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Study on Specific Energy in Grinding of DRACs: A Response Surface Methodology Approach

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Abstract**—**In this study, the effects of machining parameters on specific energy during surface grinding of 6061Al-SiC35$_P$ composites are investigated. Vol% of SiC, feed and depth of cut were chosen as process variables. The power needed for the calculation of the specific energy is measured from the two watt meter method. Experiments are conducted using standard RSM design called Central composite design (CCD). A second order response surface model was developed for specific energy. The results identify the significant influence factors to minimize the specific energy. The confirmation results demonstrate the practicability and effectiveness of the proposed approach.

Keywords**—**ANOVA, Metal matrix composites, Response surface methodology, Specific energy, Two watt meter method.

I. INTRODUCTION

DISCONTINUOUSLY reinforced aluminium composites (DRACs) is one of the important composites among the metal matrix composites, which have SiC particles with aluminium matrix is harder than tungsten carbide , which pose many problems in machining[1]-[2]. The aluminium alloy reinforced with discontinuous ceramic reinforcements is rapidly replacing conventional materials in various automotive, aerospace and automobile industries. However grinding of DRAC's is one of the major problems, which resist its wide spread engineering application [3].

A fundamental parameter derived from the force measurements is the specific energy, which is the energy required per unit volume of material removal. Specific energy in grinding is much higher than any other machining process. While DRACs specimen slides over a hard cutting tool edge during grinding, due to friction, high temperature and pressure the particles of DRACs adhere to the grinding wheel which affects the surface quality of the specimen [4]. This also results in decreased uncut chip thickness, decreased metal removal rate and hence the increased specific energy. Increase in specific energy will further increase the temperature at the wheel-work interface thus deteriorating the surface integrity. Any proposed mechanisms of abrasive workpiece interactions must be consistent with the magnitude of the specific energy and its dependence on the operating parameters [5].

Choudhury et al. [6] noted that the cutting force is highly affected by feed rate and slightly by cutting speed. This shows that the feed rate is a dominant parameter and it plays a very important role on the cutting force and hence the specific energy. Any plausible physical model of the grinding process should be able to quantitatively account for the magnitude of the specific energy and its dependence on the operating parameters [7].

Sanjay Agarwal et al. [8] conducted a study on surface and subsurface of the ground ceramic material and concluded that cutting force and specific energy (u) can considerably be reduced due to dislodgement of individual grains, resulting from microcracks along the grain boundaries. Brinksmeier et al. [9] made an attempt to quantify the size effect and possibility of using this in grinding for controlled subsurface work hardening of metals. Their investigation revealed that, main physical quantity characterizing the size effect is specific energy which increases with decreasing chip thickness. Ren et al. [10] demonstrated the correlation of specific energy (u) with the grinding process parameters and the material property parameters for the tungsten carbides. Their study revealed that specific energy (u) is related not only to grinding process parameters, but also to the physical–mechanical properties of the workpiece material. Seeman et al. [11] developed a second order response surface model for surface roughness and tool wear of Al/SiC composites. They concluded that formation of built-up edge will affect the tool wear and surface roughness Agarwal et al [12] proposed desirability function approach to optimize the CNC turning process. The authors have used cutting speed, feed, depth of cut and nose radius as the factors for study. Kwak and Kim [13] developed a second order response surface model for surface roughness and grinding force on grinding of Al/SiC/Mg composites and observed that optimum content of SiC and Mg in AC8A aluminium alloy is 30 vol% and 9 vol% respectively. Kwak [14] presented the application of Taguchi and RSM for the geometric error. A second-order response model for the geometric error was developed and the utilization of the response surface model was evaluated with constraints of the surface roughness and the MRR. Krajnik et al. [15] developed a RSM model for minimisation of surface roughness for centerless grinding of 9SMn28 material. Jones et al. [16] used RSM and Taguchi

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design to optimize the semiconductor manufacturing process. Zhang et al. [17] conducted a study on solder joint reliability to optimise the fatigue life of the joint. From the above discussions it is noted that a limited study is conducted on the specific energy calculations and its optimization. Hence in this current study an attempt is made to calculate the specific energy by two-watt meter method. Further the calculated specific energy is analysed by RSM.

