INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

ORIGINAL ARTICLE

OPEN ACCESS

Received: 16/10/2025

Accepted: 20/10/2025

Published: 05/11/2025

Citation: Tiwari VK, Khan ZA, Gangil N, Siddiquee AN (2025) Energy Efficacy of a Novel CRUM Process for Machining of Ceramic Material. Indian Journal of Science and Technology 18(41): 3270-3278. https://doi.org/10.17485/IJST/v18i41.1707

* **Corresponding author**.

ansiddiqui@jmi.ac.in

Funding: None

Competing Interests: None

Published By Indian Society for Education and Environment (iSee)

ISSN
Print: 0974-6846
Electronic: 0974-5645

Energy Efficacy of a Novel CRUM Process for Machining of Ceramic Material

Visnu Kumar Tiwari[1,2], Zahid A. Khan[2], Namrata Gangil[3], Arshad Noor Siddiquee[1]*

1 Department of Mechanical Engineering, Jamia Millia Islamia, New Delhi, 110025, India
2 Department of Mechanical Engineering, JSS Academy of Technical Education, Noida, Uttar Pradesh, 201301, India
3 Department of Mechanical Engineering, Ajay Kumar Garg Engineering College, Ghaziabad, Uttar Pradesh, 201015, India

Abstract

Background: The processing and machining of advanced ceramic material, silicon nitride have is quite challenging without surface damaging, surface, and sub-surface micro-cracks due to their extreme hardness and toughness. Previous researchers have worked on machining of silicon nitride through a grinding process at very high cutting speed and high cutting force with a very low material removal rate (MRR). Some researchers have worked to resolve these problems using laser-assisted machining. In the Laser-assisted process, high temperature reduces the silicon nitride strength and increases the MRR at low cutting force in the ductile regime, due to too high temperature arriving steep thermal gradients produce surface and subsurface cracks. Ultrasonic-assisted machining of ceramics provides solutions for eliminating thermal gradient problems, but it still affects the surface roughness of materials, because it promotes brittle fracture for the material removal process. **Objectives:** 1. To develop a novel, cost-effective, sustainable method for machining silicon nitride. 2. To compare the energy efficiency (Specific Energy) with other popular processes. **Method:** This research has employed a dual hybridization process with ultrasonic vibration and chemical assistance, known as chemically assisted rotary ultrasonic machining (CRUM). **Findings:** The feed rate is the main effective factor, and its contribution to cutting force is 76.06% and the specific energy (Energy consumption) is 95.15%. The CRUM process is found to be 5.22 times more energy efficient than the Common Grinding (CG) process. The CRUM process is 1.698 times more energy efficient than the Ultrasonic Assisted Grinding (UAG) process. **Novelty:** This work has achieved a novel chemically assisted rotary ultrasonic machining (CRUM) process to machine silicon nitride material.

Keywords: Machining; Ceramic; Silicon Nitride; Mechanochemical Machining; Energy Efficiency

1 Introduction

Ceramic Machining is an important, critical process, but ceramics are tough to machine. Popular methods of machining are based on mechanisms that involve brittle fracture and ductile regime in addition to other limitations, including sophisticated machining systems, high cutting force (machining power) [1], [2], poor surface and subsurface quality, and poor tool life [3], [4].

The most popular methods for machining of ceramics are based on a common grinding process. Reported literature shows that the machining of ceramic marks with issues of very low material removal rate (MRR) due to high hardness, poor tool life, and high cost of machining [5]. The ceramics are also machined via non-traditional routes involving ultrasonic-assisted and laser-assisted machining. It has been demonstrated that the quality of surface and subsurface machined by using ultrasonic-assisted machining of ceramic materials has problems of surface and subsurface cracks and residual stress, which affect the tribological and fatigue performance. This was attributed mainly to the material removal mechanism comprising brittle fracture, which generated surface and subsurface cracks [6]. The Laser-assisted machining of ceramics, on the other hand, produces a high thermal gradient, lower surface profile accuracy, which also lower the surface quality [7], [8]. As the machining in ductile regime is mainly responsible for the smooth surface, researchers have synergized the effect of multiple processes and used a combined ductile cum brittle fracture mechanism to obtain improved quality at higher MRR [9], [10].

