in a single matrix, hybrid composites were produced by many researchers (Güür et al (2007)). Marble dust along with flyash were mixed to prepare a polyester matrix composite. The experimental results concluded that the mixture of marble dust and flyash enhanced the strength and hardness of the composite. Chaithanyasai et al (2014) investigated the effects of eggshell on the mechanical properties of Al 6061. Powder metallurgy route was adopted to fabricate the Al- eggshell composite. The authors reported good bonding between eggshell and Al powder and eggshells were properly distributed in the matrix of Al 6061. With the increase in wt% of eggshell increased the hardness of composite also increased.

Stir casting and powder metallurgy are the two famous methods which are used to fabricate the composite materials. The problem of agglomeration of reinforcement particles in the stir casting process and need of complex tooling for the powder metallurgy process are the two main factors which limit the usage of these methods to fabricate the finely structured surface composites. To develop fine structured surface composites, friction stir processing (FSP) is used. Numerous studies have been reported in the past by using the FSP method to fabricate the AMCs. The FSP process further breaks the reinforcement particles and improves the distribution of the reinforcing particles. Owing to this the typical casting effects get eliminated and strength and ductility get improved [Dinaharan et al (2019)]. Another factor which improves the mechanical properties of the composite with FSP is the number of passes. With increase in number of passes to process a particular material. The microstructure becomes more compact which in result improves the tensile strength and hardness [Senthilkumar et al (2019)].

Mehta and Badheka (2019) studied the wear behavior of reinforced Al-6061-T6 SiC made from FSP with boron carbide (B$_2$C). Two specimens were prepared with 1 pass for capping the groove and 3 were for stirring processing. In specimen-1, the direction of successive processing passes was the same. The sample was rotated 180° for successive processing passes, thus reversing the processing moves direction. From the experiment, the author observed that the specimen-1 wear was 72.15% less than the base metal, while specimen-2 showed 74.82% less wear than base metal and 9.58% less wear than specimen-1. Patel et al (2017) studied the effect on tensile, compressive, yield strength, hardness, and toughness of reinforced Al6061 with Fly ash and E-glass fiber by stir casting method. The author saw that tensile strength, yield strength, and compressive strength, percent elongation, and hardness rises through the addition of F.A with continuous E-glass fiber but only the 6 percent fly ash sample decreases in hardness. Only by adding the fly ash reduces toughness. Prabhu et al (2019) reported some improvement of the friction stir processed Al6082/ CaCO$_3$ composite microstructure (10–12 μm) as a result of dynamic recrystallization. The reduction in grain size about 10–12 μm from 141 μm grain size, microhardness increased from 64 HV to 87 HV and the wear rate was reduced by 1/3 of AA6082 and 2/3 of FSP.
AA6082 was reported by the authors. Bannaravuri (2018) compared the effect on density, tensile, hardness, impact strength, tribology, and microstructure by fabrication of Al-4.5%Cu matrix alloy bamboo leaf ash by stir casting technique. The author discovered from this experiment that the bamboo leaf ash spread evenly throughout the matrix. Density reduces as the percentage wt of bamboo leaf ash rises, the strength of tensile and hardness increases, the rate of wear decreases as the percentage wt of bamboo leaf ash rises.

In most of the literature, waste marble dust has been used in the constructional materials. It is analyzed that marble dust particles in the aluminium matrix have proved to improve mechanical properties, however, this area needs more explanation. The preheating of the marble dust particles also affects the performance of aluminium composites. Based on these observations, aluminium composite with marble dust particles as reinforcements has been fabricated using the friction stir processing technique. The effect of preheating of the marble dust particles on the characterization and mechanical properties were evaluated.

2. Materials and method

2.1. Material selection

Al 6063 was used as the matrix material. The material was procured from Aluminium Trading Co., Delhi, India. The magnesium and silicon are the major alloying elements of it. The elemental composition of the Al 6063 as obtained by chemical spectroscopy is shown in table 1. Various mechanical tests were carried out on Al 6063 to find out the mechanical properties. Table 2 presents the mechanical properties of Al 6063 material.

