Grindability Improvement of Composite Ceramic with Cryogenic Coolant

Vijayender Singh, S. Ghosh, and P. Venkateswara Rao

Abstract— **Composite Ceramic materials have vast engineering applications. But these are also difficult to machine materials. It is required to find out the techniques which can enhance their machinability. This paper aims to present the detailed study of the grindability improvement of such material using the cryogenic as coolant. The material is ceramic matrix composite also known as conductive ceramic (AlSiTi composite ceramic). Four process parameters are selected which have profound effect on the grinding process and their effects are studied on the response variables.**

Index Terms— **composite ceramics, cryogenic, grindability, surface integrity.**

I. INTRODUCTION

Advanced ceramics are the widely used Engineering materials because of their superior physical and mechanical properties such as high hot hardness, wear resistance and strength. However, ceramics are also very brittle and have low fracture toughness which makes them difficult to machine materials and are prone to surface and subsurface cracks produced during machining. Ceramics are also susceptible to the thermal shocks and thermal residual stresses produced during grinding operations due to their poor thermal conductivity and poor fracture toughness. Thermal residual stresses lead to the sub surface damage and the cracks formation on the ground surface. With the advent of new Ceramic Matrix Composites (CMC), also known as composite ceramics and conductive ceramics, having better thermal conductivity and the fracture toughness [1], it is now possible to machine these materials using coolants and to get better surface integrity as well as to obtain reduced grinding forces and lesser specific grinding energy. Use of coolants will not lead to any thermal shock during grinding of these materials due to their better thermal conductivity and improved fracture toughness. Cryogenic coolant especially the liquid nitrogen has no adverse environmental effect whereas the conventional coolants have the adverse environmental implications. Researchers have obtained better grinding performances using cryogenic coolants in comparison to the conventional coolants [2]. The present study reveals the significant improvement in the grindability aspects of composite ceramics using cryogenic coolant. Grinding forces both tangential as well as normal are found to be low in case of cryogenic grinding. Specific grinding energy is also low in case of cryogenic grinding. Sub-surface damage length observed in the ground composite ceramic using Scanning Electron Microscope (SEM) is found to be quite low with the use of cryogenic coolant. Surface quality has also improved in comparison to dry grinding.

A. *Grinding of ceramic materials*

Grinding is a widely used machining operation which results in significant material removal along with high surface finish [3]. In some of the machining operations, grinding is final machining process. However grinding is high specific energy process [4]. Hence the heat produced at the grinding zone is very high. Heat produced during grinding has detrimental effect on the surface quality as the majority of the heat produced is transferred to the workpiece. This leads to the thermal damage in the form of surface and sub-surface damages and impairs the surface quality. This problem is even more predominant in case of the ceramic materials as these are having low thermal conductivity as well as low fracture toughness which makes them vulnerable to the cracks at the surface and sub surface levels due to the residual thermal stresses. Specific grinding energy is the material property. Ceramics have high specific grinding energy requirements. The grinding forces in the ceramic grinding are also expected to be higher than the normal engineering materials. Difficulty and the cost involved in the machining of ceramic materials are the major restrictions in their widespread use in the industries [5, 6]. So the heat generated at the grinding zone must be effectively controlled to ensure superior workpiece quality.

B. *Cryogenic coolants*

Researchers have tried to control the heat generated at the grinding zone by using various coolants and the lubricants. Liquid coolants have been the conventional choice. They have good cooling and lubricating effects and lead to the improvement in the surface quality. However, their accessibility to the grinding zone and their environmental implication restrict their use. Researchers have also used solid lubricants to enhance the surface quality of the work materials [7]. Cryogenics (especially liquid nitrogen) as coolants do not have any adverse environmental effects. Cryogenic coolant can be directly applied to the grinding zone at high pressure. Cryogenics as the coolants have been used on steels and researchers have observed substantial improvement in the surface quality of the steels along with the reduced grinding forces [8]. Cryogenic coolants serve both as the coolants and as lubricants because along with liquid nitrogen some mist is also formed which surrounds

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the liquid jet and acts as the lubricating buffer layer in the grinding zone [2]. Ceramics being highly brittle, having very low fracture toughness and poor thermal conductivity cannot be ground with cryogenic coolants. Thermal stresses produced during grinding of ceramics using cryogenic coolants may lead to the thermal shock and eventually surface and sub-surface cracks. Hence ceramics are generally ground without using the coolants. But with the advent of new ceramic matrix composites materials, having better thermal conductivity and fracture toughness, it is now possible to make use of coolants including cryogenics during grinding of such ceramics**.** This research paper experimentally investigates the effect of cryogenic coolant on the grindability aspects of composite ceramic (AlSiTi). Use of cryogenic coolants may lead to better surface quality, reduced grinding forces and higher machining rate.

