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Effect of Grinding Temperature during Cylindrical Grinding On Surface Finish of Al/Sic Metal Matrix Composites

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ABSTRACT

This paper deals with an experimental study to study the effect of operating temperature on the grindability of Al/SiC metal matrix composites (MMCs) during cylindrical grinding. The machining of MMCs is a vital area to be focussed because finishing processes, such as grinding, to obtain a good surface finish and damage free surfaces, are essential for the application of these materials. Though, the grinding of MMCs has received significant attention so far, no detailed study on the effect of grinding temperature on the grindability of Al/SiC composites has been carried out. In the present work, experiments were carried out to study the effect of cylindrical grinding parameters such as wheel velocity (V_S), work piece velocity (V_W), feed, and depth of cut, and the percentage of SiC volume fraction on the responses, such as grinding force (F_t), surface roughness (R_a), and grinding temperature (T_g). Though three responses were measured during experimentation, this paper focuses widely on grinding temperature only. In the volume fraction study, the T_g values increase with an increase in percentage of SiC volume fraction. In the parameter study, the T_g values are scattered in the range of 740–856°C at the lower and higher levels of grinding parameters. Surface integrity of the ground surfaces was assessed using a scanning electron microscope (SEM). The result of this paper concludes that the surface finish and surface integrity of the ground surface is significantly affected by the effect of grinding parameters on the grinding temperature.

Keywords: grinding parameters, grinding responses, SiC volume fraction, surface roughness, grinding temperature

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I. INTRODUCTION

The metal matrix composites (MMCs) are attractive materials in various areas of industrial application because of their superior properties. Although MMCs possess superior properties, they have not been widely applied because of their poor mach inability. While machining MMCs, the subsurface damage is caused by conventional and unconventional processes such as turning, drilling, milling, electrical discharge machining and abrasive jet machining, making it inevitable that finishing processes, such as grinding, must be used to improve the surface integrity (Zhong 2002).

Grinding plays a vital role in acquiring high dimensional accuracy and surface finish. Hence, a strategy to enhance the grinding rate and surface finish is important for the economical production of components (Cao 2013). However, it is difficult to grind Al/SiC composites, because relatively softer aluminium alloys exhibit poor grind ability, due to clogging of the wheel by chip loading, while SiC can influence rapid tool wear.

While grinding, there are many conditions affecting the responses of the Al/SiC composites. Among these conditions, the percentage of SiC volume fraction and grinding parameters, such as wheel velocity, work piece velocity, feed and depth of cut are considered to significantly affect the selected grinding responses, such as the tangential grinding force, surface roughness and grinding temperature. Though there are three responses measured during the experimentation, this paper focuses only on the effect of grinding parameters on the grinding temperature.

Grinding is a high specific energy process which generates significant amount of heat and has potential to cause surface and sub–surface damage. The properties of a ground surface depend on the grinding temperature, and knowledge of its magnitude is important to establish the grinding conditions.During grinding of advanced materials like Al/SiC composites, which has a relatively softer matrix (Al), it is essential to have better idea of the grinding temperature, so as to reduce/avoid the effects of grinding temperature on the work material being ground (Anand Ronald 2013).

Thermal damage is one of the main factors which affects the work piece quality, and limits the production rates which can be achieved by grinding; so, it is especially important to understand the underlying factors which affect the grinding temperatures (Malkin 2007). Furthermore, the thermal expansion of the work piece during grinding contributes to inaccuracies and distortions in the final product. Hence, it is important to understand the parameters which affect the temperature generated while grinding the Al/SiC composites.

Although extensive studies can be found on the grinding of Al/SiC composites, most of these studies focus only on the surface grinding process, while not much research work has been done on the cylindrical grinding of Al/SiC composites. Therefore, a study on the cylindrical grinding of Al/SiC composites is very much essential to obtain damage-free surfaces for the application of these materials in various industrial fields. This paper deals with issues related to the effects of parameters on the temperature generated during cylindrical grinding of Al/SiC metal matrix composites.

II. GRINDING TEMPERATURE

The grinding process requires high energy expenditure per unit volume of material removed. Virtually all of this energy is dissipated as heat at the grinding zone, where the wheel interacts with the work piece. This leads to the generation of high temperatures which can cause various types of thermal damage to the work piece, such as metallurgical phase transformations, softening of the surface layer with possible rehardening, un favourable residual tensile stresses, cracks and reduced fatigue strength (Hadad 2012).