The literature reviewed converges to the fact that the popular methods of machining of ceramics are costly, have low material removal rate (MRR), and apart from the fact that they are performed with costly tools and tooling. The cost of sophisticated machines also seriously limits the expanse of the machining of ceramics restricts the use due to technological, intellectual, and proprietary issues [11]. This implies that better alternatives for the machining of ceramics have a huge potential for the growth of high-end products used in critical applications, including space, aerospace, biomedical, etc.

A new chemically assisted rotary ultrasonic machining (CRUM) process has been developed with a characteristic difference. Which include, but are not limited to following

1. Dual hybridization with ultrasonic vibration coupled with chemical assistance.
2. Unlike popular vibration-assisted-based ceramic machining processes, where mostly the tool is vibrated, such as in ultrasonic machining (USM), rotatory ultrasonic machining (RUM), etc., ultrasonic vibration in the present CURM process is given to the workpiece as against to the tool, which is the case with popular processes. This configuration of CRUM imparts a very characteristic distinction, contributing to lower forces, better material removal, and enhancing MRR.
3. In contrast with the popular ceramic machining processes, which utilize sophisticated special-purpose machines, the CRUM process was developed to perform machining by reconfiguring a conventional lathe machine, reducing the equipment cost to a fraction value. This strategy results in a significant enhancement in the growth of ceramic machining because of its cost efficiency.
4. Dual hybridization by use of chemical assistance as the form of cutting fluid coupled with ultrasonic vibrations, significantly modified by material removal mechanism, which translates into very good surface and subsurface quality and MRR at the same time.

To demonstrate the merits of CRUM over ultrasonic-assisted grinding, a comparative analysis was planned. This work presents a comparative analysis of the machining force, energy consumption, and MRR during drilling of Silicon Nitride (Si_3N_4) and on the CRUM set-up. The energy-related responses above compare with the popular method for the drilling of Si_3N_4. This work demonstrates that the novel developed process provides a better and enhanced machining alternative to Si_3N_4 ceramic.

2 Methodology

2.1 Materials and Methods

Work material used is gas laser-sintered silicon nitride (Si_3N_4) supplied by N.B. Enterprises India. Table 1 shows the mechanical and thermal properties of the work material, including that the material is non-toxic and molecular weight 140.28 (Si_3N_4), along with capabilities WHMIS (Workplace Hazardous Material Information System) ratings Health-zero, flammability zero, physical hazard–zero.

Diamond-coated hollow core drill-saw tool used in the CRUM process for machining as per the specification Table 1. Diamond-coated drill saw tool (hereafter referred to as the CRUM tool) achieves high precision and smooth cuts without edge breakage, with good toughness and high strength. Electroplated diamond (as shown in Figure 1c) is uniform and has sufficient wear-resistance. The CRUM machining was performed on an in-house developed set-up comprising of self-centric

Table 1. Properties of work material and Tool Details

Properties	Value	units
Work Material	**Silicon Nitride (α-SI3N4)**	
Bending Strength	850	MPa
Compressive strength	2800	MPa
Density	3200	Kg/m^3
Young's modulus	320000	MPa
Thermal Conductivity	35	W/m.K
Thermal expansion	3.2-3.4	e-6/K
Service Temperature	20 - 1100	°C
Melting Point	1900	°C
Friction coefficient	0.1	
Tool Details		
Drill saw outer diameter	6	mm
Drill saw inner diameter	4	mm
Shank diameter	5.5	mm
Type of coating	Electroplated	
Coated material	diamond	

3-jaw precision chuck mounted on a lathe machine (Make: Kirloskar, Model: Turnmaster 350) having specifications: power supply 415V, 3-phase, 50Hz; speed range 71 to 1800rpm. The machine was configured in house with a set-up comprising of a Telesonic ultrasonic generator of the most modern construction from the SG-22 series with an amplitude controlled to -2% to +2% overloads rating from no load to nominal and mains voltage fluctuations -10% to +20% shown in Figure 2. The converter booster sonotrode unit was mounted on the bracket to ensure high rigidity, a new booster mounting system without rings but steel, ensuring fine adjustment of the parallelism, has been developed. Provisions to house stroke-dependent sensors like micro contacts, approach switch electrical distance measuring were made. The converter booster, along with a bracket assembly, was mounted on a platform made of hardened steel to provide movement along the Z axis (parallel to the lathe bed) as a single body unit. The moving platform also carried the components and mechanisms for ultra-fine feed, which was capable of providing z-feed of the order of 1 micrometer. The motion of the platform was controlled by a microcontroller-controlled stepper motor, which could be operated via a laptop computer. Each step of the stepper motor was mechanically subdivided to convert it into ultrafine linear motion on the platform. The rotation of the stepper motor was varied and controlled by coding programmed in the C language. Through this whole controlling system, achieved ultra-fine feed in microns.