C. *Ceramic matrix composites*

Ceramic matrix composites (CMC) are the composites of various ceramic materials. One such CMC known as AlSiTi (Al_2O_3-SiC-TiC, 46.1 vol.% Al_2O_3, 30.9 vol.% SiC whiskers and 23 vol.% TiC powder) has been developed by Industrial Ceramic Technology, Inc [1]. Its mechanical properties are shown in Table 1. Due to its high thermal conductivity and also high fracture toughness in comparison to other conventional ceramics, the conductive ceramics may be ground using cryogenic coolants without compromising their surface integrity.

Table 1 Physical and mechanical properties of AlSiTi [3]

Density (g/cm³)	Hardness (HV)	Fracture Toughness ($MN/m^{\frac{3}{2}}$)	Modulus of Thermal conductivity Elasticity (W/m K at 400 K) (GPa)
3.9	2400	9.6 ± 0.6	407 63

II. EXPERIMENTS

Present research work focuses on the comparative study of surface integrity (surface roughness and sub surface damage) grinding forces and specific grinding energy requirement in dry grinding and the cryogenic grinding conditions. Four process parameters including grinding wheel speed, table speed, grain size and depth of cut are considered here to calculate their effects on the surface and sub surface quality as well as grinding forces and the specific grinding energy.

A. *Design of Experiments*

The experiments were conducted by considering five levels of each parameter as explained in Table 2. The experiments were designed using the Central Composite Response Design (CCRD) technique of response surface method. Set of 31 experimental runs was conducted each for the dry grinding and the cryogenic grinding. Response variables are the subsurface damage length measured with the help of SEM and the surface roughness measured through Talysurf.

Table 2 The process parameters at five different levels

Coded values/Parameters	-2	-1	0	1	2
Wheel Speed (m/s)	10	15	20	25	30
Table Speed (m/min)	3	6	9	12	15
Grit Size (micron)	7	30	64	91	126
Depth of Cut (Micron)	5	10	15	20	25

A. *Experimental Set Up*

Schematic diagram of the experimental set up is shown in Fig [1]. Experiments were conducted using a 2- Axis CHEVALIER CNC surface grinder (Chevalier SMART-H/B1216) in dry condition and using liquid nitrogen cryogenic coolant. Experimental set up for dry grinding and for cryogenic grinding is shown in Fig [2].
A set of five metal bonded diamond grinding wheels, with different grit sizes were used. The wheels have diameter of 350 mm and width of 25mm. The work material used for the experimentation is conductive ceramic AlSiTi (with properties mentioned in Table 1). The specimens of workpiece have the dimensions of (20×20×5) mm. Process parameters considered for grinding experiments are wheel speed (V_c), table feed (V_w), grain size (D_g) and depth of cut (A) .

