Modeling and Optimization of Cylindrical Grinding of Al/SiC Composites Using Genetic Algorithms

C. Thiagarajan
thiaguresearch@gmail.com
St. Peter's Engineering College
Department of Production Engineering
600 054 Chennai, Tamilnadu, India

R. Sivaramakrishnan
srk@mitindia.edu
MIT Campus, Anna University
Department of Production Technology
600 044 Chennai, Tamilnadu, India

S. Somasundaram
som_sen@rediffmail.com
National Institute of Technical Teachers Training & Research
Department of Mechanical Engineering
600 113 Chennai, Tamilnadu, India

The Al/SiC composites have received more commercial attention than other kinds of Metal Matrix Composites (MMCs) due to their high performance. However, a continuing problem with MMCs is that they are difficult to machine, due to the hardness and abrasive nature of the SiC particles. Grinding is often the method of choice for machining Al/SiC composites to acquire high dimensional accuracy and surface finish in large scale production. Based on the full factorial design (3^4), a total of 81 experiments, each having a combination of different levels of variables, are carried out to study the effect of grinding parameters such as wheel velocity, work piece velocity, feed and depth of cut on the responses such as tangential grinding force, roughness and grinding temperature. Modeling and optimization place a vital role in controlling any process for improved product quality, high productivity and low cost. In the present work, experimental results are used to calculate the analysis of variance (ANOVA) which explains the significance of the parameters on the responses. Based on the results of ANOVA, a mathematical model is formulated using multiple regression method. A genetic algorithm (GA) based optimization procedure has been developed to optimize the grinding parameters for maximum material removal by imposing constraints on roughness. This methodology would be useful for identifying the optimum grinding parameters in order to achieve the required material removal rate (MRR).

Keywords: *metal matrix composites, cylindrical grinding, modeling and optimization, genetic algorithm*

Introduction

Extensive uses of composite materials are the recent need for different manufacturing processes due to their unique physical and mechanical properties. Almost all fields need a replacement for steel and cast iron in mechanical components with lighter high strength composite materials. The Al/SiC composites possess many advantages such as low specific density, high strength, good wear resistance and excellent thermal conductivity. In particular, they not only have good mechanical and wear properties, but are also economically viable (Kwak, 2008).

Aluminium composites are applied in various automotive components like brake rotors and pistons, machinery components, structural and electronic applications where a close dimensional tolerance is required. The effective use of these materials in such functional applications demands the machining of MMCs with good surface finish and low surface damage. Grinding places a vital role to acquire high dimensional accuracy and surface finish. However it is difficult to grind Al/SiC composites, because the reinforcement and matrix of the composite possess widely different properties like density, co-efficient of thermal expansion, thermal conductivity and young's modulus. This makes the grinding of aluminium alloy based MMC's an unpredictable process (Anand Ronald, 2009).

Previous studies on grinding of composites have shown that Al/SiC composites exhibit an improved grindability with respect to non-reinforced aluminium alloy, for the better surface finish and the lower tendency to clog the wheel. Despite various research efforts in Al/SiC grinding over the past two decades, much need to be established to standardize models for process optimization for improving product quality and increasing productivity to reduce the machining cost. Models contribute significantly to the process itself, and form the basis for the simulation of the grinding processes. They thus create a precondition for increased efficiency while ensuring a high product quality at the same time. Anne Venu Gopal and Venkateshwara Rao (2003) studied the selection of optimum conditions for maximum material removal rate with surface finish and damage as constraints in SiC grinding. The approach presented provides an impetus to develop analytical models, based on the experimental results, to predict the general trends of ground work piece roughness and percentage area of surface damage in terms of the significant parameters under consideration.

Shaji and Radhakrishnan (2003) made the analysis of the process parameters such as speed, feed, in feed and mode of dressing as influential factors, on the force components and surface finish developed based on Taguchi's experimental design methods. Taguchi's tools such as orthogonal array, signal-to-noise ratio, and factor effect analysis, ANOVA, etc. have been used for this purpose and an optimal condition has been found out. The results have been compared with the results obtained in the conventional coolant grinding following the same method. Mohanasundararaju and Sivasubramanian (2007) studied the optimization of grinding parameters to obtain desired roughness in the work rolls using Neural Network-Taguchi approach. In this paper they found that the combination of ANN model with Taguchi Technique helps to predict optimal conditions for obtaining required roughness value more accurately while grinding work rolls.

Miracle; (2005) reported a study on metal matrix composites – from science to technological significance. He stated that the measurement of grinding force components is highly essential to analyze more effectively the grindability factors of Al/SiC composites. Obikawa and Shinozuka (2005) made analysis of grinding temperature considering surface generation mechanism, in which they found that the temperature has significant influences on metal removal processes in grinding and also revealed that the temperature on the ground surface is the most important response for predicting and evaluating the integrity of the ground surface.

Most of the researches (Zhaowei Zhong, 2002; Anne Venu Gopal, 2003; Sun et al., 2006) carried out the experimental work on the grindability of Al/SiC composites in surface grinding to investigate the effect of grinding variables on responses, whereas this paper focuses the research work on the grindability of Al/SiC composites in cylindrical grinding to examine the effect of cylindrical grinding variables wheel speed, work piece speed, feed

Paper received 27 February 2011. Paper accepted 9 August 2011.
Technical Editor: Anselmo Diniz

and depth of cut on the responses tangential grinding force, roughness and grinding temperature. Analysis of Variance (ANOVA) technique has been used to find the significance of grinding variables on the responses In order to explore these relationships mathematical models have also been developed. The mathematical models thus developed are further utilized to find the optimum grinding variables using genetic algorithms (GA) employing a multi-objective function model.

