*Proceedings of 10th International Conference on Precision, Meso, Micro and Nano Engineering (COPEN 10)*
*December 07 – 09, 2017, Indian Institute of Technology Madras, Chennai – 600 036 INDIA*

# Grindability study of Ceramic Matrix Composite material using metal bonded diamond grinding wheel

**[1,2]S.K. Bhatnagar, [1]Rajesh Madarkar, 1Sudarsan Ghosh, [1]P.Venkateswara Rao**
[1]Department of Mechanical Engineering, Indian Institute of Technology Delhi, New Delhi, India
[2]Department of Mechanical Engineering, Manav Rachna International University, Faridabad, India

## Abstract

Ceramic matrix composite (CMC) material, with its extra ordinary properties, is the latest material used in advanced technology components. Grinding is usually the last and the most cost intensive operation on such material for providing the required finish and tolerances. Grinding of CMC material is done with super-abrasive like diamond and it poses some challenges. In this paper, grindability study of Alumina matrix material with reinforcement of Silicon Carbide whiskers while grinding with metal bonded diamond grinding wheel in dry condition has been performed. Effects of input parameters – cutting speed, table feed and depth of cut on surface roughness and cutting forces have been studied. These response parameters can be improved by suitably varying the input parameters.

Keywords: Ceramic matrix composite, grindability, super-abrasive

## 1. INTRODUCTION

Ceramic materials have the properties of good wear and corrosion resistance. They have high hardness and the capability to retain hardness at elevated temperatures. However the brittle nature of the material results in low toughness. In Ceramic Matrix Composite (CMC) material, reinforcement of materials like Carbon and Silicon Carbide improve the toughness. Depending upon the reinforcement material, the CMC can become electrically and thermally conducting. Grinding of these CMC materials however poses some challenges. The process input parameters in surface grinding of the material are grinding speed, table feed and depth of cut. Abrasive grit size and grit density can also be varied to improve grindability aspects. In this study, metal bonded diamond abrasive wheel of 91 micron average grit size has been used and effects of the above mentioned three parameters were studied on two vital response parameters which are tangential cutting force and surface roughness. Response Surface Methodology (RSM) was adopted to establish the relationships between the input parameters and responses. Analysis of variance was carried out using Design Expert software to study and evaluate the experimental variations.

With the help of MINITAB software, surface plots have been drawn showing variation of response against variation in two input parameters while holding the third one constant. Trends of variations of tangential cutting force and surface roughness with grinding speed, table feed and depth of cut have been analyzed based on the surface plots. The interaction between different parameters has also been investigated and their influences on the responses noted.

Grindability can be considered as the ease and the overall efficiency during grinding of a material. Low cutting forces, less surface roughness values, high material removal rate and low specific grinding energy are indicators of good grindability. By exploring the effects of the input parameters on response parameters in this study, grindability aspect of the CMC material has been analyzed.

## 2. LITERATURE REVIEW

Shih and Opoku [1] discussed fracture strength of ceramic material and its dependence on temperature, loading rate, composition, size and type of specimen, surface finish and material density. Since ceramics are brittle, no local yielding at high stress concentration points is possible. Hence fracture mechanics is applied to this failure.

Inasaki and Yokohama [2] outlined characteristic features of hard and brittle materials and discussed fundamental principles for grinding these materials to attain high efficiency during grinding. Chip formation, surface roughness, effect of material properties/grinding conditions were discussed. Ground surface has been found to improve by lowering depth of cut, increasing grinding speed and decreasing workpiece speed.

Kitajima et al. [3] evaluated grindability of ceramic materials through the measurement of grinding forces, energy, temperature, wheel wear and Scanning Electron Microscopic (SEM) examinations of ground surface and grinding swarfs.

Agarwal and Rao [4] showed that in SiC grinding, material removal was primarily due to the dislodgement of individual grains resulting from microcracks along grain boundaries. Ground surface may contain deformed layer, surface/subsurface microcracks, phase transformation, residual stresses and other types of damages.