An inhouse designed novel work table and fixture was used for conducting experiments, work table and fixture provided holding and positioning to the work material as well as the ultrasonic head as in Figure 1. The fixture allowed linear movement of workpiece in the Z direction (Z axis of lathe parallel to the bed) and restricted the motions along X axis, Y axis, rotation in the XY, YZ and ZX planes as in Figure 1. The cutting fluid supply and recirculation system used a DC submersible pump to maintain a continuous fluid supply during the machining process. The supply and the circulation system of the fluid were automatically controlled shown in Figure 1(b). The CRUM tool was mounted in the 3-jaw precision chuck.

2.2 Experimentation Process

In this study, during experimentation, the tool was held and rotated in the 3-jaw precision chuck. The work material was held in the developed fixture and positioned in front of the tool face through the vice adjustment system. The workpiece was fed towards the tool through the sonotrode (convertor booster) from the back face of the work material. The sonotrode, while pushing the work, also transmitted the ultrasonic vibration to the work material mounted on the adjustable vice. The drill saw to work machining interface was flooded with the supply of alcohol (Methanol) through a fluid supply and recirculation system. During the experimentation, three variable parameters and five constant parameters were taken in Table 2, and the duration of the machining process was 180 seconds in a single experiment. Both categories of process parameters were selected by a pilot study based on a robust trial experiment regime. After the completion of an experimental process, work material was taken out from the fixture, and subsequently, all the measurements and images were taken through the CARL ZEISS Smart Zoom 5 automated digital microscope. It provides 3D measurement and 3D profile of machined surface (Magnification range

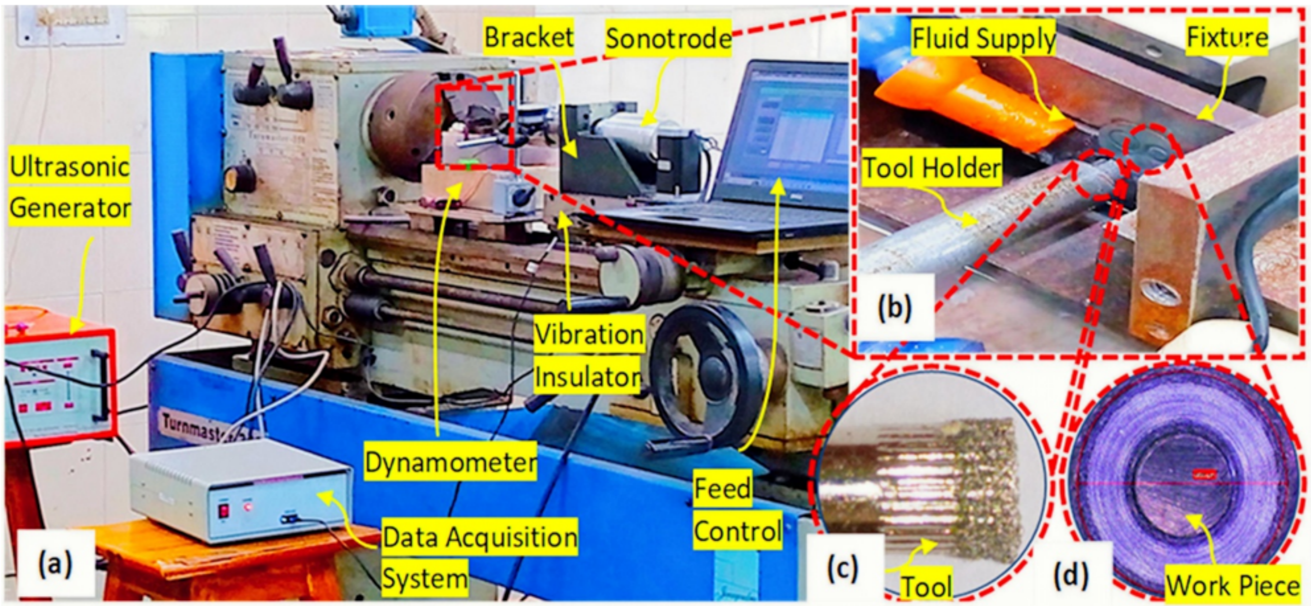

Fig 1. Diagrams of CRUM system (a) Setup (b) Fixture, fluid supply (c) Cutting tool (d) Workpiece