Nomenclature

C, C_1, C_2, C_3	= *constants in mathematical, tangential grinding force, roughness and grinding temperature models respectively*
d.o.f	= *degrees of freedom*
MRR	= *material removal rate, mm_3/mm width/min*
Q	= *grinding response*
w, w_1, w_2, w_3	= *wheel velocity exponents in mathematical, tangential grinding force, roughness and grinding temperature models respectively*
x, x_1, x_2, x_3	= *work piece velocity exponents in mathematical, tangential grinding force, roughness and grinding temperature models respectively*
y, y_1, y_2, y_3	= *feed rate exponents in mathematical, tangential grinding force, roughness and grinding temperature models respectively*
z, z_1, z_2, z_3	= *depth of cut exponents in mathematical, tangential grinding force, roughness and grinding temperature models respectively*

Experimental Design and Procedure

The Al/SiC composite specimens with dimensions ϕ30 X 200 mm are made from LM 25 aluminium alloys reinforced with 13 μm SiC particles. A vitrified-bonded white aluminium oxide grinding wheel is used to grind the MMC specimens LM25Al/SiC/4p (4% SiC by volume). Grinding experiments are carried out on a high precision horizontal spindle cylindrical grinding machine and the schematic diagram of the experimental set-up is shown in Fig. 1.

The mathematical modeling of responses in the grinding of composites involved lots of other factors, such as work material, type of wheel abrasives, grain size, etc. However, to facilitate the experimental data collection, only 4 dominant factors are considered in the planning of the experimentation. The factors considered are wheel velocity (V_s), work piece velocity (V_w), feed (f) and depth of cut (d). The experiments are planned using a complete 3^4 factorial design (Anne Venu Gopal, 2003). Based on this, a total of 81 experiments, each having a combination of different levels of variables are carried out and the details are shown in Table 1. Before every grinding experiment, dressing was carried out. A single point diamond dresser was used for the dressing of Al_2O_3 grinding wheels.

Table 1. Grinding variables and their levels.

Variables	Levels		
	1	**2**	**3**
Cutting velocity of grinding wheel, V_s (m/s)	23.57	33.77	43.98
Cutting velocity of work piece, V_w (m/min)	6.11	12.72	26.72
Feed, f (m/min)	0.06	0.09	0.17
Depth of cut, d (μm)	10	20	30

The responses measured are tangential grinding force (F_t), roughness (R_a) and grinding temperature (G_t). The average values of F_t, R_a and G_t are calculated from the three values measured on each ground surface, for each process condition. A Variable Frequency Drive (VFD) is integrated to the grinding wheel motor so that the wheel is capable of changing speed. The tangential grinding force (F_t), tangent to the wheel-work contact, when multiplied by wheel speed (V_s) and a constant determines the power used by the operation (ASM Metals Handbook: Machining, Vol. 16, 1989). The equation for Power (P) is:

$$P = \frac{F_t\, V_s}{33000} \tag{1}$$

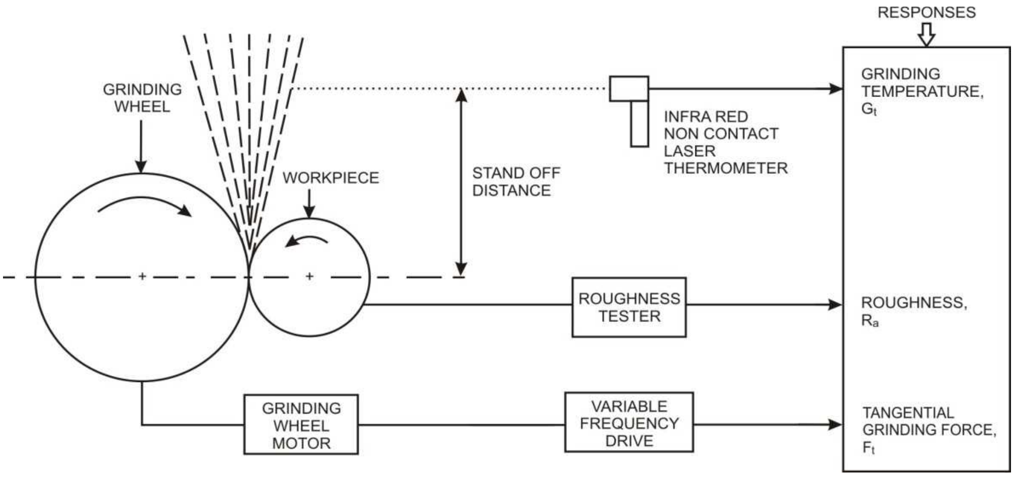

Figure 1. Schematic diagram of the experimental set-up.

The equation (1) for power is valid for horse power, using pounds of force and feet per minute for F_t and V_s respectively. And the VFD is utilized to measure the power of the grinding wheel motor, so that the tangential grinding force (F_t) can be calculated from Eq. (1). The roughness (R_a) of the cylindrical ground specimens is measured in the direction perpendicular to the grinding direction using a roughness tester. The cut-off is 0.8 mm and evaluation length is 4 mm. An infrared non-contact laser thermometer is used to measure the grinding temperature (G_t) with a standoff distance of 8 cm from the wheel-work interface and emissivity correction of 0.02. The details of cylindrical grinding machine and measuring equipments are given in Table 2.

Table 2. Specifications of cylindrical grinding machine and measuring equipment.

Machine and Equipment Used	Specifications
Grinding Machine	Horizontal spindle cylindrical grinding machine (G13P HMT)
Grinding Wheel	Vitrified-bonded white aluminium oxide wheel (AA60K5V8)
Work piece	LM25Al/SiC/4p Matrix- LM25 Aluminium alloy Reinforcement -13 µm SiC particles (4% SiC by volume)
Variable Frequency Drive	5.5 KW / 7.5 HP Inverter drive (ABB Make ACS 350- 03E-12A5-4)
Thermometer	Infrared non-contact laser thermometer (METRAVI MT - 9)
Roughness Tester	Surfcorder - SE 1200 (Kosaka Make)

Methodology

In order to obtain applicable and practical predictive quantitative relationships, it is necessary to model the grinding responses and the grinding variables. These models would be of great use during optimization of the cylindrical grinding of Al/SiC composites using GA. In this work, experimental results are used to calculate the analysis of variance (ANOVA) which explains the significance of the variables on the responses. A commercially available statistical tool MINITAB is used to provide the ANOVA results. Based on the results of ANOVA, a mathematical model is formulated using multiple regression method by using a non-linear fit between the responses and the significant variables. The purpose of developing the mathematical models is to relate the grinding responses to the variables and thereby to facilitate the optimization of the grinding process. Using these mathematical models, the multi objective function and process constraints can be formulated, and the optimization problem can then be solved with the help of genetic algorithms (GA).