Agarwal and Rao [5] showed that material removal in SiC grinding was primarily due to the microfracture and grain dislodgement or lateral cracking along grain boundaries. The parameters set were grinding speed, feed rate and depth of cut.

Greubelle and Maiti [6] discussed about a finite element scheme which can capture the complex dynamic initiation and propagation of inter-granular cracks, near surface plasticity and subsequent fragmentation of the ceramic material during scratch test. Material removal by three mechanisms were discussed – (1) microfracture and chipping of individual grains, (2) removal of large chunks of material by propagation of cracks parallel to the surface (lateral cracks) and (3) intragranular microfracture and grain dislodgement.

Ngoi and Sreejith [7] showed that under certain controlled conditions, it is possible to machine brittle materials such as ceramics using single or multipoint diamond tools so that material is removed by plastic flow, leaving a crack-free surface. This process is called ductile regime machining. If the scale of deformation is very small, the material deforms plastically and results in ductile regime grinding.

Kopac and Krajnik [8] showed that for grinding of unconventional materials like advanced ceramics, use of super-abrasives (diamond or CBN – Cubic Boron Nitride) and high

ISBN: 978-93-80689-28-9

speed grinding (HSG) result in reduction in grinding forces, grinding wheel wear and workpiece surface roughness.

Zhang and Howes [9] discussed material removal mechanisms in grinding of ceramics. This may be brittle fracture or plastic deformation depending on strength, hardness and fracture toughness of the material or it may be in powder regime for very small depth of cut or for a single point diamond. For ceramic material, powder regime rather than ductile regime is observed. When the depth of cut is below a critical value, material pulverization occurs.

Komanduri [10] studied micro-mechanisms of material removal and surface generation process in finishing of advanced ceramics and glasses. Also, differences in mechanisms of material removal for metals and for advanced ceramics (conventional and modern methods like mechano – chemical polishing) were discussed.

Li and Liao [11] summarized the information in published works on grinding induced microcracks, residual stresses and degradation of flexure strength of ceramics. Quantitative relationships between grinding parameters, machining damage and fracture strength were also discussed with the objective of optimizing ceramic grinding processes. .

Venugopal and Rao [12] studied the effect of grit size, grit density, depth of cut and work feed on surface finish and damage produced during grinding of SiC. GA (genetic Algorithm) was developed to optimize the grinding conditions for maximum material removal imposing surface roughness and surface damage as the constraints. Results showed that the material removal and the cost of grinding were influenced more by the constraint on surface roughness than by surface damage.

Kwak and Kim [13] evaluated the effects of grinding parameters on the surface roughness and grinding forces and then optimized the grinding parameters using the S/N (signal to noise) ratio. Second order response surface was developed for predicting surface roughness and grinding force. These can be used to make competitive decisions of the grinding conditions.

As is evident from the above literature review, very little work has been done on grinding of CMC. Consequently, there exists ample scope to study its overall grindability.

## 3. MATERIAL AND METHODS

The experiments were carried out on Chevalier Surface Grinder model SMART – H1224 of Taiwan make. The load was sensed by the piezoelectric Kistler dynamometer model 9257A. The dynamometer was connected to a Data Acquisition Card (DAC) through a charge amplifier. The force is measured in Newtons in two components – Tangential ($F_x$) and normal ($F_y$). Surface roughness is measured in microns by the Center Line Average (CLA) value using Talysurf – Taylor Hobson unit of UK. The diamond stylus of 0.2 micron tip radius was used. The workpieces of dimensions 25x25x6.5 mm of CMC (Ceramic Matrix Composite) CRYSTALOY 2301 were ground on the side having the dimensions of 25x6.5 mm. The material consists of Alumina matrix with reinforcement of SiC ($Al_2O_3$/SiC) whiskers. For grinding, metal bonded diamond grinding wheel (350 mm OD, 127 mm ID, 25 mm width and 3mm depth of diamond abrasive layer) was used. The average size of diamond abrasive grits was 91 microns. The wheel was balanced and trued prior to starting of the grinding operations. After careful consideration of the effects of variations of the input parameters on the responses, it was decided to take three input parameters namely grinding speed (m/s), table feed (m/min) and depth of cut (microns) with five levels of each. Full factorial experiments for this combination would involve a total number of $5^3 = 125$ experiments.