Marble stones were used as the reinforcing agent. Marbles stones are the natural stones having calcareous (CaCO₃) and dolomite CaMg (CO₃) major elements [El-Sherbiny et al (2015a, 2015b)]. There were two types of waste obtained while cutting and polishing of marble. First waste was during the cutting and polishing of the marble dust was called marble waste slurry and the second waste was the broken pieces of marble. The total quantity of waste obtained while processing the blocks and slabs of marbles varies with the machining process was between 30% and 50% of the volume of all processed blocks. These wastes affect both nature and the economy and have harmful effects. The solid waste of marbles was stored in the huge factory warehouses. The marble slurry was refined as much as possible from the water through the treatment unit and the marble waste sludge was obtained. This amount of waste was too large for marble companies to be able to store. For this reason, with controlled or uncontrolled access, these marble wastes were dumped into nature. Because of this, the waste causes considerable pollution of the environment. This concern about the disposal of marble dust is the main basis of this research. The chemical composition of the marble dust used to fabricate the composite material is shown in table 3. From table 3 it is revealed that the major portion of the marble dust is CaO, which was produced by the CaCO₃ upon heating during the testing. The conversion of CaCO₃ to CaO usually took place at higher temperatures. The presence of CaO in the marble dust shall be from the source material from where it was procured and therefore it is being detected during the testing of marble dust composition.

2.2. Experimental setup

FSP machine was used for the processing of Al6063. Table 4 shows the full specifications of the FSP machine which was used for fabrication of composite. This machine consists of a 3-phase powerful motor that drives the FSP tool and provides an efficient torque to it. It has a hydraulic system which makes it efficient to use and work with accuracy. The hydraulic system was used to clamp the materials, up and down motion of the tool and the
transverse motion of the base. The discharge of the hydraulic was controlled by the actuators using a nob. This affects the motion of the tool and the base plate.

2.2.1. FSP tool
The FSP tool shape and material greatly affects the performance of the processing. FSP tool specifications and material properties were very critical to select and designing the tool-tip. The tool material basically depended on the application of tools and type of work-piece. The tool consists of a prob/tip, shoulder to generate frictional heat and apply the required downward force to consolidate and maintain the soften metal underneath of shoulder surface. Generally, the outer surface of shoulder consists of conical or cylindrical in shape. The diameter of the shoulder and tip were in a ratio of 3:1. The most common and straight forward design is the flat shoulder end surface. This shoulder does not entrap the material under the surface and the unwanted material flashed out. The dimensions of plate, tool and groove are presented in table 5.

The tool pin was mainly responsible for distributing the contacting surface of the work-piece, cut the metal in face of the tool and move the plasticized metal behind the tool. The depth of processed zone and maximum traverse speed were controlled by the pin geometry. Various forms and characteristics, including threads, apartments or flutes, can be regarded on the exterior surface of the pin. Thread-less pins were better options for processing high strength or highly abrasive alloys as these characteristics can be readily worn away.

| Components | wt% |
|------------|-----|
| CaO        | 42.45 |
| MgO        | 1.52  |
| SiO₂       | 26.35 |
| Al₂O₃      | 0.520 |
| Fe₂O₃      | 9.40  |

Table 3. Marble dust composition.

| Parameter     | Property                                      |
|---------------|-----------------------------------------------|
| Machine Size  | 1300 × 1650 × 2000 mm                         |
| Welding Geometry | Straight                                   |
| Machine Travel (x, y, z) | 600, 200, 300 mm                           |
| Axis Thrust Force | 250–2500 Kgf (x-axis), 400–4000 Kgf (y-axis) |
| Spindle Speed | 1440 rpm                                      |

Table 4. Friction stir processing setup specifications.