Mathematical formulation

The data collected from the experiments are used to build a mathematical model using multiple regression analysis. Multiple regression analysis is practical, economical and relatively easy to use, and is widely used for modeling and analyzing experimental results. The mathematical models commonly used for the cylindrical grinding with the variables under consideration are represented by:

$$Q = \phi\ (V_s, V_w, f, d) \tag{2}$$

where Q is the grinding response, ϕ is the response function and V_s, V_w, f, d are grinding variables. Expressed in non-linear form, Eq. (2) becomes

$$Q = C\ V_s^{\,w}\, V_w^{\,x} f^{\,y} d^{\,z} \tag{3}$$

The following mathematical models are formulated in this work: Tangential grinding force model:

$$F_t = C_1\ V_s^{\,w1}\, V_w^{\,x1}\, f^{\,y1}\, d^{z1} \tag{4}$$

Roughness model:

$$R_a = C_2\ V_s^{\,w2}\, V_w^{\,x2}\, f^{\,y2}\, d^{z2} \tag{5}$$

Grinding temperature model:

$$G_t = C_3\ V_s^{\,w3}\, V_w^{\,x3}\, f^{\,y3} d^{z3} \tag{6}$$

These mathematical models are linearized by performing a logarithm transformation to facilitate the determination of constants and variables. The above function can be represented in linear mathematical form as follows:

$$\ln Q = \ln C + w \ln V_s + x \ln V_w + y \ln f + z \ln d \tag{7}$$

The constants and variables C, V_s, V_w, f and d can then be solved by using multiple regression analysis with the help of experimental results.

Optimization using genetic algorithms

Genetic Algorithms (GA) are search algorithms for optimization based on the principle of genetics and natural selection. The searching process simulates the natural evaluation of biological creatures and turns out to be an intelligent exploitation of a random search. The simplicity of operation and computational efficiency are the two main attractions of the GA approach. A candidate solution (chromosome) is represented by an appropriate sequence of numbers. In many applications the chromosome is simply a binary string of 0 and 1. The quality of its fitness function, evaluates a chromosome with respect to the objective function of the optimization problem. A selected population of solution (chromosome) initially evolves by employing mechanisms modeled after those currently believed to apply in genetics.

Generally, the GA mechanism consists of three fundamental operations: reproduction, cross over, and mutation. Reproduction is the random selection of copies of solutions from the population according to their fitness value to create one or more offsprings. Cross over defines how the selected chromosomes (parents) are recombined to create new structures (offspring) for possible inclusion in the population. Mutation is a random modification of a randomly selected chromosome. Its function is to guarantee the possibility to explore the space of solutions for any initial population and to permit the freeing from a zone of local minimum. Generally, the decision of the possible inclusion of crossover/mutation offspring is governed by an appropriate filtering system. Both crossover and mutation occur at every cycle, according to an assigned probability. The aim of the three operations is to produce a sequence of population that, on the average, tends to improve.

Results and Discussions

Effect of grinding variables on responses

The effect of the cylindrical grinding variables on the selected responses tangential grinding force (F_t), roughness (R_a) and grinding temperature (G_t) are evaluated by conducting experiments and the results are shown graphically in Figs. 2 to 4.

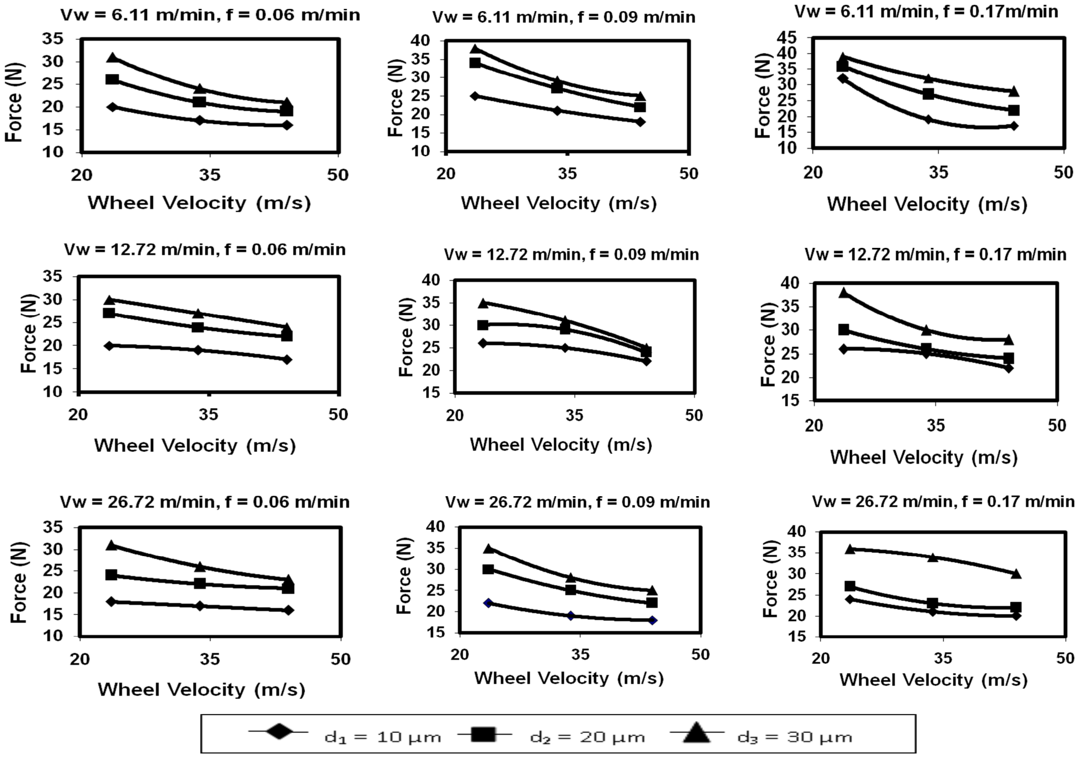

Figure 2. Effect of grinding variables on tangential grinding force.