A. Design of Experiments

In an experiment, deliberate changes to one or more process variables (or factors) are made in order to observe the effect that those changes will have on one or more response variables. Design of experiments (DOE) is an efficient procedure for planning experiments so that the data obtained can be analyzed to yield valid and objective conclusions. In this study the influence of three principal factors such as volume percentage of SiC (X_1), feed (X_2) and depth of cut (X_3) on specific energy were investigated.

The Response Surface Methodology (RSM) is an empirical modeling approach for determining the relationship between various parameters and responses with the various desired criteria and searching the significance of these process variables on the coupled responses. It is a sequential experimentation strategy for building and optimizing the empirical model [2]. Therefore, RSM is a collection of mathematical and statistical procedures that are useful for the modelling and analysis of problems in which response of demand is affected by several variables and the objective is to optimize this response. Through using the design of experiments and applying regression analysis, the modelling of the desired response to several independent input variables can be gained.

In RSM, the quantitative form of relationship between the desired response and independent input variables is represented as $y = F(X_1, X_2, X_3)$**,** where y is the desired response and F is the response function (or response surface). In the procedure of analysis, the approximation of y was proposed using the fitted second-order polynomial (quadratic) regression model. The quadratic model $\hat{y}$ can be written as [12]

$$\hat{y} = a_0 + \sum_{i=1}^{n} a_i X_i + \sum_{i=1}^{n} a_{ii} X_i^2 + \sum_{i<j} a_{ij} X_i X_j \quad (1)$$

where a_o is constant, a_i, a_{ii}, and a_{ij} represent the coefficients of linear, quadratic, and interaction terms, respectively. X_i reveals the coded variables that correspond to the studied factors.

The necessary data for building the response models are generally collected by the experimental design such as Central Composite Design (CCD). The factorial portion of CCD is a full factorial design with all combinations of the factors at two levels (high, +1 and low, −1) and composed of the six axial points and six central points (coded level 0) which is the midpoint between the high and low levels[18]. The star points are at the face of the cubic portion on the design which corresponds to a value of axial distance α as unity. This type of design is commonly called the face-centered CCD.

II. Experimental Procedure

Al/SiC specimens having aluminum alloy 6061 as the matrix and containing 8 vol.%,10 vol.% and 12 vol.% of silicon carbide particles of mean diameter 35µm in the form of cylindrical bars of length 120mm and diameter 20mm. The specimens were manufactured at Vikram Sarbhai Space Centre (VSSC) Trivandrum by Stir casting process with pouring temperature 700-710°C, stirring rate 195rpm. The specimen were extruded at 457°C, with extrusion ratio 30:1, and direct extrusion speed 6.1m/min to produce length 120mm and Ø22mm cylindrical bars. The extruded specimens were solution treated for 2 hr at a temperature of 540°C in a muffle furnace; Temperatures were accurate to within ±2°C and quench delays in all cases were within 20s. After solution treatment, the samples were water quenched to room temperature. Further the specimen is machined to 17mm square cross-section.

TABLE I
Levels of Independent Factors

Factors	Levels		
	Low	Medium	High
Vol% Percentage SiC (X_1)	8	10	12
Feed (mm/s) (X_2)	60	70	80
Depth of Cut (µm) (X_3)	8	12	16

Experiments were conducted on 1.5 HP, 2880rpm, conventional surface grinding machine (Bhuraji make) with automatic (hydraulic) table-feed and Norton make diamond abrasive grinding wheel ASD76R100B2 with outer diameter 175mm, width 12.5mm, thickness 5mm and inner diameter 31.75 mm. The honing stick having specification GN0390220K7V7 is used for dressing the wheel. The experiments conducted under dry conditions. The levels and factors selected for the experimentation are given in Table I. Selection of factors for experimentation was based on preliminary experiments [2], prior knowledge of the literature, and known instrumental limitations. The spindle power necessary for the calculation of specific energy is measured by two-watt meter method. The sum of the power measured in both the watt meter gives the spindle power. The experimental set-up is shown in Fig 1. The volume of metal removal is calculated during grinding. Time required for machining the each specimen is measured. The volume of metal removed per unit time gives the metal removal rate.