| Table 5. Dimensions of workpiece and tool. |
|--------------------------------------------|
| Dimensions of tool                        |
| Tool Length (mm)                          | 100 mm                                     |
| Shoulder Diameter (mm)                    | 19.95 mm                                   |
| Pin Width (mm)                            | 5 mm                                       |
| Pin Diameter (mm)                         | 7 mm                                       |
| Pin type                                  | Triangle                                   |
| Dimensions of plate                       |
| Plate length (mm)                         | 200                                        |
| Plate width (mm)                          | 75                                         |
| Plate thickness (mm)                      | 10                                         |
| Dimensions of groove                      |
| Groove width (mm)                         | 2                                          |
| Groove depth (mm)                         | 2                                          |
| Groove length (mm)                        | 200                                        |
3. Experimental procedure

3.1. Friction stir processing
Friction Stir Processing was carried out with the help of the friction stir welding machine. The groove \((2 \times 2)\) was created on the Al6063 plate by the milling machine and the composite was fabricated, by using the FSP machine. The groove was properly cleaned by using acetone and the pre-heated marble dust particles were filled and closed by the closing method. The marble dust was preheated at a temperature 100 °C and 200 °C temperatures. The preheating temperature of the marble dust was selected to make sure to eliminate any amount of moisture content from the marble dust. In this work, the effects of preheating marble dust particles have been evaluated. An induction furnace was used to heat the marble particles \([\text{Rajak and Aherwar (2016), Rajak et al (2019)}]\). The required amount of the marble dust was kept in an aluminium foil and kept in an induction furnace for 3 h. The temperature of the induction furnace was closely observed during the preheating of the marble dust particles.

In the groove closing method, the groove was filled by marble dust and then it was closed by FSP probe-less tool to prevent escaping of the micro-particles. The principle of frictional heat was used for the closing of the groove. The frictional heat was generated by the phenomenon of the rubbing action between the tool probe-less tool and the workpiece. After the closing of the material, the plate was subjected with the help of FSP tool with the probe. On the basis of literature review, FSP parameters were selected to carry out the experimental work as shown in figure 1. Table 6 shows the process parameters.

3.2. Characterization and mechanical testing

3.2.1. Microstructure
The distribution of the reinforcement particles in the matrix material greatly affects the performance of the composite. An optical microscope was used to obtain the micrographs for the fabricated composite materials. To obtain the image, the surface of the materials were polished using 100, 120, 220, 320, 400, 600, 1200, 2000 grits ambry paper. After that, wet polishing was done by contacting the samples with fine-grit emery paper against the rotating disc. Lastly, polishing was done on a proprietary cloth using alumina powder. Ethanol was used to wash the surface to remove contaminants. The samples were etched using Keller’s reagent solution to unveil the grain structure. The microscope images were obtained at a magnification of 100X.

3.2.2. X-ray diffraction (XRD)
The XRD works on the principle of constructive interference of a monochromatic x-ray. The x-rays were focused and aimed at the prepared sample. The interaction of the incident ray with the sample results in constructive interference (a diffracted ray) when conditions fulfill the law of Bragg. This law refers to the wavelength of electromagnetic radiation to the diffraction angle and the lattice spacing in a crystalline sample. The XRD was done for characterization of the composite material and the base metal to compare the mixing of reinforcement. After cutting the samples polishing was done with the help of fine emery paper to eliminate the roughness and to make even surface.

3.2.3. Tensile strength
The tensile strength of the prepared composites was evaluated using a Tinius Olsen made ultimate tensile testing machine. The specimens for the tensile testing were obtained from the friction stir processed zone using the wire electric discharge machining as per the ASTM-E8. Figure 2 (a) presents the dimensional configuration of the tensile specimen and figures 2 (b) shows the actual specimens used to test the tensile strength. Each experiment was performed at a strain rate of 1 mm min \(^{-1}\) and at room temperature. Three tests were formed for a single composite and average of three was considered to draw the results.

3.2.4. Micro hardness
The hardness measurement was done as per ASTM E-384 standards. The Microhardness test was carried on Fischer made microhardness tester machine. Prior to the experiment, samples were polished from 100 to 1200 grit fine emery paper to remove the oxide layer and other scales from the surface. The Vickers microhardness values were taken using the load of 300 mN with a dwell time of the 20 s on the processed regions. For each specimen, ten observations were taken and the average of ten was used for analysis.