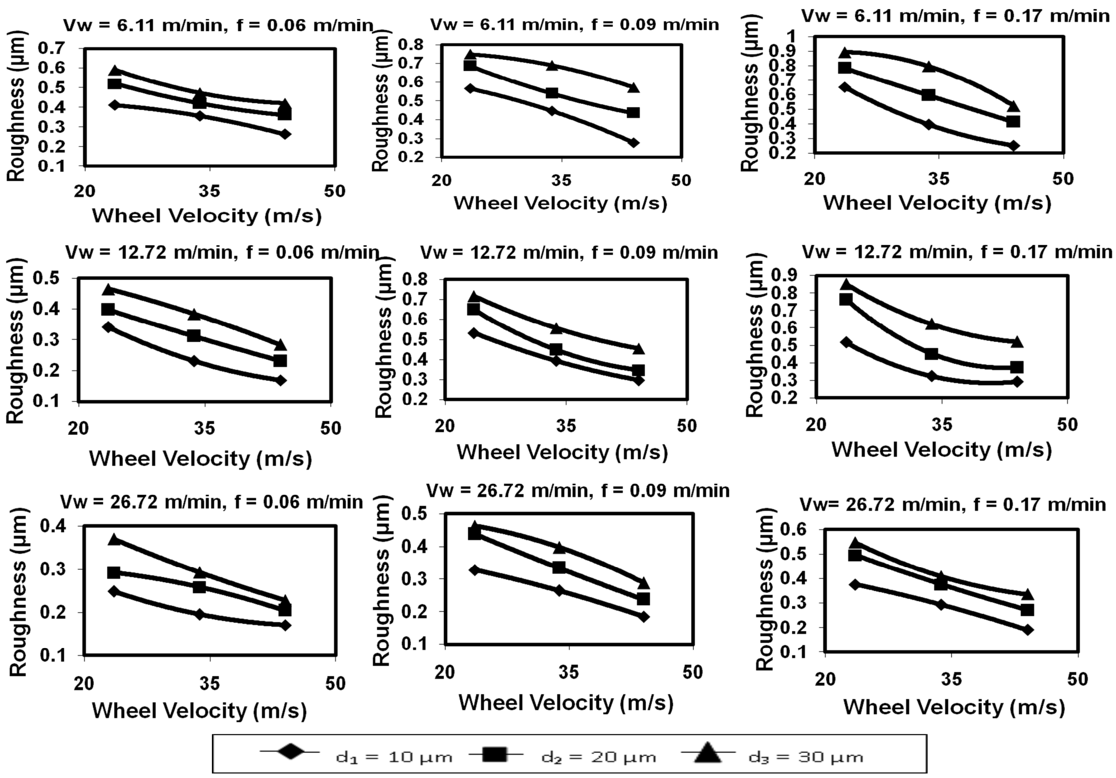

Figure 3. Effect of grinding variables on roughness.

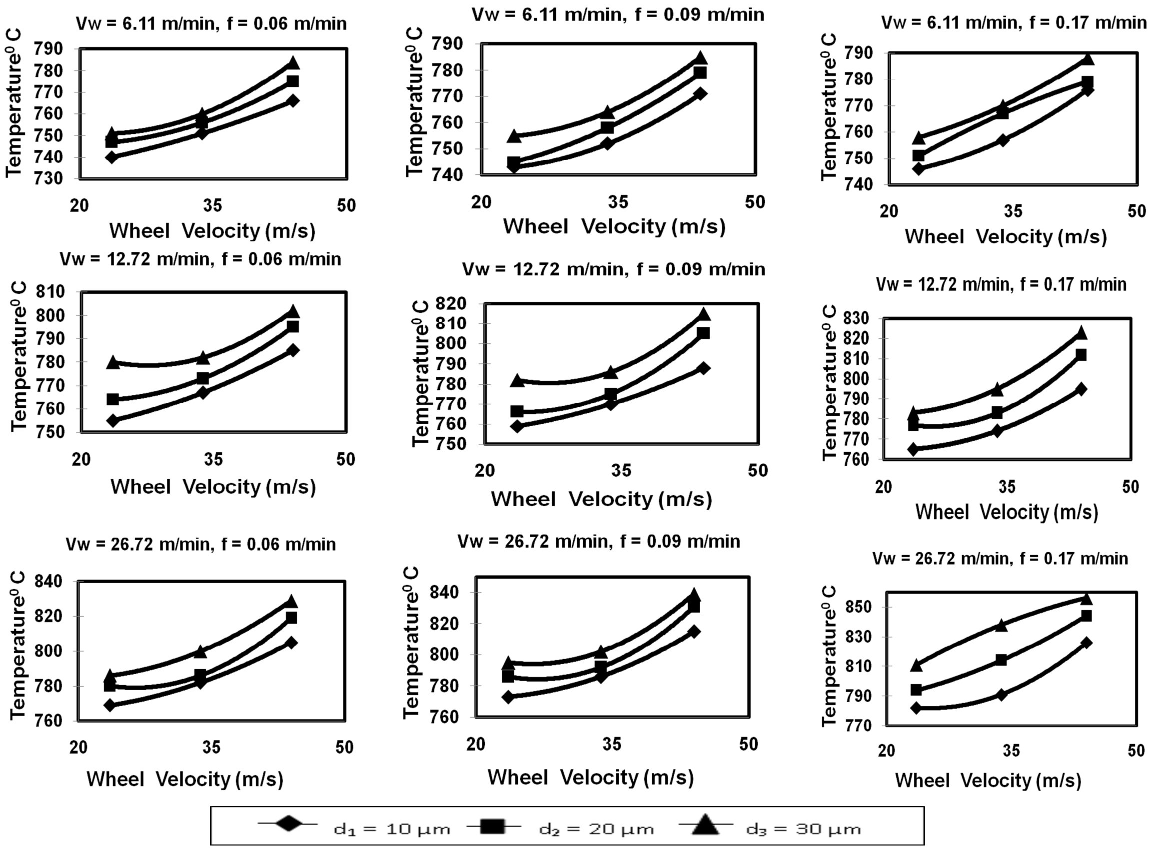

Figure 4. Effect of grinding variables on grinding temperature.

It is observed from the results shown in Fig. 2 that the tangential grinding force (F_t) decreases with an increase in wheel velocity (V_s) and work piece velocity (V_w). This could be attributed to thermally induced softening of the matrix at high speeds. As the grinding wheel velocity increases, the heat generated in the deformation zone increases and softens the aluminium matrix, and thereby the force required to remove the material is reduced.