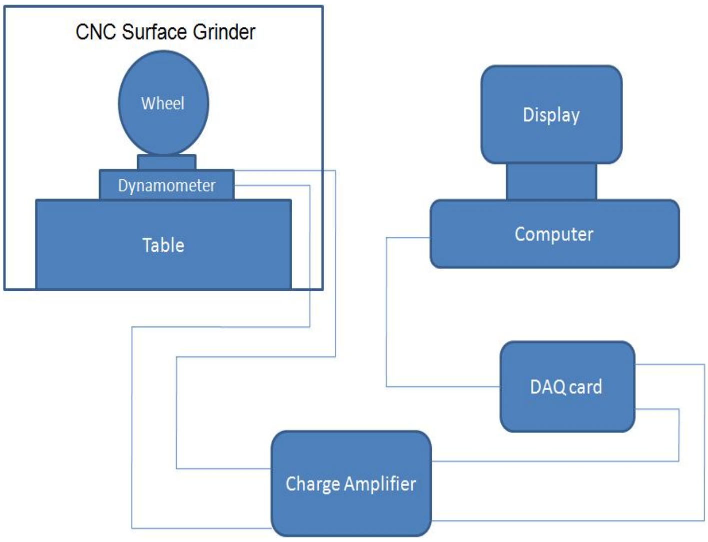


Fig 1 Schematic diagram showing the grinding operation

(a) Experimental Set up, dry grinding

(b) Cryogenic applied on grinding zone

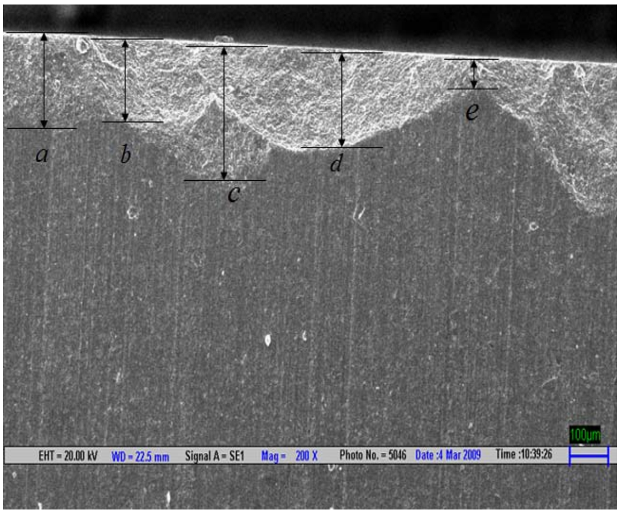
(c) Cryogenic dewar at 4 bar pressure

Fig 2

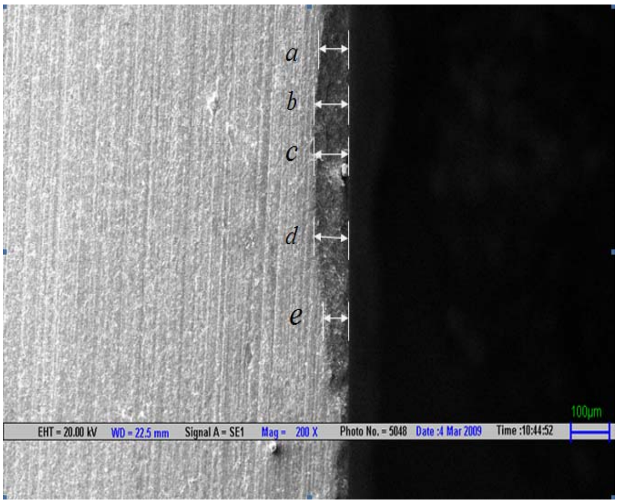
III. EXPERIMENTAL RESULTS & DISCUSSION

A. Sub surface damage

SEM images are taken at magnification of 200X. Sub surface damage lengths are calculated at five different points. Process parameters taken are grinding wheel speed of 20m/s, table speed of 9 m/min, grit size of 64 µm and depth of cut of 15 µm. In case of Fig 3 (a) the sub surface damage in case of dry grinding can be observed below the top ground surface, whereas in case of Fig 3 (b), in cryogenic grinding, the ground surface is right vertical face in the diagram and the sub surface damage length is shown by the arrow's lengths.



(a) Sub surface damage in dry grinding



(b) Sub surface damage in cryogenic grinding

Fig 3

It is clear from the diagrams that the sub surface damage in case of dry grinding is far more than that in case of cryogenic grinding. It may be due to the fact that in case of cryogenic grinding, the thermal stresses are controlled due to the coolant application.

B. Surface roughness

As shown in the Fig 4, Surface roughness value (R_a) is plotted with respect to depth of cut at wheel speed of

20m/s , table speed 9m/min, and grain size 64µm. It is observed that there is improvement in the surface quality of the ground surface with the cryogenic coolants and this improvement increases with depth of cut. Such improvement may be because of the lubricating effect of the cryogenic mist which reaches at the grinding zone under the high pressure application. Conventional coolants cannot reach the adverse high pressure grinding zone. Due to application of cryogenic coolant under high pressure (3-4 bar), it is possible for it to reach at the grinding zone and act as the lubricating buffer between the workpiece material and the wheel cutting edges.