10X to 2020X). During the experiments, cutting forces were measured by using a strain gauge-based tool dynamometer having capacity of 500kg and a data sample of 1000 per in a single direction. For measuring the material removal process, a precision electronic weight machine was used, and the weight of the workpiece before and after the machining was considered. After the completion of all machining, the work material was cleaned in an ultrasonic bath and dried in dry air. The work material was ready for the next experiment and similarly performed all experiments. The experiments were selected based on three levels of variable parameters, as shown in Table 3, and follow the L_4 design of experimentation process as shown in Table 4. All experiments were conducted three times in a repeat in the same manner, and the best-of-three result was used in this study.

Table 2. Process Parameters

Variable parameters	**Ranges**
Tool rotation speed	710rpm -1880 rpm
Feed rate	2.4μm/s. – 7.4μm/s.
Amplitude	5.0μm/s. – 4.0μm/s
Constant parameter	**Value**
Frequency	20KHZ
Alcohol	Mythel alcohol (CH_3OH)
Alcohol flow rate	80 lit./Hr
Tool Diameter	6mm
Work Material	Silicon Nitride (SI_3N_4)

Table 3. Factors & their Levels

Factor	**Symbol**	**Unit**	**Level 1**	**Level 2**	**Level 3**
Amplitude (5μm)	A	(%)	100	90	80
Rotational speed	B	(rpm)	710	1120	1800
Feed Rate	C	(μm/s)	2.4	4.8	7.2

Table 4. Results of the CRUM Process

Exp. No.	Amplitude (5μm) (%)	Rotational Speed (rpm)	Feed Rate (μm/s)	Cutting force(N)	MRR (mm^3/min.)	Cutting Force/MRR	Specific Energy (J/mm^3)
1	100	710	2.4	11.472	2.0937	5.4793	61.0777
2	100	1120	4.8	11.952	6.7700	1.76544	31.0434
3	90	710	4.8	12.368	6.863	1.80213	20.0883
4	90	1120	2.4	10.563	3.1250	3.38016	59.4367

2.3 Mechanism of Material Removal

Grinding action of the CRUM tool, ultrasonic vibrations, and chemical reaction between Si_3N_4 and Methanol were separately considered to analyze and explain the material removal mechanism. It was considered that the material removal mechanism comprised two simultaneous actions:

(a) The material removal from the surface of Si_3N_4 involved the grinding action of the diamond grit embedded on the rotating CRUM tool, along with the impact of ultrasonic vibrations. The rotation of the CRUM tool under contact with Si_3N_4 resulted in the typical grinding action coupled with brittle fracture. The ultrasonic vibrations imparted to the work material were superposed over the grinding action and resulted in high-frequency impacts. The impacts and grinding resulted in brittle fracture; consequently, the material from the surface was removed. The debris generated as a result of material removal made room for the constant fine of the work of material towards the tool face. The machining forces measured demonstrated that the power utilized during the machining by the CRUM process was less than 10% of the load capacity of the ultrasonic generator.

(b) A mechanochemical reaction (as per **Eqn-1 and 2**) takes place between the Methanol cutting fluid and the Si_3N_4. This mechano-chemical reaction weakens a thin interface layer of the Si_3N_4which eases the material removal and reduces the cutting forces. Under constant flooding of Alcohol (CH_3OH) between the silicon nitride surface and the tool face, along with grinding by rubbing, catalyzes a reaction between CH_3OH and silicon nitride. The chemical reaction forms silicon alkoxide and hydrocarbon as reaction products as per **equation (1)**. So, the material removal mechanism during the machining of silicon nitride comprises a combination of the grinding process and the mechanochemical reaction process.

$$\mathrm{Si_3N_4 + n - ROH \underset{(2)\ Hydrolysis}{\overset{(1)\ Milling}{\longrightarrow}} SiO_2\ (gel)\ +\ Hydrocarbons} \tag{1}$$

$$\begin{array}{l} \mathrm{Si_3N_4 \overset{Oxidation}{\rightarrow} Si(OR)_n(OH)_{4-n} \longrightarrow \underset{Polyoxysilane}{(-O-Si(OR)_n(OH)_{2-n}-O-)_m} \overset{Hydrolysis}{\rightarrow} SiO_2\ (gel)} \\ \mathrm{R : CH_3} \end{array} \tag{2}$$