It is also observed from Fig. 2 that F_t increases with an increase in feed and depth of cut. When feed and depth of cut are increased, the increase in material removal rate and in chip thickness accounts for the increase in the F_t values. The minimum value of F_t obtained is 16N at V_s of 43.98 m/s, V_w of 26.72 m/min, f of 0.06 m/min and d of 10 µm. The maximum value of F_t obtained is 39N at V_s of 23.57 m/s, V_w of 6.11 m/min, f of 0.17 m/min and d of 30 µm.

The effect of cylindrical grinding variables on roughness (R_a) is evaluated by conducting experiments and the results are shown in Fig. 3. This figure shows that roughness decreases with an increase in V_s and V_w. This is mainly due to the increase in relative velocity between the wheel and work piece and the fact that the reduction in contact time reduces the chip thickness. It can also be observed from Fig. 3 that the roughness increases with an increase in feed and depth of cut. When feed and depth of cut are increased, the increase in material removal rate and in chip thickness accounts for the increase in the R_a values. The minimum value of R_a obtained is 0.171 µm, at V_s of 43.98 m/s, V_w of 26.72 m/min, f of 0.06 m/min and d of 10 µm. The maximum value of R_a obtained is 0.893 µm, at V_s of 23.57 m/s, V_w of 6.11 m/min, f of 0.17 m/min and d of 30 µm. The results comply with the trends available in the literature (Zhaowei Zhong, 2002; Anne Venu Gopal, 2003).

The effect of cylindrical grinding variables on grinding temperature (G_t) is evaluated by conducting experiments and the results are shown in Fig. 4. It is observed from the results that G_t increases with an increase in the values of V_s, V_w, f and d. G_t values are scattered in the range of 740-856°C at lower and higher levels of grinding variables. The temperature measured is the spark temperature and it is a good representative of the grinding zone temperature and useful for process monitoring purposes. The spark temperature is measured at the standoff distance of 8 cm from the wheel-work interface. Under the given grinding conditions, the spark temperature is found to increase as the laser thermometer is moved away from the grinding zone along with the spark stream, up to a distance of 8 cm; thereafter, it drops off. Based on this, the stand-off distance is fixed at 8 cm from the wheel-work interface and the temperature is measured.

It is to be noted 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. The results are in line with the trends available in the literature (Nee, 1981; Deivanathan, 1999).

SEM analysis of cylindrical ground surfaces

The surface textures of the cylindrical ground specimens are assessed using a scanning electron microscope and are presented in Figs. 5 to 9. The SEM micro structure of LM25Al/SiC/4p in Fig. 5 shows the matrix of the cast specimen prepared for metallographic examination. It shows uniform distribution of the dark SiC particles (13 µm) in the aluminium matrix before grinding. In general, the SiC particle distribution is nearly identical in all the specimens observed. The metal matrix composite contains script/spike shaped Al-Si eutectic particles, the size of which ranges between 40 µm and 50 µm.

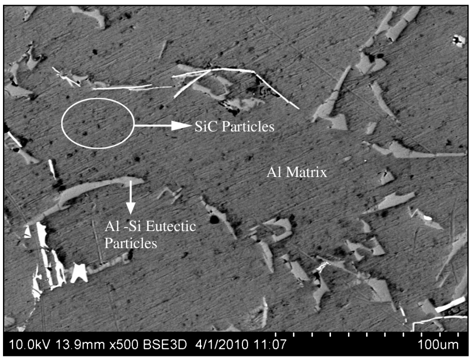

Figure 5. Uniform distribution of SiC particles in Aluminium Matrix.

Figure 6. Rough ground surface of LM25Al/SiC/4p (Vs 23.57 m/s, Vw 6.11 m/min, f 0.17 m/min, d 30 µm).

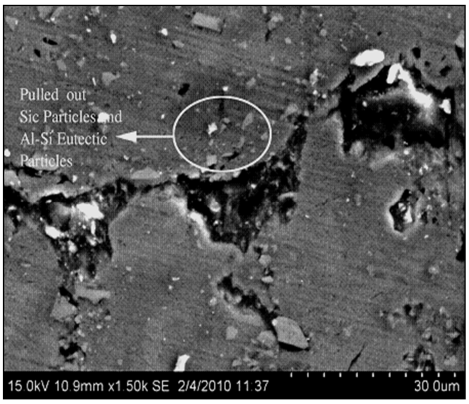

Figure 7. Rough ground surface of LM25Al/SiC/4p with high magnification of 1500X (Vs 23.57 m/s, Vw 6.11 m/min, f 0.17 m/min, d 30 µm).

Figure 6 shows the SEM micrograph of rough ground surface. In this figure, the banding on the work piece surface is the effect of the grinding wheel, due to high feed and depth of cut. As a result of the force of the wheel and depth of cut, the Al_2O_3 grains of the wheel are embedded and also disintegrated on the surface of the work piece. Figure 7 shows the rough ground surface of the Al/SiC specimen at high magnification (1500X). This micrograph clearly reveals that the set grinding variables, such as low wheel and work piece velocities and high feed and depth of cut, lead to the fragmentation and pulling out of the loosely bound SiC particles from the surface. It is probable that a casting defect at that location might have caused the effect. Figure 8 shows the rough ground surface at higher magnification (2100X). This figure shows the micro cracks that occurred on the work piece surface and the fragmentation of the Al-Si eutectic (white globular) particles. The development of the micro cracks on the ground surface is probably due to the generation of heat with differential thermal expansion between the metal matrix and the composites (SiC). The fragmentation of the Al-Si eutectic particles is due to the high feed and depth of cut.

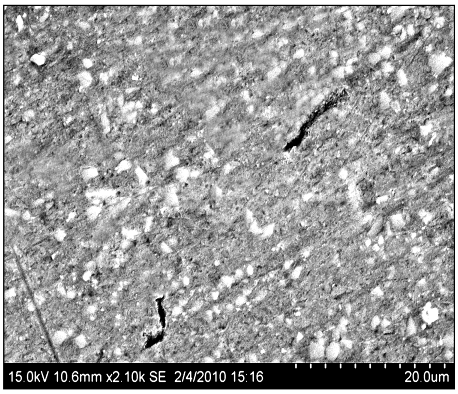

Figure 8. Rough ground surface of LM25Al/SiC/4p with higher magnification of 2100X (Vs 23.57 m/s, Vw 6.11 m/min, f 0.17 m/min, d 30 µm).