**Table 1: Factors and levels**

| Process Parameters | Levels | | | | |
|---|---|---|---|---|---|
| | -1.68 | -1 | 0 | 1 | 1.68 |
| Grinding Speed, Vc (m/s) | 10.27 | 13 | 17 | 21 | 23.73 |
| Table Feed Rate, Vf (m/min) | 3.95 | 6 | 9 | 12 | 14.05 |
| Depth of Cut d (micron) | 6.59 | 10 | 15 | 20 | 23.41 |

Table 2 gives the DOE (Design of Experiments) along with the average values of the responses. The combination involves twenty experiments with six central points.

**Table 2: Experiments design and Results**

| Run | Factor 1 A Grinding speed m/s | Factor 2 B Table Feed m/min | Factor 3 C Depth of Cut micron | Respon se 1 Ft N | Response 2 Ra micron |
|---|---|---|---|---|---|
| 1 | 17 | 9 | 15 | 33.76 | 0.35 |
| 2 | 17 | 9 | 15 | 36.95 | 0.3589 |
| 3 | 13 | 12 | 10 | 34.13 | 0.4273 |
| 4 | 17 | 9 | 24 | 52.55 | 0.4296 |
| 5 | 24 | 9 | 15 | 28.82 | 0.2153 |
| 6 | 17 | 9 | 7 | 16.02 | 0.2861 |
| 7 | 21 | 12 | 10 | 26.04 | 0.253 |
| 8 | 17 | 9 | 15 | 33.96 | 0.3493 |
| 9 | 21 | 6 | 10 | 18.56 | 0.2161 |
| 10 | 13 | 12 | 20 | 53.91 | 0.2881 |
| 11 | 21 | 12 | 20 | 50.71 | 0.3504 |
| 12 | 17 | 9 | 15 | 34.29 | 0.356 |
| 13 | 13 | 6 | 20 | 45.8 | 0.4221 |
| 14 | 17 | 4 | 15 | 27.44 | 0.2841 |
| 15 | 10 | 9 | 15 | 40.79 | 0.4952 |
| 16 | 17 | 14 | 15 | 45.46 | 0.427 |
| 17 | 13 | 6 | 10 | 24.56 | 0.3576 |
| 18 | 17 | 9 | 15 | 37.59 | 0.3613 |
| 19 | 17 | 9 | 15 | 37.28 | 0.3603 |
| 20 | 21 | 6 | 20 | 35.79 | 0.279 |

However, using partial factorial design of Central Composite Design (CCD), a number of 20 experiments were performed which could show the effect of all the input parameters on the responses. The experimental order was randomized. The factors (input parameters) and levels chosen to know the effect on responses are given in table 1 below.

## 4. RESULTS AND DISCUSSIONS

Using design Expert software, ANOVA tables were made for the two response parameters as shown in Table 3 and Table 4.