The chemical reaction process produces silica gel and long-chain hydrocarbons. Silica gel formation shown by **equation (2)** during machining, silicon alkoxide ($Si(OR)_n(OH)_{4-n}$) was formed by oxidation and esterification reaction of Si_3N_4 with alcohol[(12)],[(13)]. The products are soft and are formed as a thin layer at the interface, which eases the removal of materials. It is reported that during machining, the high temperature and the reaction also develop a vapor cloud, which hinders the chemical activity and consequently hampers the machining.

During machining by the CRUM process, the estimation of specific energy consumption during cutting is done by using **equation (3).**

$$\text{Specific energy} = \frac{2\pi\ \mathrm{NFR}}{60\ \mathrm{MRR}} \tag{3}$$

Unit of specific energy is (J/mm^3)

Where N is the Rotational speed of the tool in rpm, F is the cutting force in Newtons, R is the mean radius of the drill saw in mm, and MRR is the material removal rate in (mm^3/min).

3 Results and Discussion

To tackle the problem of vapor shielding, in the present CRUM process, instead of the tool, the workpiece was vibrated, and the CRUM tool was given a simple rotational speed. The vibration of the work material effectively broke the vapor cloud due to hammering-cavitation. Thus, this novel strategy stopped the vapor shielding of the interface and enabled a constant chemical activity, which supported the machining mainly in the ductile regime.

Figure 2 shows the wire mesh schematic along with dimensions and profile of the machined surface as generated by the measuring microscope. Experiments were performed as per the L_4 orthogonal array (OA) shown in Table 4. The parameters that were kept fixed during the CRUM process are shown in Table 2.

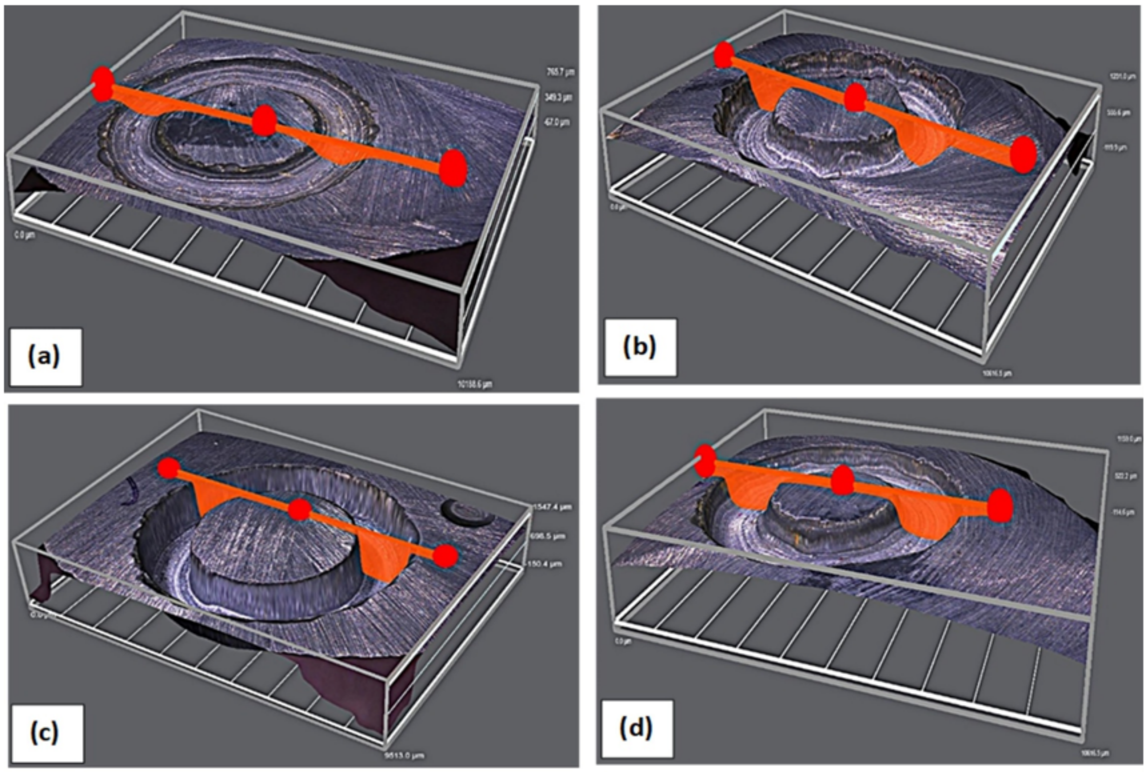

Fig 2. (a) to (d) Stereo-zoom images of the machined surface at various rotational speeds and feed rates