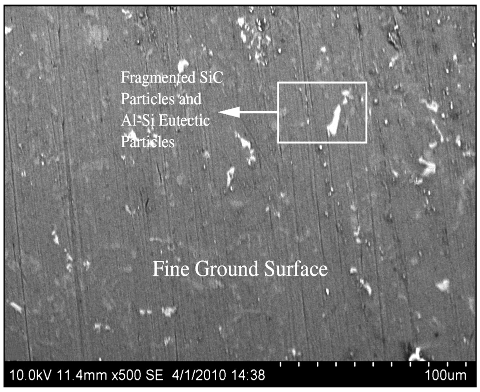

Figure 9. Fine ground surface of LM25Al/SiC/4p (Vs 43.98 m/s, Vw 26.72 m/min, f 0.06 m/min, d 10 µm).

Figure 9 shows the SEM micrograph of fine ground surface. The fine grinding marks shown on the SiC particles in this figure ensured that both the SiC particles and aluminium matrix are removed by cylindrical grinding at high wheel and work piece velocities and low feed and depth of cut. During the cylindrical grinding, the aluminium matrix has undergone plastic deformation and the SiC particles were covered by the aluminium matrix. This image is taken at 500X and the size of the Al-Si eutectic particles can be compared with Fig. 5, which shows the morphology of the Al-Si eutectic particles in 'as-cast' condition before grinding. This figure reveals that owing to better grinding parameters, the size of the Al-Si eutectic particles (40 µm - 50 µm) was reduced to a finer size (10 µm) by disintegration. There are no cracks and defects found on the fine ground surfaces when observed with the SEM. Hence, there is a high potential of using Al_2O_3 wheels for the cylindrical grinding of Al/SiC composites.

ANOVA and Modeling of Responses

The experimental results are used to calculate the analysis of variance (ANOVA) which explains the significant grinding variables affecting the responses such as tangential grinding force (F_t), roughness (R_a) and grinding temperature (G_t). The ANOVA results for the responses are shown in Tables 3 to 5.

Tangential grinding force (F_t) model

Accurate measurement of the grinding force has great research value and practical significance on studies in the field of grinding. The measurement of grinding force is highly essential to analyze more effectively the grindability factors of Al/SiC composites. The results of ANOVA for tangential grinding force are shown in Table 3. It indicates that all the four grinding variables are significant at 95% confidence interval and the interactions between them are not significant at the same confidence interval. The non-linear fit between response and significant variables is expressed as:

$$F_t = 464.054 \ (V_s)^{-0.448} \ (V_w)^{-0.021} \ (f)^{0.178} \ (d)^{0.323} \tag{8}$$

Table 3. ANOVA for Tangential grinding force (F_t).

Source	d.o.f	Sum of squares	Mean squares	F_{cal}	$F_{0.05}$	Remarks
V_s	2	732.321	366.160	227.49	3.63	Significant at 95% CI
V_w	2	41.210	20.605	12.80		
f	2	376.025	188.012	116.81		
d	2	1075.877	537.938	334.21		
V_sV_w	4	16.472	4.218	2.62	3.01	Insignificant at 95% CI
V_sf	4	17.904	4.476	2.78		
V_sd	4	16.036	4.009	2.49		
V_wf	4	17.068	4.267	2.65		
V_wd	4	18.224	4.556	2.83		
fd	4	13.780	3.445	2.14		
V_sV_wf	8	21.802	2.725	1.69	2.59	Insignificant at 95% CI
V_sV_wd	8	6.321	0.790	0.49		
V_sfd	8	12.025	1.503	0.93		
V_wfd	8	19.802	2.475	1.54		
ERROR	16	25.753	1.610			
TOTAL	80	2410.62				

The multiple correlation R^2 is 0.989. It could be seen from the model that the tangential grinding force decreases with increase in wheel velocity and work piece velocity, but increases with increase in feed and depth of cut.

Roughness (R_a) model

The dimensional accuracy and surface finish of any manufacturing process have become critical because of increased quality demands. There are various factors that govern surface finish in grinding and, hence, the development of analytical model between roughness and significant grinding variables provides a reliable prediction of grinding performance. The ANOVA results for roughness are shown in Table 4. It indicates that the interactions between the grinding variables are not significant at 95% confidence interval when compared to individual variables which are significant at 95% confidence interval. Hence, while developing the model for roughness, only the individual variables V_s, V_w, f, d are considered and that is given by:

$$R_a = 424.113 \ (V_s)^{-0.855} \ (V_w)^{-0.339} \ (f)^{0.342} \ (d)^{0.402} \tag{9}$$

Table 4. ANOVA for Roughness (R_a).

Source	d.o.f	Sum of squares	Mean squares	F_{cal}	$F_{0.05}$	Remarks
V_s	2	0.679609	0.339805	476.38	3.63	Significant at 95% CI
V_w	2	0.587223	0.293612	411.62		
f	2	0.396096	0.198048	277.65		
d	2	0.449710	0.224855	315.23		
V_sV_w	4	0.006956	0.001739	2.44	3.01	Insignificant at 95% CI
V_sf	4	0.005276	0.001319	1.85		
V_sd	4	0.003724	0.000931	1.31		
V_wf	4	0.005932	0.001483	2.08		
V_wd	4	0.004676	0.001169	1.64		
fd	4	0.005476	0.001369	1.92		
V_sV_wf	8	0.012605	0.001576	2.21	2.59	Insignificant at 95% CI
V_sV_wd	8	0.006186	0.000773	1.08		
V_sfd	8	0.004863	0.000608	0.85		
V_wfd	8	0.007435	0.000929	1.30		
ERROR	16	0.011413	0.000713			
TOTAL	80	2.187180				

The multiple correlation R^2 is 0.995. It could be seen from the model that the roughness decreases with increase in wheel velocity and work piece velocity, but increases with increase in feed and depth of cut.