**Table 3: ANOVA of Ft**

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F |
|---|---|---|---|---|---|
| Model | 2060.7165 | 6 | 343.45276 | 123.27141 | < 0.0001 |
| A-Grinding Speed | 164.73087 | 1 | 164.73087 | 59.124891 | < 0.0001 |
| B-Table Feed | 362.76113 | 1 | 362.76113 | 130.20154 | < 0.0001 |
| C-Depth of cut | 1525.8729 | 1 | 1525.8729 | 547.6634 | < 0.0001 |
| AB | 2.7848 | 1 | 2.7848 | 0.9995151 | 0.3357 |
| AC | 0.0968 | 1 | 0.0968 | 0.0347433 | 0.8550 |
| BC | 4.47005 | 1 | 4.47005 | 1.6043819 | 0.2275 |
| Residual | 36.219962 | 13 | 2.7861509 | | |
| Lack of Fit | 19.832479 | 8 | 2.4790598 | 0.7563882 | 0.6551 |
| Pure Error | 16.387483 | 5 | 3.2774967 | | |
| Cor Total | 2096.9365 | 19 | | | |

In table 3, the Model F-value of 123.27 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.

Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.

The "Lack of Fit F-value" of 0.76 implies the Lack of Fit is not significant relative to the pure error. There is a 65.51% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good.

| | |
|---|---|
| R-Squared | 0.982727 |
| Adj R-Squared | 0.974755 |
| Pred R-Squared | 0.938744 |
| Adeq Precision | 38.8804 |

The "Pred R-Squared" of 0.9387 is in reasonable agreement with the "Adj R-Squared" of 0.9748.

"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 38.880 indicates an adequate signal. This model can be used to navigate the design space.

In table 4, the Model F-value of 75.20 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.

Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, AB, $A^2$, $A^2B$, $AB^2$ are significant model terms. Values greater than 0.1000 indicate the model terms are not significant

The "Lack of Fit F-value" of 3.42 implies the Lack of Fit is not significant relative to the pure error. There is a 12.35% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good.

**Table 4: ANOVA of Ra**

| Source | Sum of Squares | DoF | Mean Square | F Value | p-value |
|---|---|---|---|---|---|
| | | | | | Prob > F |
| Model | 0.124784 | 13 | 0.009599 | 75.19933 | < 0.0001 |
| A-Grinding Speed | 0.01998 | 1 | 0.01998 | 156.5293 | < 0.0001 |
| B-Table Feed | 8.32E-05 | 1 | 8.32E-05 | 0.651853 | 0.4503 |
| C-Depth of cut | 0.000136 | 1 | 0.000136 | 1.066444 | 0.3416 |
| AB | 0.023393 | 1 | 0.023393 | 183.2665 | < 0.0001 |
| AC | 0.000703 | 1 | 0.000703 | 5.508491 | 0.0573 |
| BC | 0.000627 | 1 | 0.000627 | 4.908815 | 0.0686 |
| A^2 | 0.005284 | 1 | 0.005284 | 41.39262 | 0.0007 |
| B^2 | 2.35E-06 | 1 | 2.35E-06 | 0.018436 | 0.8964 |
| C^2 | 0.000613 | 1 | 0.000613 | 4.800364 | 0.0710 |
| ABC | 0.000764 | 1 | 0.000764 | 5.988577 | 0.0500 |
| A^2B | 0.001217 | 1 | 0.001217 | 9.535058 | 0.0214 |
| A^2C | 6.4E-05 | 1 | 6.4E-05 | 0.501346 | 0.5055 |
| AB^2 | 0.003531 | 1 | 0.003531 | 27.66503 | 0.0019 |
| Residual | 0.000766 | 6 | 0.000128 | | |
| Lack of Fit | 0.000311 | 1 | 0.000311 | 3.424595 | 0.1235 |
| Pure Error | 0.000455 | 5 | 9.09E-05 | | |
| Cor Total | 0.125549 | 19 | | | |

| | |
|---|---|
| R-Squared | 0.993899905 |
| Adj R-Squared | 0.980683033 |
| Adeq Precision | 34.76310863 |

"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 34.763 indicates an adequate signal. This model can be used to navigate the design space.