Numerous methods have been developed to measure grinding temperatures using either thermocouples or infrared thermometers. However, considerable difficulties may arise in interpreting such measurements, due to the extreme temperature gradients in time and space near to the surface, and to the size of the temperature probe or measuring area being bigger than the individual heat source cutting points. Among the various techniques, infrared thermometers, utilizing the black body radiation of objects, provide an accurate measurement of grinding temperatures (Maris 1973, Kim 1997).

Deiva Nathan et al (1999) employed a technique of spark temperature monitoring by a non-contact type infrared radiation pyrometer in their study, whereby the sensitivity of the spark temperature to the grinding process variations was studied. The variation in the temperature of the grinding sparks along the spark stream as it is ejected out of the grinding zone was measured in the manner described in Figure 1.

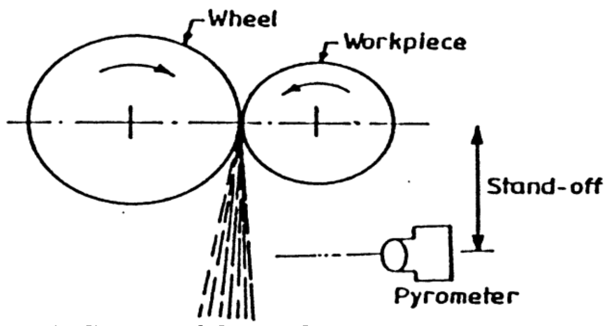


Fig. 1Schematic diagram of the spark temperature measurement

From their study it was understood that the spark temperature was found to increase as the pyrometer was moved away from the grinding zone along the spark stream, up to a distance of 2.8 cm; thereafter it dropped off, as shown in Figure 2.

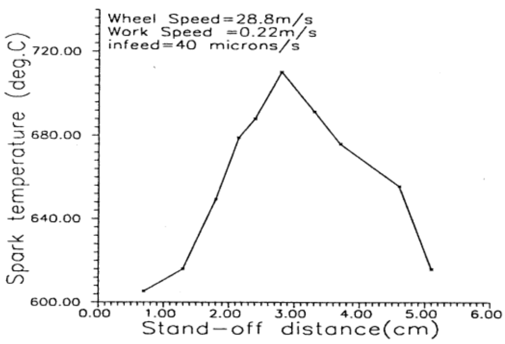


Fig.2Variation of the spark temperature with stand-off distance

This indicates that the sparks are due to an exothermic reaction of the hot chips with the atmospheric oxygen. As the nascent chips travel through the atmosphere, they gain heat due to the exothermic reaction, and their temperature rises. Subsequently, the atmospheric cooling effect predominates, leading to a drop in the temperature of the chips (Huang Ren1992). Based on this, the stand-off distance was fixed at 2.8 cm from the grinding zone, for further experiments.

In their study, the similarity of the spark temperature and the grinding zone temperature was established. Based on their experimental results, it was ascertained that the spark temperature can be considered to be a good representative of the grinding zone temperature, and hence, a useful parameter for the monitoring of the grinding process.

Hence, in the present study, the grinding temperature (T_g) which is the important quality characteristic having direct impact on the process results, has been selected as the response to be measured. Therefore, in the present work, an attempt has been made by conducting experiments to examine the effect of cylindrical grinding parameters and the percentage of SiC volume fraction on the grinding temperature.

III. EXPERIMENTAL PROCEDURE

III.I. Volume fraction study and grind ability study

The presence of SiC in the metal matrix is reported to increase the hardness, tensile strength and heat resistance. The rate of change in these properties is dependent on the volume fraction of SiC added to the matrix alloy. The surface quality of composites depends on the shape, size, and volume fraction of the reinforcement.

The efficient grinding of Al/SiC composites requires an appropriate selection of grinding parameters to obtain good surface quality and low surface damage. The main objective of the grindability study of Al/SiC composites is to evaluate the effect of the cylindrical grinding parameters on the grinding temperature by conducting experiments.

III.I.I. Effect of the Percentage of SiC Volume Fraction on the Cylindrical Grinding Responses

The properties of the composite depend upon the particular constituents and percentage of volume fraction used (Padmanabhan 2004). The cylindrical specimens of the LM25Al/SiC were fabricated with various percentages of SiC volume fractions (2%, 4%, 8%, and 12%) for the experimentation. The effect of the percentage of SiC volume fraction on the grinding temperature (T_g) had been studied and analyzed.