Results of machining of silicon nitride, cutting force, MRR, and specific energy consumption for different combinations of the CRUM process are also shown in Table 4. Specific energy consumption during cutting in the CRUM process was calculated using **equation (3)**.

Table 5. Results of the ratio of cutting force to MRR during the CRUM process

Expt. No	Amplitude (5μm) (A) %	Rotational Speed (B) rpm	Feed rate (C) μm/s	Ratio of Cutting force to MRR
1	100	710	2.4	5.4793
2	100	1120	4.8	1.7654
3	90	710	4.8	1.8021
4	90	1120	2.4	3.3802

Table 5 shows the ratio of cutting force to MRR for different combinations of the CRUM process. Figure 3 shows the main effects plot for means of the ratio of the cutting force to the MRR. The plot reveals that the factor C creates more significant effect on the cutting force in comparison to the factor A and factor B. It may be noted that during machining feed rate (factor C) was the main factor responsible for the feed force along the Z-direction and consequently produced the dominating effect. The impact of ultrasonic vibrations was responsible for the minor load along the Z-direction as the amplitude is reversing in nature, and it is smaller than the feed rate. Table 6 shows the ANOVA results for the ratio of cutting force and MRR. It can be seen from Table 6 that factor C is the most significant factor as its contribution is the maximum (76.02%) followed by factor B (12.39%) and factor A (11.55%).

Fig 3. Main Effects plot for means of ratio of cutting force to MRR

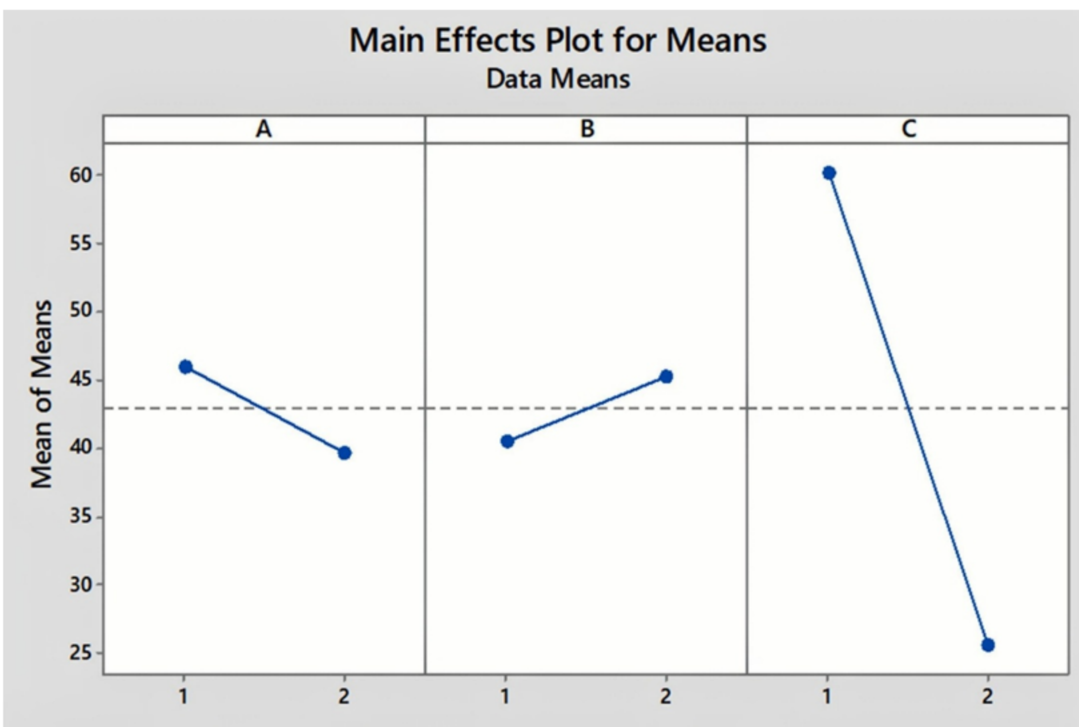

Fig 4. Main Effects plot for means of specific energy

Table 6. ANOVA result for the ratio of cutting force to MRR

Source of Variation	Sum of Square (SS)	DF	Mean Square (MS)	% Contribution
Amplitude (A)	1.0634	1	1.0634	11.55
Rotational Speed (B)	1.1404	1	1.1404	12.39
Feed Rate (C)	7.0013	1	7.0013	76.06
Error	-	-		
Total	9.2051	3		