The tables showed significant parameters, $R^2$ and $R^2$ adjusted values (found 0.9 and above) and finally gave the equations for Ft and Ra relating to the input parameters. The same are given below.

$$F_t = 18.96 - 1.39\left(Grindingspeed\right) + 0.13\left(Tablefeed\right) + 1.57\left(Depthofcut\right)$$

$$+0.05(Grindingspeed)x(Tablefeed)+0.006(Grindingspeed)x(Depthofcut)$$

$$+0.05(Tablefeed)x(Depthofcut)$$

$$\begin{aligned} R_a &= 1.29 + 0.02\left(Grindingspeed\right) - 0.21\left(Tablefeed\right) - 0.01\left(Depthofcut\right) \\ &+0.005(Grindingspeed)x(Tablefeed)+0.001(Grindingspeed)x(Depthofcut) \\ &-0.002(Tablefeed)x(Depthofcut)-0.004(Grindingspeed)^2+0.02(Tablefeed)^2 \\ &+0.0003(Depthofcut)^2+0.0002(Grindingspeed)x(Tablefeed)(Depthofcut) \\ &0.0004(Grindingspeed)^2x(Tablefeed)-0.0001(Grindingspeed)^2x(Depthofcut) \\ &-0.001\left(Grindingspeed\right)x\left(Tablefeed\right)^2 \end{aligned}$$

Variations in tangential force $F_t$ and surface roughness $R_a$ with variations in two input parameters while keeping the third one constant are shown in Fig.1 to Fig.6.

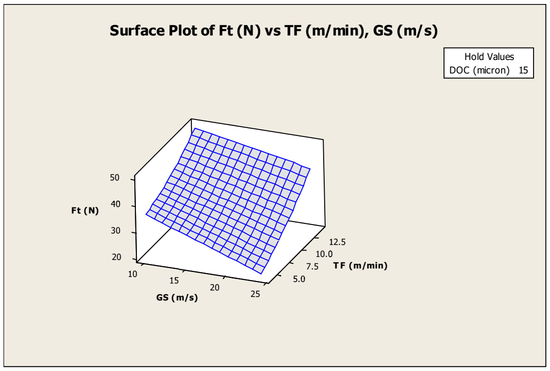

**Fig.1. Surface plot of Tangential Force (Ft) against Grinding Speed (GS) and Table Feed (TF) with Depth of Cut (DOC) kept constant at 15 microns**

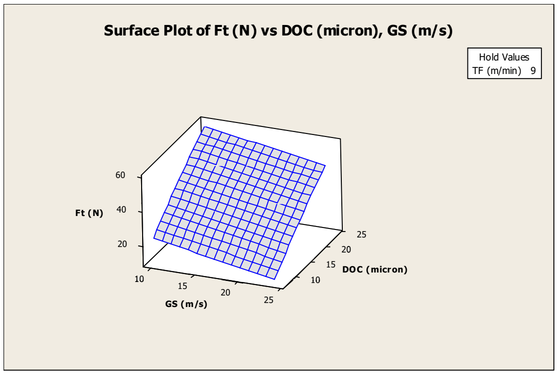

**Fig.2. Surface plot of tangential force (Ft) against Grinding Speed (GS) and Depth of Cut (DOC) with Table Feed (TF) kept constant at 9 m/min**

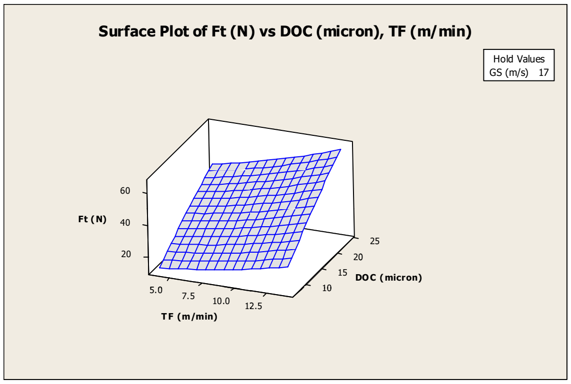

**Fig.3. Surface plot of Tangential Force (Ft) against Table Feed (TF) and Depth of Cut (DOC) with Grinding Speed (GS) kept constant at 17 m/s**

From the figure 1, it is seen that the tangential force decreases with increase in grinding speed and increases with increase in table feed. Figure 2 indicates that the tangential force decreases with increase in grinding speed and increases with increase in depth of cut.