III.I.II. Effect of the Cylindrical Grinding Parameters on the Responses

In order to achieve a better surface finish with a better Material Removal Rate (MRR), a proper combination of the grinding parameters must be selected within their operating ranges. In the grindability study, only four significant parameters, namely, wheel velocity (V_s), work piece velocity (V_w), feed (f) and depth of cut (d) were considered in the planning of the experimentation, to facilitate the data collection. In this study, the effects of the selected grinding parameters on the grinding temperature of Al/SiC composites had been studied and analyzed. In order to study the significance of the parameters and their interactions, the experiments were planned using a full factorial design (3^4) with a total of 81 experiments, each having a combination of different levels of parameters (Anne Venu Gopal 2003).

III.II. Measurement of the grinding temperature (T_g)

An accurate analysis of the temperature in grinding requires a repeatable and stable measurement technique. A non-contact infrared thermometer (MT-9, METRAVI make) was used to measure the grinding zone temperature by measuring the spark temperature. It was ascertained from the experimental results of Deiva Nathan et al (1999) that the spark temperature can be considered to be a good representative of the grinding zone temperature. In their study, the similarity of the spark temperature and the grinding zone temperature was established.

In the present work, while measuring the temperature, the spark temperature was found to increase as the infrared thermometer was moved away from the grinding zone along the spark stream, up to a distance of 8 cm; thereafter, it dropped off. This indicates that, as the chips leave the grinding zone at high temperature, they are subjected to an exothermic reaction with oxygen, which causes their temperature to rise. Subsequently, the atmospheric cooling effect predominates, leading to a drop in the temperature of the chips. Based on this, a stand-off distance of 8 cm from the grinding zone was fixed for further experiments, to measure the temperature.

Hence, in this study, the grinding zone temperature was measured by measuring the spark temperature with the stand-off distance of 8 cm and an emissivity correction of 0.02.

IV. RESULTS AND DISCUSSION

The significance of the cylindrical grinding parameters on the grinding temperature was evaluated by conducting experiments and the results are presented in this section.

IV.I. Effect of the percentage of the SiC volume fraction on the grinding temperature (T_g)

The effect of the percentage of the SiC volume fraction on the grinding temperature (T_g) was evaluated by conducting experiments and the results are shown in Figure 3.

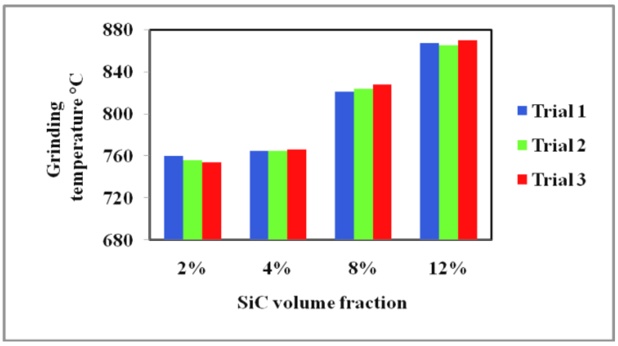


Fig. 3 Effect of the percentage of the SiC volume fraction on the grinding temperature

It can be observed from the results shown in Figure 3 that the T_g values increase with an increase in the percentage of the SiC volume fraction from 2% to 12%. The minimum and maximum values of T_g obtained are 754°C and 870°C for the specimens of 2% and 12% SiC volume fractions respectively, at constant medium level grinding parameters.

In the volume fraction study, the average values of F_t, R_a and T_g obtained for the specimens having lower percentages of the SiC volume fractions (2% and 4%) are minimum and almost equal, when the same are compared with the specimens having higher percentages of the SiC volume fractions (8% and 12%). Among the specimens having lower percentages of the SiC volume fractions (2% and 4%), the hardness of the 4% specimens (55 HB) is more than that of the 2% ones (50 HB).

Further, the introduction of a higher percentage of SiC particles(8% and 12%) into the aluminium alloy results in a significant reduction in the ductility of the specimens (Mc Daniels 1985).