Grinding temperature (G_t) model

Grinding temperature is one of the most important factors affecting the quality of a ground surface. The properties of a ground surface depend on the grinding temperature, and knowledge of its magnitude is important to establish the grinding conditions. Hence, the development of analytical model between the grinding temperature and the significant variables provides a reliable prediction of grinding performance. The results of ANOVA for grinding temperature are shown in Table 5. It indicates that all the four grinding variables are significant at 95% confidence interval and the interactions being insignificant at the same confidence interval. The non-linear fit between response and significant variables is expressed as:

$$G_t = 411.579 \ (V_s)^{0.069} \ (V_w)^{0.037} \ (f)^{0.016} \ (d)^{0.022} \tag{10}$$

Table 5. ANOVA for grinding temperature (G_t).

Source	d.o.f	Sum of squares	Mean squares	F_{cal}	$F_{0.05}$	Remarks
V_s	2	18651.28	9325.64	112.90	3.63	Significant at 95% CI
V_w	2	16196.47	8098.23	98.04		
f	2	389.06	194.53	9.16		
d	2	1525.21	762.60	9.23		
V_sV_w	4	362.57	90.64	1.10	3.01	Insignificant at 95% CI
V_sf	4	474.86	118.72	1.44		
V_sd	4	446.04	11.51	1.35		
V_wf	4	350.24	87.56	1.06		
V_wd	4	523.31	130.83	1.58		
fd	4	422.72	105.68	1.28		
V_sV_wf	8	898.72	112.34	1.36	2.59	Insignificant at 95% CI
V_sV_wd	8	688.54	86.07	1.04		
V_sfd	8	460.25	57.53	0.70		
V_wfd	8	1337.88	167.23	2.02		
ERROR	16	1321.60	82.60			
TOTAL	80	44048.85				

The multiple correlation R^2 is 0.973. It could be observed from the above model that G_t increases with increase in wheel velocity, work piece velocity, feed and depth of cut. Hence these analytical models could be employed to maximize the material removal rate by selecting proper grinding parameters. The mathematical model equations developed for all the responses (F_t, R_a, G_t) are valid only for the experimental conditions used in this study.

Optimization of Al/SiC cylindrical grinding using genetic algorithms (GA)

Optimization analysis of machining parameters is usually based on maximizing production rate or finest possible surface quality by using the empirical relationship between the responses and the process parameters. Hence in cylindrical grinding, an effort has been made to estimate the tangential grinding force, roughness and grinding temperature using experimental data. It has also been attempted to optimize the grinding process using GA in order to achieve good surface finish.

A simple GA code is used in the present study. The steps involved in the optimization of Al/SiC composite grinding process using GA can be stated as follows:

Step 1: The GA parameters are initialized. This involves specifying the maximum number of generations, the string length of each variable, the mutation probability, etc. The upper and lower limits of each of the process variables are specified. The maximum allowable roughness is also defined.

Step 2: An initial feasible random population is generated.

Step 3: The fitness of each individual in the population is evaluated.

Step 4: Once the fitness of all the individuals is available, GA operations are performed. A new set of process variables is then created which is possibly better than that of the previous generation.

Step 5: The generation number is incremented. If the current generation number is greater than the maximum number of generations allowed, then the process is terminated. Otherwise, the process is repeated from step 3.

The problem of optimization of Al/SiC composites grinding process can be described as maximizing the MRR subjected to the criteria of a set of constraints on roughness and input variables.

In order to optimize the present problem using GA:

(a) Following parameters are specified by practice, to get optimal solutions with less computational effort:
- Maximum number of generations = 800
- Total string length = 60
- Mutation probability = 0.1
- Cross over probability = 0.65

(b) Constrained optimization problem is stated as follows:
- Maximize MRR subjected to

$$R_a \le (R_a)_{max} \text{ and}$$
$$x_i^l \le x_i \le x_i^u$$
$$MRR = fd$$
$$R_a = 424.113\,(V_s)^{-0.855}\,(V_w)^{-0.339}\,(f)^{0.342}\,(d)^{0.402}$$
$$23.57 \text{ m/s} \le V_s \le 43.98 \text{ m/s}$$
$$6.11 \text{ m/min} \le V_w \le 26.72 \text{ m/min}$$
$$0.06 \text{ m/min} \le f \le 0.17 \text{ m/min}$$
$$10\ \mu\text{m} \le d \le 30\ \mu\text{m}$$

where $(R_a)_{max}$ is the maximum allowable value of roughness and x_i^l and x_i^u are the lower and upper bounds on grinding variables x_i.

The GA program has been written in the MATLAB environment. The maximizing function is written facilitating the user to set the constraints. The optimization is carried out for different values of constraints on roughness (0.15-0.45 µm). The optimal inputs and the corresponding output values obtained by the GA are presented in Table 6.

Table 6. Optimization results of GA at various values of R_a.

Constraints	Output of GA				Values of constraints using output of GA	
(R_a) max µm	V_s m/s	V_w m/min	f m/min	d µm	(R_a) µm	MRR (mm^3/mm/min)
0.150	43.9833	26.7181	0.0552	9.1082	0.1492	0.5028
0.180	43.9692	24.5862	0.0693	10.9024	0.1784	0.7555
0.210	43.9508	23.0861	0.0814	12.5067	0.2036	1.0180
0.240	43.9358	21.5667	0.0962	13.9629	0.2306	1.3432
0.270	43.9328	20.9728	0.1273	14.8862	0.2629	1.8950
0.300	43.9096	19.4472	0.1385	16.8710	0.2921	2.3366
0.330	43.8975	17.6571	0.1458	20.0232	0.3291	2.9194
0.360	43.8829	16.9752	0.1572	22.5663	0.3592	3.5474
0.390	43.8600	15.9967	0.1611	25.0124	0.3854	4.0295
0.420	43.8409	14.8763	0.1670	27.7625	0.4172	4.6363
0.450	43.8075	13.0124	0.1692	29.3577	0.4488	4.9673

It is observed from the optimization results of GA that it will be more advantageous to grind Al/SiC composites at wheel velocity 43.9833 m/s, work piece velocity 26.7181 m/min with a feed of 0.0552 m/min and depth of cut of 9.1082 µm. It is also found from the table that higher wheel and work piece velocities are required for all the values of roughness constraints to obtain good surface finish. The results of optimization show that the material removal rate increases by 10 times, by increasing the roughness constraint from 0.15 to 0.45 µm. Hence, it is concluded from the above results that the MRR is influenced more by the roughness constraint and this methodology would be useful for identifying the optimum grinding parameters in order to achieve the required MRR with a constraint on roughness.