From figure 3 it is concluded that the tangential force increases with increase in depth of cut as well as with increase in table feed. It is seen that the variation in tangential force with changes in the input parameters is directly proportional in nature.

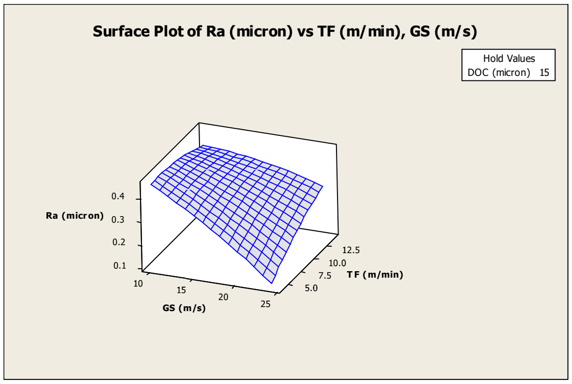

**Fig.4. Surface plot of Surface Roughness (Ra) against Grinding Speed (GS) and Table Feed (TF) with Depth of Cut (DOC) kept constant at 15 microns**

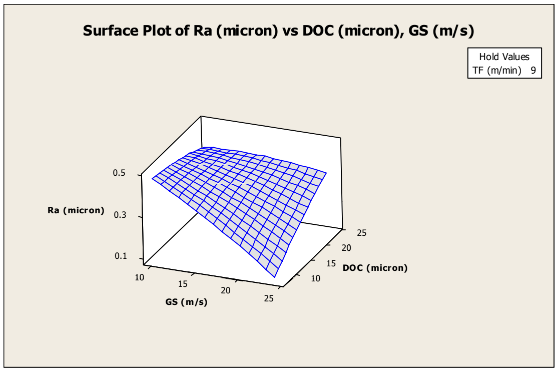

**Fig.5. Surface plot of Surface Roughness (Ra) against Grinding Speed (GS) and Depth of Cut (DOC) with Table Feed (TF) kept constant at 9 m/min**

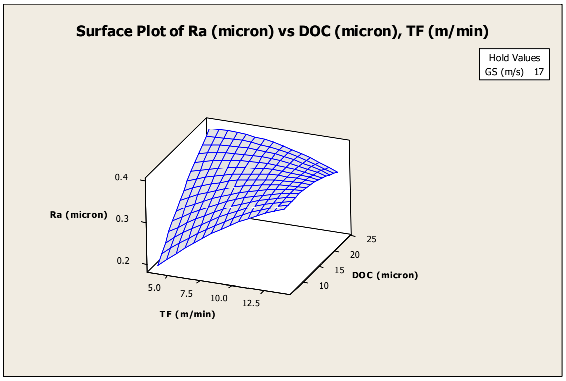

**Fig.6. Surface plot of Surface Roughness (Ra) against Table Feed (TF) and Depth of Cut (DOC) with Grinding Speed (GS) kept constant at 17 m/s**

Figure 4 shows that the surface roughness decreases with increase in grinding speed at low value of table feed. However, the decrease is less at higher table feed which implies that interaction effect of table feed with grinding feed exists. Similarly, interaction effect of grinding speed is seen in the variation of surface roughness with table feed. At low grinding speed, surface roughness decreases with increase in the table feed whereas the trend is reversed at higher grinding speed. Plot of surface roughness versus grinding speed and depth of cut (DOC) in figure 5 indicates that surface roughness decreases with increasing grinding speed but the decrease is very small at higher value of DOC. It proves the interaction effect of depth of cut with speed. At low grinding speed, roughness decreases slightly with increasing DOC whereas at higher speed the roughness increases with DOC. Figure 6 shows that both the input parameters have interaction effect on the behavior of roughness generation. Roughness values increase with table feed at low values of depth of cut and decreases with table feed at higher values of depth of cut. Similarly, at low table feed, $R_a$ increases with increasing depth of cut and remains more or less constant at higher value of table feed.