3.2.5. Tribological testing
The wear and frictional behavior of the prepared specimens were evaluated using a pin on disc setup as per ASTM-G99 Standards. In pin on disc setup, the fabricated material was used as a pin which is slide against a disc. EN-31 steel (Vicker hardness number-746 HV) was used as the disc material.
For the testing, a pin on 8 mm diameter and 4 mm height was cut from the friction stirred zone of the composite material. The pin was held in a mounting and later attached with a bell crack lever mechanism of the pin on disc setup. Dead weights were applied on the other side of the lever. Pin on disc setup had a friction sensor installed on it, which was used to measure the friction force between the pin and disc specimen, later the friction force was converted to the coefficient of friction.

The wear from the pin specimens was measured with the help of a precise weighing balance having an accuracy of 0.0001 g. The specific wear rate was calculated from the wear obtained from the pin. Table 7 presents the experimental parameters for the evaluation of wear and friction behavior. Figures 3 and 4 presents the test specimens before and after the wear test.

**Table 6.** Processing parameters used for the fabrication of composite material.

| Material               | Feed rate (mm min⁻¹) | Tool angle (Degree) | Rotational speed (RPM) | Preheat temp. (°C) |
|------------------------|----------------------|--------------------|------------------------|--------------------|
| Sample 1 (Al 6063)     | —                    | —                  | —                      | —                  |
| Sample 2 (Al-MD)       | 25                   | 0°                 | 900                    | Room temp          |
| Sample 3 (Al-MD)       | 25                   | 0°                 | 900                    | 100                |
| Sample 4 (Al-MD)       | 25                   | 0°                 | 900                    | 200                |
4. Results

4.1. Microstructure

The optical micrographs obtained from the microscope are presented in figures 5(a)–(d). The presence of marble dust particles was detected for the prepared composites. The microstructure of the friction stir processed composites presents smaller grains as compared to the unprocessed Al 6063 (figure 5(a)). The grains were further found to get finer as the preheating temperature gets increased. Figures 5(b)–(d), show the microscopic

| Parameters             | Value |
|------------------------|-------|
| Disc temperature (°C)  | 50    |
| Disc Speed (RPM)       | 300   |
| Sliding Distance (m)   | 500   |
| Load (N)               | 40    |
| Sliding Distance (m)   | 500   |

Figure 2. (a) Tensile Specimen design (b) tensile specimen after wire cutting.

Figure 3. Wear test preparation.
images for composite prepared with marble dust heated to room temperature, 100 °C and 200 °C temperature respectively.

4.2. X-ray diffraction
The XRD was done for the detection of the intermetallic compound in the samples. The rays are subjected at a range of 2θ angle from 10°–80° throughout the analysis. The peaks are detected in this analysis. The results reveal the particles present in the sample of the Al6063 and in the processed samples. XRD results show that the major element in Al6063 was Al and Al-Fe-Si. The XRD of unprocessed Al6063 is shown in figure 6.

Figures 7(a)–(d) shows the elements like Ca, Si, O, Al, and Mg which proves the presence of marble dust in the composite. The bonding between the M.D and the Al was shown in the microstructure. The XRD results also show that aluminum reacts with the atmosphere to form its oxide. Ca–Mg–Si was the main element formed in marble dust from the reaction. Ca–Mg–Si was seen at a 31° 2θ angle.

4.3. Micro-hardness
The Vickers hardness of the specimen was calculated by taking 10 readings on the samples. The microhardness variation observed for the processed samples along the width is presented in figure 8(a). The AA 6063 aluminium had a Vicker hardness of 67 HV. The sample prepared with the marble dust heated to room temperature exhibits decrease in the hardness value with maximum hardness of 65 HV achieved at center of the processed zone. The low bonding between the Al and marble dust reduce the surface hardness of the processed sample. With increase in the preheating temperature to 100 °C the maximum hardness value reached to 69 HV. The presence of CaO, SiO₂, MgO, and Al₂O₃ improved the hardness of the fabricated materials [Prasat et al (2011), Lakshmi et al (2017)]. The increased preheating temperature of the marble dust particles removed any leftover amounts of the moisture and friction stirring resulted in finer grain structure. With further increase in the preheating temperature, a compact finer grain structure at a higher temperature helped in further improving the micro-hardness. The better bonding strength of Aluminium with marble dust at higher preheating temperatures also enhanced the microhardness for the prepared composite [Rajak et al (2019)].