Roughness values obtained through the experiments are mathematically modeled. Regression analysis and analysis of variance (ANOVA) using design expert software is done for these experimental values. Following equations are obtained for high degree of correlation (R square value). Equations (1) and (2) are plotted as shown in fig 4 for roughness values obtained in dry and cryogenic grinding.

$$R_{a,,dry}=0.375-0.01V_c+0.0005V_w+0.0014D_g+0.0014A +0.0003V_c^2-0.00004D_g^2+5.8X10^{-7}V_c^2D_g +7.4X10^{-6}V_wA^2 +2.97X10^{-7}D_g^3 \quad (1)$$

$$R_{a,\ cryo} = 0.26-0.002V_c-0.02V_w+0.002D_g +0.002A+ 0.001V_w^2-3.07X10^{-5}D_g^2- 1.51X10^{-6}V_w^2D_g +1.95X10^{-7}D_g^3 \quad (2)$$

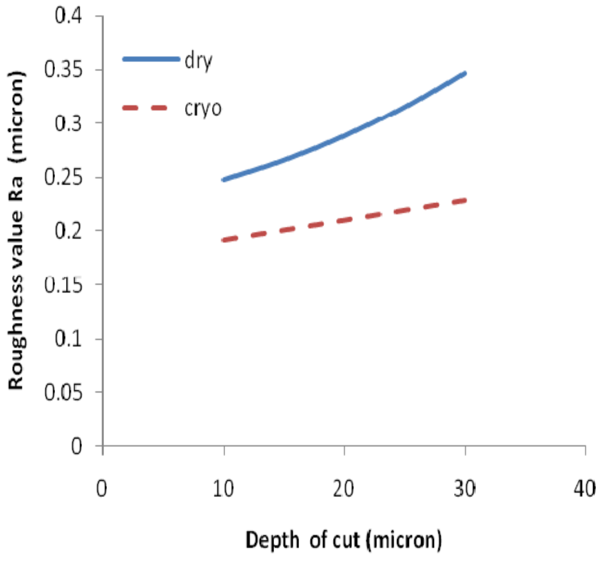


Fig 4 Roughness value (Ra) with depth of cut

C. Grinding forces

On the basis of the experimental values obtained through the 31 experiments conducted, following empirical relations are obtained for the grinding forces in terms of grinding process parameters.

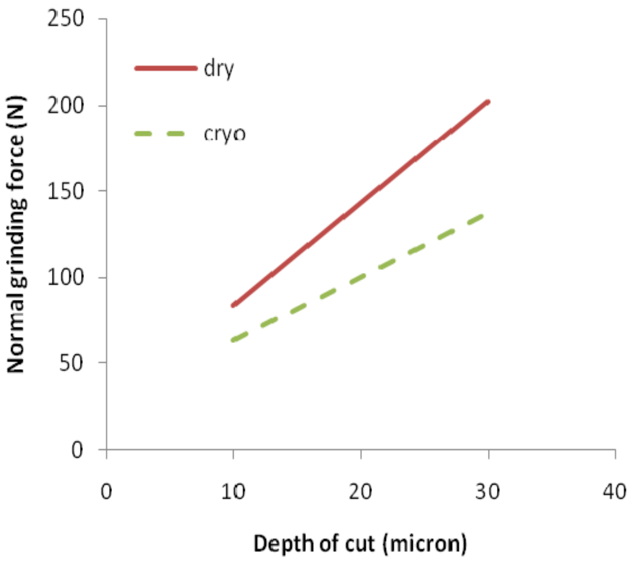
$$F_{n,dry}=125.19-1.54V_c-5.78V_w-0.66D_g-1.49A+0.06V_w D_g+ 0.44 V_w A+0.022 D_gA \quad (3)$$

$$F_{n,cryo}=87.66-1.09V_c-3.33V_w-0.46D_g-0.74A+0.044 V_wD_g+0.26V_wA+0.01D_gA \quad (4)$$