Hence the specific energy is calculated as

$$u = \frac{P}{Q_w} \quad \text{J/mm}^3 \quad (2)$$

where P is the spindle power in Watts and Q_w is the metal removal rate in mm^3/s

Fig. 1 Experimental setup

III. Results and Discussion

Planned set of experiment based on central composite design (CCD) were conducted on Al-SiC$_{35P}$ composites with eight star point, six axial points and six central points. Vol% of SiC, feed and depth of cut are used as factors to investigate its effect on specific energy. Table II gives the experimental results.

TABLE II
EXPERIMENTAL RESULTS

Sr. No	Levels of Input variables: SiC Vol %	Feed (mm/s)	DOC (µm)	Watt meter reading (Watts)	MRR (mm^3/s)	Specific energy (J/mm^3)
1	8	60	8	900	6.054	148.772
2	12	60	8	840	6.644	126.42
3	8	80	8	720	7.324	98.307
4	12	80	8	700	9.293	75. 36
5	8	60	16	1200	8.962	134.849
6	12	60	16	1160	9.553	121.956
7	8	80	16	1180	11.91	70.485
8	12	80	16	840	14.10	66.933
9	8	70	12	720	7.894	91.209
10	12	70	12	660	8.558	77.136
11	10	60	12	920	7.927	116.272
12	10	80	12	860	12.31	69.862
13	10	70	8	780	6.799	114.723
14	10	70	16	840	9.877	85.046
15	10	70	12	780	8.379	93.090
16	10	70	12	860	8.994	95.619
17	10	70	12	700	8.379	83.542
18	10	70	12	740	8.364	88.474
19	10	70	12	840	8.994	93.396
20	10	70	12	860	8.979	95.779

A. Development of Mathematical Model

The mathematical relationship between specific energy and grinding variables were established using experimental test results from planned set of experiments; face-centered CCD. Table III shows the estimated regression coefficient for the specific energy.

TABLE III
REGRESSION COEFFICIENT FOR SPECIFIC ENERGY

Term	Coef	P-value
Constant	691.319	0.000
SiC	3.3397	0.003
Feed (mm/s)	-10.4195	0.000
DOC (microns)	-21.3668	0.001
SiC*SiC	-0.81835	0.106
Feed *Feed	0.05621	0.081
DOC *DOC	0.77742	0.004
SiC*Feed	0.05463	0.889
SiC*DOC	0.45084	0.159
Feed *DOC	-0.05582	0.549

It is observed from the regression analysis of that, linear terms and square of depth of cut are more significant as their P-value is less than 0.05. Equation (3) represents the regression model for specific energy.

$$\hat{y} = 691.319 + 3.339X_1 - 10.4195X_2 - 21.3668X_3 - 0.818X_1^2 + 0.0562X_2^2 + 0.777X_3^2 + 0.0546X_1X_2 + 0.4508X_1X_3 - 0.0558X_2X_3 \quad (3)$$

where X_1, X_2 and X_3 are the decoded values of SiC volume percentage, feed and depth of cut respectively. The developed model has R^2 value also called as coefficient of regression value as 96.83 % and R^2 *(Adj)* an approximately unbiased estimate of the R^2 is 93.91%. Higher the R^2 value, better the fitness of the model. Further closeness of the values of R^2 and R^2 *(Adj)* indicates the better fitness [11].

B. Analysis of the Developed Model

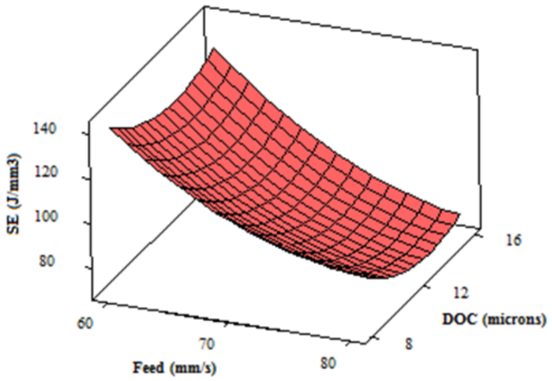
The Analysis of Variance (ANOVA) and F- ratio test have been performed to justify the goodness of fit of the developed mathematical model. The calculated values of F- ratios for lack-of-fit have been compared to standard values of F- ratios corresponding to their degrees of freedom to find the adequacy of the developed mathematical models.