Table 7 shows the results of the specific energy during the CRUM process. Figure 4 depicts the main effects plot for the means of specific energy. It can be seen from Figure 4 that the nature of the main effects of factor A and factor C is similar to that of Figure 3. The factor that results in higher cutting forces is also responsible for the higher energy consumption. Consequently, factor C produces dominating effect on the specific energy (J/mm^3), in comparison to the other two factors. Table 8 shows the ANOVA result for the specific energy, which reveals that factor C is the most significant factor as its percentage contribution is the maximum (95.15%) followed by factor A (3.14%) and factor B (1.71%). Table 7 shows that the maximum energy consumption during the machining of silicon nitride using the CRUM process is obtained at amplitude (100%), 710 rpm and feed rate 2.4μm/s is 61.0777 J/mm^3, and the minimum energy consumption (20.0883 J/mm^3) is observed at amplitude (90%), 710 rpm and feed rate 4.8μm/s.

Table 7. Results of the specific energy during the CRUM process

Expt. No	Amplitude (5μm) (A) %	Rotational Speed (B) rpm	Feed rate (C) μm/s	Specific energy (J/mm^3)
1	100	710	2.4	61.0777
2	100	1120	4.8	31.0434
3	90	710	4.8	20.0883
4	90	1120	2.4	59.4367

Table 8. ANOVA result for specific energy

Source of Variation	Sum of Square (SS)	DF	Mean Square (MS)	% Contribution
Amplitude (A)	39.67	1	39.67	3.14
Rotational Speed (B)	21.69	1	21.69	1.71
Feed Rate (C)	1203.49	1	1203.49	95.15
Error	-	-		
Total	1264.84	3		

3.1 Comparisons of the CRUM Process with other Popular processes

Comparison of the machining of Si_3N_4 using the CRUM process with other popular machining processes like Common grinding (CG) and ultrasonic assisted grinding (UAG) process in terms of cutting force and specific energy (J/mm^3) parameters has been made in this study. In the CG process, cutting force lies in the range 65N to 82N at various lubrication conditions, and in the UAG Process, cutting force lies in the range 30N to 42N[14] at various lubrication conditions. During machining of silicon nitride using the CRUM process cutting force range is found to be 10.563N to 12.368N. This shows that the cutting force during machining of Si_3N_4 using the CRUM process is much less than that of the CG and UAG processes. For the best condition, cutting force in the CRUM process is found to be 83.7% less than that of the CG process, and 64.8% less than that of the UAG process. Thus, the CRUM process is 5.15 times more efficient than the CG process and 1.84 times more efficient than the UAG process in terms of cutting force.

The range of specific energy in the CG process is 125 J/mm^3 to 160 J/mm^3, and in the UAG process, it is in the range of 55 J/mm^3 to 82 J/mm^3 at various lubrication conditions[14]. The specific energy during machining of silicon nitride using the CRUM process is found to be in the range from 20.088 J/mm^3 to 61.077 J/mm^3. For the best condition, specific energy consumption in the CRUM process is 83.9% less than the specific energy consumption in the CG process, and 63.5% less than the UAG process. Thus, it can be deduced that based on the energy consumption, the CRUM process is 5.22 times more efficient than the CG process and 1.698 times more efficient than the UAG process.

4 Conclusions

Conclusions of the present study are as follows:

1. Feed rate is the most significant factor to affect the ratio of the cutting force to MRR in the CRUM process as its contribution is maximum (76.06%) followed by rotational speed (12.39%) and amplitude (11.55%).
2. Feed rate is the most significant factor for specific energy during machining using the CRUM process as its contribution is maximum (95.15%) followed by amplitude (3.14%) and rotational speed (1.71%).
3. The required cutting force in the CRUM process is 83.7% less than that of the CG process, and 64.8% less than that of the UAG process.
4. The CRUM process is 5.15 times more efficient than the CG process and 1.84 times more efficient than the UAG process in terms of cutting force
5. Energy consumption in the CRUM process is 83.9% and 63.5% less than the energy consumption in the CG and UAG processes, respectively.
6. The CRUM process is 5.22 times more efficient than the CG process and 1.698 times more efficient than the UAG process in terms of energy consumption.