Based on the facts discussed and the results of the volume fraction study, 4% SiC volume fraction specimens were preferred over those with a less percentage of 2 and higher percentages of 8 and 12 for conducting the grindability study experiments.

Based on the results of the volume fraction study, it can be concluded that the higher percentage of the SiC volume fraction in the aluminium matrix, results in higher grinding temperature due to the increase of the energy required to grind a unit volume of the material. The results are in line with the trends available in the study of Outwater and Shaw (1952).

IV.II. Effect of the cylindrical grinding parameters on the grinding temperature (T_g)

The grinding temperature is one of the most important parameters affecting the quality of a ground surface. In order to ascertain the correct grinding conditions, it is necessary to know the effect of each of the grinding parameters and their influences on the grinding temperature (T_g). The effect of the wheel velocity, work piece velocity, feed and depth of cut on T_g is shown in Figures 4 to 6.

In Figures 4a, 5a and 6a it is observed that when the feed (f) is kept constant at 0.06 m/min and the remaining grinding parameters are maintained at lower values (V_s 1414 m/min, V_w 6.11 m/min and d 10 µm) the minimum value of T_g obtained is 740°C. In Figure 6a, when the remaining parameters are increased to higher values (V_s 2639 m/min, V_w 26.72 m/min and d 30 µm), the grinding temperature is increased to the maximum of 829°C.

In Figures 4b, 5b and 6b, when f is kept constant at 0.09 m/min and the remaining grinding parameters are maintained at lower values (V_s 1414 m/min, V_w 6.11 m/min and d 10 µm), the minimum value of $T_g$obtained is 743°C. In Figure 6b, when the remaining parameters are increased to higher values (V_s 2639 m/min, V_w 26.72 m/min and d 30 µm), the grinding temperature is increased to the maximum of 839°C.

In Figures 4c, 5c and 6c, when f is kept constant at 0.17 m/min and the remaining grinding parameters are maintained at lower values (V_s 1414 m/min, V_w 6.11 m/min and d 10 µm), the minimum value of T_g obtained is 746°C. In Figure 6c, when the remaining parameters are increased to higher values (V_s 2639 m/min, V_w 26.72 m/min and d 30 µm), the grinding temperature is increased to the maximum of 856°C.

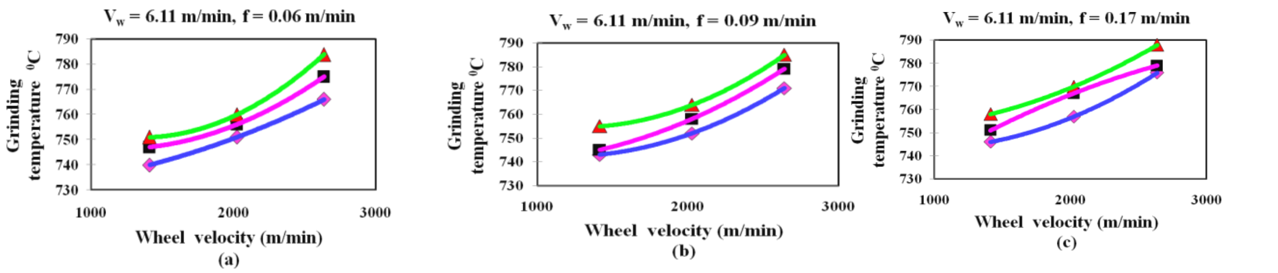


Fig. 4 Effect of the grinding parameters on the grinding temperature at a workpiece velocity of 6.11 m/min and feed rates of (a) 0.06 m/min, (b) 0.09 m/min, (c) 0.17 m/min