The average micro-hardness values for the complete friction stirred zone are presented in figure 8(b). The average micro-hardness in the case of the composite prepared at 200 °C pre-heat temperature was 77.396 HV, this increment was about 15% from the base material.

4.4. Tensile strength
The strength behavior of the processed samples is presented in figure 9. The low bonding strength between the Al matrix and the marble dust particles preheated to room temperature and 100 °C resulted in some decreases in the tensile strength and ductility. The sample with preheated marble dust particle to 200 °C improved the strength of Al alloy. The tensile strength of Al 6063 alloy was 157 MPa and for sample 4 (pre-heated at 200 °C) was 202 MPa. There was an increment tensile strength of about 29%. The tensile strength gets increased with increase in pre-heating temperature of the marble dust particles before FSP. The preheated (200 °C) marble dust particle leads to an increase in tensile strength due to the excellent wettability and excellent bonding with the Al matrix. The refining of grains during the FSP and uniform distribution of marble particles in the Al 6063 matrix also helped in improving the tensile strength for the 200 °C preheated marble dust mixed composite. The loads applied were transmitted in the composite to the marble dust particles, which increases the load-bearing capacity [Atuanya et al (2012), Hassan and Aigbodion (2015)]. Elongation was also increased from 6.5 mm for
Figure 5. Optical micrographs for (a) unprocessed material Al 6063 (b) composite prepared with marble dust heat to room temperature (c) composite prepared with marble dust heat to 100 °C temperature (d) composite prepared with marble dust heat to 200 °C temperature.
Al6063 to 7.2 mm for processed sample at 200 °C. Table 8 shows the tensile strength and elongation values of all samples.

4.5. Tribology testing
The tribological investigation was done on Al6063 and Al6063/marble dust composite using a pin on disc method [Sharma et al (2018)]. The wear and friction properties of the material directly depends on the hardness and fracture toughness of the materials and tensile strength have limited effects on the wear and friction of the material [Alajmi and Shalwan (2015)]. This experimental study is limited to the evaluation of microhardness and tensile strength of the prepared material. For better correlation between the mechanical properties and wear behavior, the fracture toughness is need to be evaluated.

Figure 10 presents the variation of the specific wear rate for the processed samples. It is observed that sample 4 had the least amount of specific wear rate. The presence of finer grains in the aluminium matrix processed at 200 °C played an important role in decreasing the wear rate. The hardness of the samples and also the formation of the protective layer of Al₂O₃ in the presence of air helped in reducing the wear from the pin samples [Singh et al (2019), Sharma et al (2019)]. Sample 2 and sample 3 also reduces the wear rate.

The coefficient between the composite pins and EN-31 disc is shown in figure 11, the presence of marble dust particles with compact structure at a higher temperature (sample 4) reduces the coefficient of friction between the tribopairs. This trend of variation of wear rate and coefficient of friction is similar as obtained by Rajak et al (2019). Rajak et al (2019) prepared the aluminium marble dust composites and investigated the wear and friction variations as one of the parameters.

Also, the trends obtained for variation of tensile strength and wear rate does not correlate. This presents the limited dependence of wear rate on the tensile strength of the composite materials. A similar correlation was reported by Alajmi and Shalwan (2015).

For a better understanding of the wear behavior scanning electron microscope (SEM) images were obtained at 600X magnification and 15 kV (figures 12(a)–(d)). There were traces of wear debris on the surface but the voids were not observed. The wear area had heat-affected cliff edges. Plastic yielding was reported for sample 1, sample 2 and sample 3. However, the AA 6063 (sample 1) was the most affected with the plastic yielding. No visible yielding was observed for sample 4.