## 5. CONCLUSIONS

In surface grinding of ceramic matrix composite material, the vital input parameters are grinding speed, table feed and depth of cut. In the present study, grinding wheel of average grit size 91 microns has been used to investigate the effects of variations of these parameters on the responses - tangential force and surface roughness. Reduced tangential grinding force and reduced surface roughness result in an enhanced grindability of the material. The results of the experiments can be summarized as follows.

1. Increase in grinding speed results in decreased tangential force and decreased surface roughness value. This will improve grindability and also enhance functionality of the product. Reduction of tangential force will also result in reduction in specific grinding energy which is also an index of grindability
2. Increase in table feed rate increases the tangential grinding force as well as surface roughness. Material removal rate (MRR) can be increased by increasing grinding speed and table speed. But, as discussed above, increasing table feed rate will have a detrimental effect on grinding force as well as surface roughness. Hence it is desirable to keep table feed rate low and increase grinding speed to increase MRR.
3. Depth of cut has adverse effect on both tangential force and surface roughness. However, low depth of cut will cause high specific energy consumption due to size effect and results in low material removal rate (MRR). A tradeoff is required to balance the above conflicting situations.
4. Interaction has been observed in input parameters and often trends are reversed / effect minimized in case of low grinding speed and high table feed rate.

## References

1. Shih TT, Opoku J, Application of fracture mechanics to ceramic materials – A State-of-the- art review, *Engineering Fracture Mechanics,* **12**, (1979) 479-498
2. Inasaki, Yokohama, Grinding of hard and brittle materials, *Annals of the CIRP*, **36** (2), (1987) 463-471
3. Kitajima K, Kumagai N, Tanaka Y, Zheng HW Study of mechanism of ceramic grinding, *Annals of the CIRP*, **41** (1), (1992):367-371
4. Agarwal S, Rao P. V., Experimental investigation of surface/subsurface damage formation and material removal mechanism in SiC grinding, *International Journal of Machine Tools and Manufacture*, 48, (2008) 698-710
5. Agarwal S, Rao P. V., Grinding characteristics, material removal and damage formation mechanism in high removal rate grinding of Silicon Carbide, *International Journal of Machine Tools and manufacture*, **50**, (2010) 1077-1087
6. Geubelle PH, Maiti S, Simulation of damage mechanism in high speed grinding of structural ceramics, *ICF 10922 OR, University of Illinois, USA* (2001)
7. Ngoi BKA, Sreejith PS Ductile regime finish machining – A review, *International Journal of Advanced Manufacturing Technology*, **16**, (2000) 547-550
8. Kopac J, Krajnik P, High performance grinding – A review, *Journal of Materials Processing Technology*, **175**, (2006) 278-284
9. Zhang B, Howes TD, Material removal mechanism in grinding ceramics, *Annals of the CIRP*, **43** (1), (1994), 305-308
10. Komanduri R, On material removal mechanisms in finishing of advanced ceramics and glasses, *Annals of CIRP*, **45** (1), (1996) 505-514
11. Li K, Liao TW, Review - Surface/subsurface damage and the fracture strength of ground ceramics, *Journal of Materials Processing Technology*, **57**, (1996) 207-220
12. Venugopal A, Rao P.V., Selection of optimum conditions for maximum material removal rate with surface finish and damage as constraints in SiC grinding, *International journal of Machine Tools and Manufacture*, **43**, (2003) 1327-1336
13. Kwak JS, Kim YS, Mechanical properties and grinding performance on aluminum based metal matrix composites, *Journal of Materials Processing technology*, **201**, (2008) 596-600