Consolidation of the results explained and the phenomenology in detail

- Better surface finish and damage free surfaces are obtained due to low grinding force at high wheel and work piece velocities. The tangential grinding force (F_t) decreases with an increase in wheel velocity and work piece velocity. As the grinding wheel velocity increases, the heat generated in the deformation zone increases and softens the aluminium matrix, thereby the force required to remove the material is reduced.
- The roughness (R_a) values decrease with an increase in wheel velocity and work piece velocity. This is mainly due to the increase in relative velocity between the wheel and the work piece and the reduction in contact time reduces the chip thickness.
- The tangential grinding force and roughness increase with an increase in feed and depth of cut. When the feed and depth of cut are increased, the increase in material removal rate and the increase in chip thickness account for the increase of the F_t and R_a values
- The grinding temperature (G_t) increases with an increase in wheel velocity (V_s), work piece velocity (V_w), feed (f) and depth of cut (d). The G_t values are scattered in the range of 740°C-856°C at the lower and higher levels of grinding variables. The temperature measured is the spark temperature and it is a good representative of the grinding zone temperature and useful for process-monitoring purposes. It is to be noted that as the chips leave the grinding zone at high temperature, they are subjected to an exothermic reaction with oxygen, due to which their temperature rises. Subsequently, the atmospheric

cooling effect predominates, leading to a drop in the temperature of the chips.

- The results of ANOVA for tangential grinding force (F_t), roughness (R_a) and grinding temperature (G_t) indicate that all the four grinding variables are significant at 95% confidence interval and the interactions between them are not significant at the same confidence interval. The analytical models of responses agree with the general trends of grinding force, roughness and grinding temperature.
- It is observed from the optimization results of GA that it will be more advantageous to grind Al/SiC composites at wheel velocity 43.9833 m/s, work piece velocity 26.7181 m/min with a feed of 0.0552 m/min and depth of cut of 9.1082 µm. It is found from the results of optimization that the material removal rate increases by 10 times, by increasing the roughness constraint from 0.15 to 0.45 µm and this ensures that the MRR is more influenced by the roughness constraint. This methodology would be useful for identifying the optimum grinding parameters in order to achieve the required MRR with a constraint on roughness.

Conclusions

The experimental investigations of this study indicate that the grinding parameters such as wheel velocity, work piece velocity, feed and depth of cut are the primary influencing factors during the cylindrical grinding of Al/SiC composites. The experimental results are used to calculate the analysis of variance (ANOVA) which explains the significant grinding parameters affecting the responses such as tangential grinding force, roughness and grinding temperature. The results of ANOVA for responses indicate that all the four grinding variables are significant at 95% confidence interval and the interactions between them are not significant at the same confidence interval.

In this work, optimal grinding parameters are obtained using GA, for maximization of material removal, computed by the models developed, with a set of constraints on roughness. The results of optimization show that the material removal rate increases by 10 times by increasing the roughness constraint from 0.15 to 0.45 µm and thus ensuring that the MRR is more influenced by the roughness constraint. The results obtained would serve to understand the process better and widen the applications of low fracture toughness composite materials. This methodology establishes the optimization of Al/SiC composites grinding and hence facilitates the effective use of Al/SiC composites in industrial applications.

References

Anand Ronald, B., Vijayaraghavan, L., Krishnamoothy, R., 2009, “Studies on the influence of grinding wheel bond material on the grindability of metal matrix composites”, *Journal of Materials and design*, Vol. 30, pp. 679-686.

Anne Venu Gopal., Venkateswara Rao, P., 2003, “Selection of optimum conditions for maximum material removal rate with surface finish and damage as constraints in SiC grinding”, *International Journal of Machine Tools & Manufacture*, Vol. 43, pp. 1327-1336.

Deivanathan, R., Vijayaraghavan, L., Krishnamurthy, R., 1999, “In-process monitoring of grinding burn in the cylindrical grinding of steel”, *Journal of Materials Processing Technology*, Vol. 91, pp. 37-42.

Kwak, J.S., Kim, Y.S., 2008, “Mechanical properties and grinding performance on aluminium-based metal matrix composites”, *Journal of Materials Processing Technology*, Vol. 201, pp. 596-600.

Lindsay, R.P., 1989, “Principles of Grinding”, In: Davis, J.R. (Editor), “ASM Metals Hand book: Machining”, Ohio, USA, Vol. 16, pp. 421-429.

Miracle, D.B., 2005, “Metal matrix composites – From science to technological significance”, *Composites Science and Technology*, Vol. 65, pp. 2526-2540.

Mohanasundararaju, N., Sivasubramanian, R., 2007, “Combined artificial neural network and Taguchi technique for selection of optimal process parameters in steel roll grinding”, *Manufacturing Technology Today*, pp. 11-17.

Nee, A.Y.C., Tay, A.O., 1981, “On the measurement of surface grinding temperature”, *International Journal of Machine Tools & Manufacture*, Vol. 21, pp. 279-291.

Obikawa, T., Shinozuka, J., 2005, “Analysis of grinding temperature considering surface generation mechanism”, *Key Engineering Materials*, Vols. 291-292, pp. 97-102.

Shaji, S., Radhakrishnan, V., 2003, “Analysis of process parameters in surface grinding with graphite as lubricant based on the Taguchi method”, *Journal of Materials Processing Technology*, Vol. 141, pp. 51-59.

Sun, F.H., Li, X.K., Wang, Y., Chen, M., 2006, “Studies on the Grinding Characteristics of SiC Particle Reinforced Aluminium-based MMCs”, *Key Engineering Materials*, Vols. 304-305, pp. 261-264.

Zhaowei Zhong., Nguyen Phu Hung., 2002, “Grinding of alumina/aluminum composites”, *Journal of Materials Processing Technology*, Vol. 123, pp. 13-17.