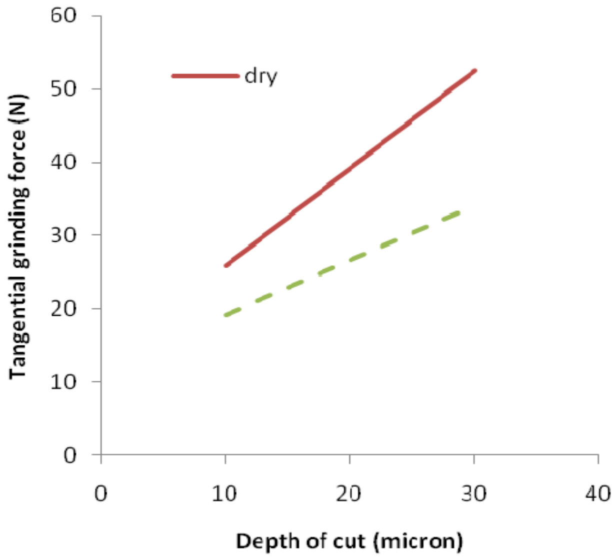
$$F_{t,dry}=33.86-0.49V_c-1.88V_w-0.20D_g+0.41A +0.03V_wD_g+0.08V_wA \quad (5)$$

$$F_{t,cryo}= 20.26-0.38 V_c -0.53V_w-0.15D_g+0.75A + 0.02V_wD_g \quad (6)$$

where $F_{n,dry}$ and $F_{t,dry}$ are the normal grinding force and tangential grinding forces in dry conditions and $F_{n,cryo}$ and $F_{t,cryo}$ are the normal grinding force and tangential grinding forces with cryogenic coolant. V_c is grinding wheel speed in m/s, V_w is table speed in m/min, D_g is grit size in micron and A is depth of cut in micron.



(a) Normal grinding force with depth of cut



(b) Tangential grinding force with depth of cut

Fig 5

From Fig 5 it is clear that both normal and tangential grinding forces in case of cryogenic grinding are less than that in case of dry grinding. One of the reasons for the reduced grinding forces in case of cryogenic grinding may be the grit sharpness which is maintained during cryogenic grinding [9]. In case of dry grinding, the abrasive grits are worn out and cannot maintain their edge sharpness and hence the force required is more due to the rubbing and ploughing action taking place along with the shearing. In case of cryogenic grinding, due to sharp cutting edges retained of the abrasive grits, the rubbing phenomena is less and the grinding forces also are reduced.

D. Specific grinding energy

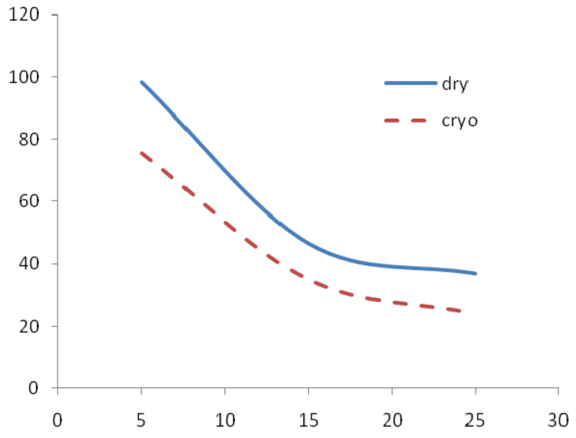


Fig 6

Specific grinding energy requirement in case of cryogenic grinding is substantially lower than that in case of dry grinding as shown in Fig 6. One of the reasons for reduced specific grinding energy in case of cryogenic grinding may be reduced grinding forces obtained in this case , another may be the increased material removal rate possible in case of cryogenic grinding due to more cutting action possible with the sharp grit edges. As in dry grinding the abrasive grits are worn out and along with the shearing action, there is significant rubbing and ploughing action also, which does not lead to any material removal but leads to substantial energy loss. Hence the dry grinding leads to higher specific energy consumption. In case of cryogenic grinding, the amount of rubbing and ploughing is comparatively less than that in dry grinding, hence the specific energy consumption is lower as shown in Fig 6.

IV. CONCLUSION

This paper experimentally verifies the beneficial effects of the use of cryogenic coolants in grinding of composite ceramic material. Ceramic materials generally are ground without the use of any coolant. Better thermal conductivity and fracture toughness of ceramic matrix composite have been used in this study to enhance the grindability of this difficult to machine material. The present study not only provides the means to enhance the machinability of composite ceramic materials but also shows the efficacy of cryogenic as the environmental friendly coolant to be used during machining of such materials. Faster rate of industrial production with enhanced surface quality can be obtained for these materials, using the cryogenic coolants.

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