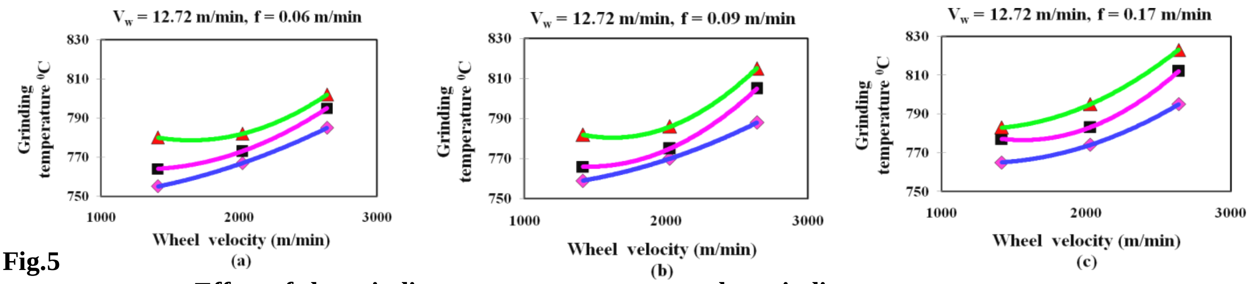


Fig.5 Effect of the grinding parameters on the grinding temperature at a workpiece velocity of 12.72 m/min and feed rates of (a) 0.06 m/min, (b) 0.09 m/min, (c) 0.17 m/min

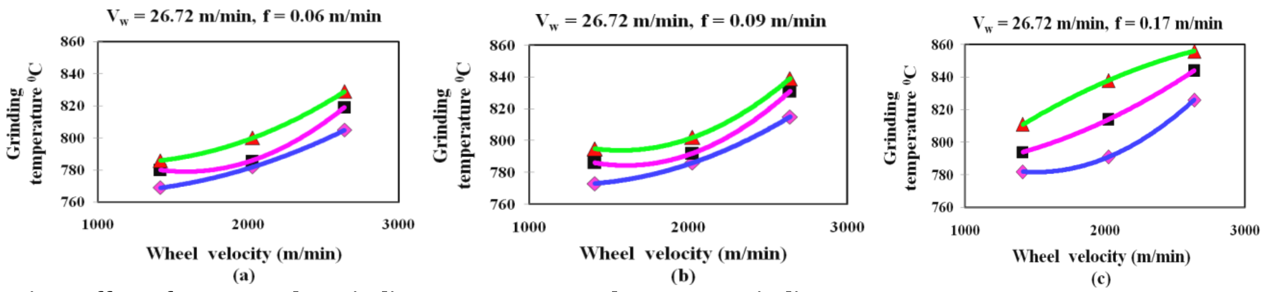
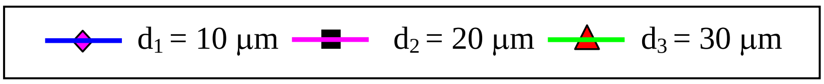


Fig.6 Effect of the grinding parameters on the grinding temperature at a workpiece velocity of 26.72 m/min and feed rates of (a) 0.06 m/min, (b) 0.09 m/min, (c) 0.17 m/min



The minimum and maximum values of the grinding temperature obtained at different feed rates and their differences are tabulated in Table 1.

Table 1 Variation of the grinding temperature at different feed rates

Level of feed	Feed f	Minimum grindingtemperatureT_g	Maximum grindingtemperatureT_g	Difference in grindingtemperature
Low	0.06 m/min	740°C	829°C	89°C
Medium	0.09 m/min	743°C	839°C	96°C
High	0.17 m/min	746°C	856°C	110°C

The difference between the minimum and maximum grinding temperatures is higher in the case of the f at 0.17 m/min, when the same is compared with the f at 0.06 m/min and 0.09 m/min. A higher feed in combination with a higher depth of cut, increases the wheel-work contact area, leading to an increase in grit penetration, which subsequently increases the grinding temperature.

In Figures 4a, 4b and 4c it is observed that when the work piece velocity (V_w) is kept constant at 6.11 m/min and the remaining grinding parameters are maintained at lower values (V_s 1414 m/min, f 0.06 m/min and d 10 µm) the minimum value of T_g obtained is 740°C. In Figure 4c, when the remaining parameters are increased to higher values (V_s 2639 m/min, f 0.17 m/min and d 30 µm), the grinding temperature is increased to the maximum of 788°C.

In Figures 5a, 5b and 5c, when the V_w is kept constant at 12.72 m/min and the remaining grinding parameters are maintained at lower values (V_s 1414 m/min, f 0.06 m/min and d 10 µm), the minimum value of T_g obtained is 755°C. In Figure 5c, when the remaining parameters are increased to higher values (V_s 2639 m/min, f 0.17 m/min and d 30 µm), the grinding temperature is increased to the maximum of 823°C.