5. Discussion
As explained in the experimental results, it is seen that the preheating of the marble dust particles greatly influenced the mechanical properties of the aluminium metal composites. The results obtained from the microhardness measurement indicated that the marble dust particles heating to 200 °C temperature improved the microhardness of the prepared composite. However, the composite prepared with marble dust heated to 100 °C and room temperature reduced the microhardness. The low bonding between the marble dust and aluminium when preheated to lower temperature resulted in reduces microhardness. Similar trends were
Figure 7. XRD results for (a) Al 6063 (b) composite prepared with marble dust heat to room temperature (c) composite prepared with marble dust heat to 100 °C temperature (d) composite prepared with marble dust heat to 200 °C temperature.
Figure 8. (a) Vicker’s hardness along the processed zone (b) average vicker hardness for the prepared samples.

Figure 9. Variation of tensile strength for the fabricated composites.
obtained during the tensile testing as well. The presence of moisture content in the marble dust particles at room temperature and preheated at 100 °C resulted in low bonding strength between the marble dust and aluminium particles. This resulted in poor tensile strength. With further increase in the preheating temperature the tensile strength of the processed composite gets increased. At 200 °C, the residue moisture contents in the marble dust particles gets eliminate and a strong bonding between the marble dust and aluminium is obtained. Also, the completely dry marble dust preheated at 200 °C resulted with a finer microstructure. The authors did not further increase the preheating temperature beyond 200 °C as the marble dust particles were completely dried at 200 °C and heating it beyond 200 °C would not further improve the mechanical properties of the processed composites.

For the wear and friction properties, the presence of marble dust particles in the aluminium matrix improved the tribological properties. The uniform distribution of the marble dust particles provides the necessary dry lubrication between the testing surfaces which reduces the wear and friction coefficient. The scanning electron microscope images also indicated thin wear lines for the composite processed with 200 °C preheated marble dust particles.

| Specimen | Strength (MPa) | Elongation(mm) |
|----------|----------------|----------------|
| Sample-1 | 157            | 6.5            |
| Sample-2 | 97.6           | 2.7            |
| Sample-3 | 121            | 1.8            |
| Sample-4 | 202            | 7.2            |
Figure 12. SEM images for (a) Al 6063 (b) composite prepared with marble dust heat to room temperature (c) composite prepared with marble dust heat to 100 °C temperature (d) composite prepared with marble dust heat to 200 °C temperature.
6. Conclusions

In this work, the effects of preheated marble dust particles on the performance of aluminium marble dust composites was evaluated. Three aluminium marble dust composites were fabricated with the help of friction stir processing technique. The marble dust particles were preheated to a temperature of 100, 200 °C and reinforced in the Al 6063 material. A sample with marble dust particles heated to room temperature was also fabricated to compare the effects of preheating of marble dust on the tensile strength, microhardness, specific wear rate and coefficient of friction of the aluminium marble dust composite.

- The morphological analysis showed a finer grain size for friction stir processed aluminium marble dust composites. The preheating of the marble dust particles helped in achieving finer grain size. The composite with 200 °C preheated marble dust particles exhibited finer grain sizes as compared to the composite with marble dust particles heated to room temperature. The presence of marble dust was evident in friction stir processed composites. The x-ray diffraction study revealed the presence of Ca, Si, O, Al, and Mg in the processed composites.
- The micro-hardness value for the 200 °C preheated marble dust particles composite was higher as compared to microhardness of composite with marble dust particles heated to room temperature. There was about 29% improvement in the microhardness of 200 °C preheated marble dust composite as compared to room temperature heated marble dust composite.
- The preheating of the marble dust particles also improved the tensile strength. There was a 52% improvement in the tensile strength for the 200 °C preheated marble dust composite as compared to room temperature heated marble dust composite.
- The tribological properties of the fabricated composite also get improved with the preheating of the marble dust. The composite with 200 °C preheated marble dust resulted in a 23% lower coefficient of friction value and 25% low specific wear rate as compared to room temperature heated marble dust composite. The SEM images also showed that the voids, cracks, cliff edges and wear debris were lesser in case of FSP products.

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