TABLE IV
ANOVA FOR REGRESSION

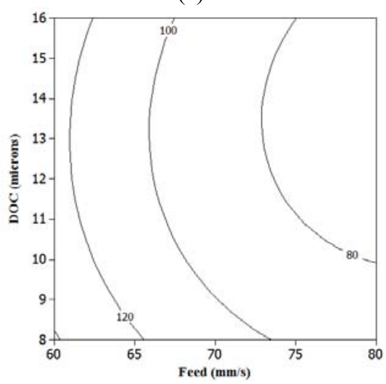
Source	DOF	Seq Sum of Square	Adj Mean Square	F-Ratio	P-value
Regression	9	9635.3	1070.59	33.57	0.000
Linear	3	8431.8	2810.6	88.14	0.000
Square	3	1050	349.99	10.98	0.002
Interaction	3	153.5	51.17	1.6	0.25
Residual Error	10	318.9	31.89		
Lack-of-Fit	5	205.1	41.03	1.8	0.267
Pure Error	5	113.8	22.75		
Total	19	9954.2			

Table IV shows the ANOVA for specific energy. The standard percentage point of F distribution for 95% confidence level ($F_{0.05,5,5}$) is 5.05. Since the F-value for lack of fit is less than the standard value, it is evident that the developed model is adequate at 95% confidence level.

From equation (3) surface plot and contour plot for specific energy at different feed and depth of cut are plotted (Fig 2). These response plots can help in predicting the specific energy at any zone of the experimental domain. It is clear from these plots that the specific energy decreases with increase in feed. It may be due to the reason that the energy consumed in the grinding process is spent on deforming and cutting new surfaces in the workpiece material. The new surface area produced is therefore a measure of the energy required. Increasing feed at constant depth of cut, surface area decrease exponentially with increase in feed thus decreasing the specific energy. It can also be observed that increase in depth of cut will decrease the specific energy initially and increases further with increase in depth of cut.



(a)



(b)

Fig 2 (a) surface plot and (b) Contour plot for Specific Energy

C. Confirmation Experiments

In confirmation of the second-order response surface model (3) with the experimental results, verification tests were conducted. Table V shows the test results. One test was performed for the test conditions given in trial number 11 of Table II (Test 1), and other two experiments at the selected condition (tests 2and test 3) that were not carried out in Table II. In test 2, Al-6061-8%vol SiC , feed 60mm/s and depth of cut 12µm were used and test 3 is conducted with Al-6061-12%vol SiC , feed 60mm/s and depth of cut 12µm. It can be observed from confirmation tests that the results obtained from the developed model and those from the experimental results are fairly close. Deviation of the experimental results and the test results are within 9%.

TABLE V
CONFIRMATION EXPERIMENTS

Test No.	Process variables: SiC vol %	Feed (mm/s)	DOC (µm)	Validation	Response (Specific energy, J/mm^3)
1	10	60	12	Experimental	116.272
				RSM	107.24
2	8	80	12	Experimental	77.173
				RSM	74.172
3	12	80	14	Experimental	60.83
				RSM	58.612

IV. CONCLUSION

In this study power measured from two wattmeter method is used for the calculation of specific energy. The Response surface methodology was applied for analyzing the specific energy during surface grinding of DRACs. Following conclusions were drawn from the study

1) Specific energy is mainly affected by depth of cut and feed during grinding of DRACs.

2) Initially, increase in depth of cut will decrease the specific energy up to the critical limit. Further increase in depth of cut will result in increased specific energy. This may happen because of chip accommodation problem with large volume of chip produced at higher depth of cut which results in increased cutting force and decrease in metal removal rate.

3) It is observed that, specific energy decrease with increase in feed. It may be due to the reason that, surface area decrease exponentially with increase in feed thus decreasing the specific energy. Further, increase in feed increase the metal removal rate and thus decrease in specific energy.

4) Response surface methodology is used to develop a second order model for specific energy in terms of the process variables namely SiC vol%, feed and depth of cut. It is observed that fitted value is very close to the experimental value. ($R^2 > 0.95$).

5) Confirmation tests were performed to validate the second order response surface model for specific energy. The predicted results are in conformance to the experimental test results. A maximum of 9% deviation is observed between the experimental and predicted results.

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