References

1) Xu W, Li C, Xu P, Wang W. Grinding mechanics of ceramics: from mechanism to modeling. *Advances in Manufacturing*. 2025. https://doi.org/10.1007/s40436-025-00553-0.
2) Rong B, Eleonora F, Yinfei Y, Jun Q. Experimental Investigation on Ductile Mode Micro-Milling of ZrO2 Ceramics with Diamond-Coated End Mills. *Micromachines*. 2018;9(3):127. https://doi.org/10.3390/mi9030127.
3) Yanhao H, Ying N, Zhipeng S, Yuanxiao L, Jingjing N. Surface/subsurface damage mechanisms and inhibition strategies in machining of hard and brittle materials: A systematic review. *Surfaces and Interfaces*. 2024;54:105088. https://doi.org/10.1016/j.surfin.2024.105088.
4) Xiong Y, Wang W, Jiang R, Huang B, Liu C. Feasibility and tool performance of ultrasonic vibration-assisted milling-grinding SiCf/SiC ceramic matrix composite. *Journal of materials research and technology*. 2022;19:3018–3033. https://doi.org/10.1016/j.jmrt.2022.06.063.
5) Craig S, Manigandan K. Defect-free grinding of silicon nitride at high material removal rate. *Heliyon*. 2024;10:e30232. https://doi.org/10.1016/j.heliyon.2024.e30232.
6) Muhammad NR, Shen YL. Experimental Investigation of Milling Performance of Silicon Nitride Ceramic Subject to Different Assisted Systems. *Materials*. 2023;16(1). https://doi.org/10.3390/ma16010137.
7) Pu Y, Zhao Y, Zhao G, Zhang H. Experimental study on laser assisted machining of silicon nitride ceramics based on acoustic emission detection. *Optics & Laser Technology*. 2025;180:111497. https://doi.org/10.1016/j.optlastec.2024.111497.
8) Jiaxuan W, Chongjun W, Dihao Z, Zishan D, Steven Y. Laser prefabricated circular groove-assisted grinding of Si3N4 ceramics: Surface quality analysis and process optimization. *Journal of Manufacturing Processes*. 2025;136:148–161. https://doi.org/10.1016/j.jmapro.2025.01.074.
9) Ziyuan L, Rong S, Ziguang W, Yu L, Shengfang Z. Characterization of Material Removal and Crack Propagation of Silicon Nitride Ceramics Under Mechanical Stressing. *Int J of Precision Engineering and Manufacturing*. 2025;26:1877–1888. https://doi.org/10.1007/s12541-025-01238-1.
10) Honghao W, Xuyang L, Min C, Chenguang B. Sintering densification behavior of silicon nitride (Si3N4) ceramics: A molecular dynamics study. *Ceramics International*. 2025. https://doi.org/10.1016/j.ceramint.2025.10.200.
11) Kumar S, Dwivedi A. On machining of hard and brittle materials using rotary tool micro-ultrasonic drilling process. *Materials and Manufacturing Processes*. 2019;34(7). https://doi.org/10.1080/10426914.2019.1594255.
12) Hibi Y, Enomoto Y. Mechanochemical reaction and relationship to tribological response of silicon nitride in n-alcohol. *Wear*. 1999;231:185–194. https://doi.org/10.1016/S0043-1648(99)00094-0.
13) Hibi Y, Enomoto Y. Chemical analysis of mechanochemical reaction products of α-Si3N4 in ethanol and other lower alcohols. *Journal of Materials Science letters*. 1997;16:316–319. https://doi.org/10.1023/A:1018517621801.
14) Yusuf DS, Changhe L, Mohd S, Ahmad AD. Grindability Evaluation of Ultrasonic Assisted Grinding of Silicon Nitride Ceramic Using Minimum Quantity Lubrication Based SiO2Nanofluid. *Chinese Journal of Mechanical Engineering*. 2024;37:25. https://doi.org/10.1186/s10033-024-01011-x.