In Figures 6a, 6b and 6c, when the V_w is kept constant at 26.72 m/min and the remaining grinding parameters are maintained at lower values (V_s 1414 m/min, f 0.06 m/min and d 10 µm), the minimum value of T_g obtained is 769°C. In Figure 6c, when the remaining parameters are increased to higher values (V_s 2639 m/min, f 0.17 m/min and d 30 µm), the grinding temperature is increased to the maximum of 856°C.

The minimum and maximum values of the grinding temperature obtained at different work piece velocities and their differences are tabulated in Table 2.

Table 2 Variation of the grinding temperature at different work piece velocities

Level of Work piece velocity	Work piece Velocity V_w	Minimum grinding Temperature T_g	Maximum grinding Temperature T_g	Difference in grinding temperature
Low	6.11 m/min	740°C	788°C	48°C
Medium	12.72 m/min	755°C	823°C	68°C
High	26.72 m/min	769°C	856°C	87°C

The difference between the minimum and maximum grinding temperatures is higher in the case of the V_w at 26.72 m/min, when the same is compared with the V_w at 6.11 m/min and 12.72 m/min. A higher work piece speed increases the grinding temperature, since each individual grain has to remove a chip of the thicker section.

It is observed from the results shown in Figures 4 to 6 that the grinding temperature (T_g) increases with an increase in the wheel velocity, work piece velocity, feed and depth of cut. The minimum value of T_g is 740°C obtained at the set of lower level grinding parameters (V_s 1414 m/min, V_w 6.11 m/min, f 0.06 m/min and d 10 µm). The maximum value of T_g is 856°C obtained at the set of higher level grinding parameters (V_s 2639 m/min, V_w 26.72 m/min, f 0.17 m/min and d 30 µm).

The higher values of the grinding parameters (V_s, V_w, f and d) result in higher grinding temperatures due to the increase of the energy required to grind a unit volume of the material. The results are in accordance with the trends available in the studies presented by Nee and Tay (1981).

SEM AND EDX ANALYSES

The effect of different set of grinding parameters on the grinding temperature was evaluated through the imaging of the surface using a high resolution SEM. Therefore, the SEM images of the ground surfaces obtained at different grinding parameters were taken. The different images of the surfaces along with the parameters followed, and the effect of grinding temperature on the ground surface, are presented in Figures 7 and 8.

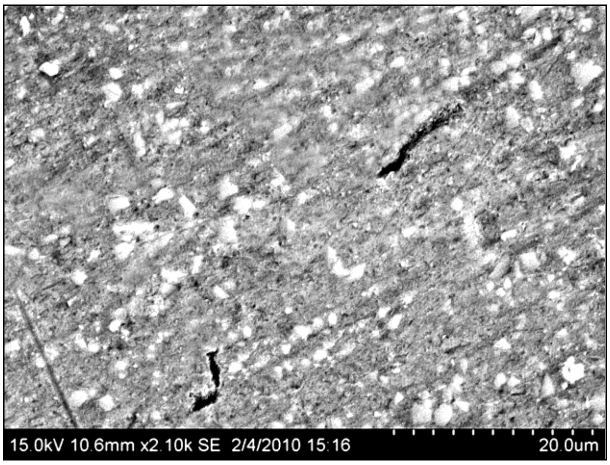


Fig.7 Rough ground surface of the LM25Al/SiC/4p with cracks at a higher magnification of 2100x (V_s2639 m/min, V_w26.72 m/min, f 0.17 m/min, d 30 µm)

Figure 7 shows the rough ground surface of the specimen imaged at a higher magnification (2100x). This surface, obtained at high wheel and work piece velocities, high feed and depth of cut (V_s2639 m/min, V_w26.72 m/min, f 0.17 m/min and d 30 µm) shows the micro cracks and the fragmentation of the Al-Si eutectic (white globular) particles. The fragmentation of the Al-Si eutectic particles is due to the high feed and depth of cut (f 0.17 m/min, d 30 µm).

The higher values of the grinding parameters (V_s 2639 m/min, V_w 26.72 m/min, f 0.17 m/min, d 30 µm) result in higher grinding temperature of 856°C. The development of the micro cracks on the ground surface is probably due to the generation of heat, with a differential thermal expansion between the metal matrix and the reinforced particles (SiC).

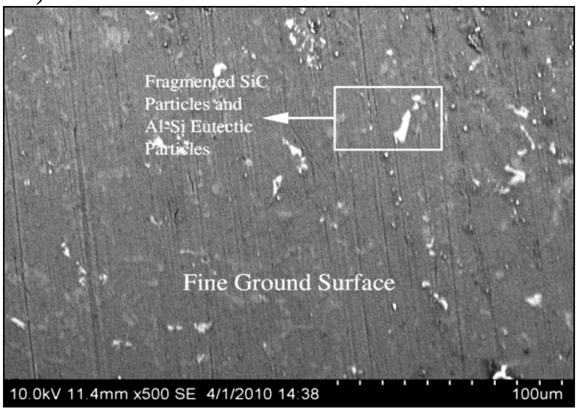


Fig.8 Fine ground surface (500x) of the LM25Al/SiC/4p (R_a is 0.171 µm at V_s1414 m/min, V_w6.11 m/min, f 0.06 m/min, d 10 µm)

Figure 8 shows the SEM micrograph of the fine ground surface having an R_a of 0.171 µm. The fine grinding marks shown on the SiC particles in this figure ensured that both the SiC particles and the aluminium matrix were removed by cylindrical grinding at low wheel and work piece velocities (V_s1414 m/min, V_w 6.11 m/min), low feed and depth of cut (f 0.06 m/min, d 10 µm). Figure 8 reveals that, owing to better grinding parameters (V_s 1414 m/min, V_w 6.11 m/min, f 0.06 m/min, d 10 µm), the minimum value of T_g obtained is 740°C. There were no cracks and defects found on the fine ground surfaces, when observed with the SEM.

V. CONCLUSIONS

The investigations of this study provided an insight into the effect of cylindrical grinding parameters on grinding temperature to obtain a better surface finish and damage free surfaces. The conclusions of the volume fraction studyand the parameter study on the grinding temperature are summarized and given below:

1. The results of the volume fraction study show that the grinding temperature (T_g) increases with an increase in the percentage of the SiC volume fraction. The higher percentage of SiC volume fraction (12%) resulted in the increase of T_g by 15%, when compared to grinding with lower percentage of SiC volume fraction (2%).
2. Based on the results of the volume fraction study, 4% SiC volume fraction specimens were preferred over those with a less percentage of 2 and higher percentages of 8 and 12 for conducting the grindability study experiments.
3. In the grindability study, an experimental investigation was carried out to study the effect of the cylindrical grinding parameters (wheel velocity, work piece velocity, feed and depth of cut) on the grinding temperature using 4% SiC volume fraction specimens based on the full factorial design (3^4).
4. The results of the grindability study show that the grinding temperature (T_g) increases with an increase in the wheel velocity, work piece velocity, feed and depth of cut. The higher values of the grinding parameters result in higher grinding temperature due to the increase of the energy required to grind a unit volume of the material.
5. The higher level grinding parameters (V_s 2639 m/min, V_w 26.72 m/min, f 0.17 m/min and d 30 µm) resulted in the increase of T_g by 16%, when compared to grinding at lower level grinding parameters (V_s 1414 m/min, V_w 6.11 m/min, f 0.06 m/min and d 10 µm).
6. Further, from the SEM images, it can be concluded that the higher level grinding parameters (V_s2639 m/min, V_w26.72 m/min, f 0.17 m/min and d 30 µm) leads to the maximum value of T_g (856°C). The development of the micro cracks on the ground surface is mainly due to the effect of these parameters and maximum temperature.
7. The SEM micrograph also ensured that the lower level grinding parameters (V_s 1414 m/min, V_w6.11m/min, f 0.06 m/min and d 10 µm) leads to the minimum value of T_g (740°C) and fine ground surface. There were no cracks and defects found on the fine ground surfaces at these grinding conditions.
8. The results of the grindability study and SEM images reveal that the surface finish and surface integrity of the ground surface of Al/SiC composites is significantly affected by the effect of grinding parameters on the grinding temperature.

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During his tenure as senior research scientist at Department of Atomic Energy for nearly two decades, he has made several pioneering contributions in the field of characterization of advanced nuclear materials and in the development of novel surface engineering processes that are in use in our nuclear reactors. He has over 50 publications in refereed journals and at least another 50 presentations in Conferences. He has 2 patents and is coauthor of 3 books and has been conferred several National awards. He is a recipient of several National awards including the Young Engineers Award from INAE, Young Metallurgists Award from IIM, Shiksha Bharathi Puraskar award and Mother Terasa Excellence Award.