Manufacturing Science and Technology 3(1): 10-15, 2015 http://www.hrpub.org
DOI: 10.13189/mst.2015.030102

An Overview of Machining Process of Alumina and Alumina Ceramic Composites

Pravin Pawar*, Raj Ballav, Amaresh Kumar

Department of Manufacturing Engineering, National Institute of Technology, Jamshedpur, 831014, India
*Corresponding Author: pravin.1900@gmail.com

Abstract The present paper gives a critical review of Alumina and alumina composite ceramic materials machined by different machining process. The article shows that a review on machining of alumina and alumina composites with different input parameters and different output responses such as Material Removal Rate (MRR), Tool Wear Rate (TWR),Surface Roughness(Ra) etc. using a different mechanism of machining technique, SWOT Analysis & its summery results of literature review.

Keywords Alumina, Material Removal Rate, Tool Wear Rate, Surface Roughness, USM, AWM, EDM, ED Milling, ECDM, SWOT

1. Introduction

The machining of advanced nonconductive ceramic like aluminum oxide (Al_2O_3) ceramic continues to be a major challenge for user industries. Advanced ceramic materials are gradually becoming very important for their superior properties such as high hardness, wear resistance, chemical resistance, low density, superior wear and corrosion resistance, and high-temperature strength and high strength to weight ratio, often result in low material removal rate (MRR), relatively poor surface quality and subsurface damage, which may grow into a spontaneous fracture during machining [3][9][13].

Aluminium oxide (Al_2O_3) used for making machine tool inserts, aerospace, electrical and electronic components, ballistic armor, ceramic composite automotive brakes, diesel particulate filters, a wide variety of prosthetic products, piezoceramic sensors and next-generation computer memory [2][15]. Al_2O_3 is a material with high potential for use in biomedical implants because of its low wear rate and excellent biocompatibility [4][20]

One factor limiting the industrial application of these ceramics is the inability to attain sufficient dimensional control during net-shape fabrication. Thus the additional machining processes is required[14]. Ceramics are known as very difficult to machine materials. The main factors that cause ceramics to be difficult-to-machine are their extreme hardness, non-electrical conductivity and brittleness [11][18][19].

2. Classification of Machining Process

2.1. Ultrasonic Machining Process (USM)

H.frei et al [1] has experimented on materials of Al_2O_3 & ZrO_2 - Al_2O_3 using ultrasonic machining process & after that authors were found out for Al_2O_3 strengthening mechanism is depended on a direct correlation between roughness and strength: The lower, roughness the higher the strength. In case of ZrO_2 - Al_2O_3 there is no direct correlation between strength and roughness. Henrik Dam et al [2] has studied machining process using USM applied into tough and brittle materials and finally results were found out such as production rate, tool wear, and surface roughness. Tai-Chiu Lee et al [7] has studied the effect of whisker orientation on the material removal rate and mechanisms in ultrasonic machining of SiC whisker-reinforced alumina ceramic composites.

B. Ghahramani et al [8] was taken case study of machining of Al_2O_3 using USM and discussed in briefly in USM process, mechanism, dynamics and its trends. Deng Jianxin et al [9] have found out in this research MRR is dependent on the effect of the properties & Microstructure of the workpiece materials of alumina-based ceramic composites. The experimental results showed that fracture toughness plays a major role with respect to MRR and surface roughness in USM of alumina-based ceramic composites. Z.C. Li et al [14] has produced holes on ceramic matrix composites & Alumina materials using rotary ultrasonic machining and comparing their results based on cutting force, MRR, chipping thickness and chipping size.

2.2. Abrasive Waterjet Machining (AWM)

GI SANG CHOI et al [3] has developed an analytical model for the material removal rate in AWJM and this model was applied into experimentally on Alumina material. The results show that material removal rate of AWJM in cutting Brittle and a hard material are high. Also show that abrasion mechanisms for ductile and brittle materials are different.

Manabu Wakuda et al [11] has experimentally identified material removal response of alumina ceramics to the abrasive particles such as aluminum oxide, silicon carbide, synthetic diamond impact in the AJM process. J.wang et al [12] has experimentally analyzed performance of multipass AWJ machining. The results obtained were proved that superior performance using multipass over single passes AWJ cutting on alumina material. D.K. Shanmugam et al [20] has investigated experimentally minimise or eliminate the kerf taper in AWJ cutting of alumina ceramics by using a kerf-taper compensation technique. This technique suggested predicting the kerf taper angle both qualitatively and quantitatively within the tested range of the process parameters.

2.3. Electro Discharge Machining (EDM)

J. H. Zhang et al [4] has used electro discharge machine for machining of conductive ceramics (Al_2O_3+TiC+WC Hot pressed plate). The output response was discovered out such as material removal rate, surface roughness, and diameter of discharge points by using various input parameters. Biing Hwa Yan et al [6] have to check feasibility of machining of material was Al_2O_3/6061Al using rotary EDM with ball burnishing. The results were found out machining rate, surface roughness and improvement of surface roughness.

2.4. Electro Discharge Milling (ED Milling)

Y.H. Liu et al [18-19] have developed a new novel technique of Electro Discharge milling. In this ED milling author used a thin copper sheet fed to the tool electrode along the surface of the workpiece as the assisting electrode, and uses a water-based emulsion as work fluid to machined insulating Al_2O_3 ceramic. This novel technique results shows that high MRR.

2.5. Electro Chemical Discharge Machining (ECDM)

B. Bhattacharya et al [5] has designed and modified ECDM setup and producing novel ECDM setup. In this author developed the modular mechatronic feature of the indigenously designed ECDM set up to machined Al_2O_3 ceramic materials. The final output results were measured material removal rate and accuracy of machined materials. Sanjay K. Chak et al [17] has developed unique new technique of trepanning method into ECDM setup to machined Al_2O_3 ceramic material. Choosing this technique the author found out the results were improved dimensional accuracy, surface integrity of the machined profile and improvement in the quality of holes produced.

2.6. Laser Machining

Chwan-Huei Tsai et al [10] has developed novel designed laser machining applied the concept of fracture machining element. Using this closed cavity for alumina ceramic can be successfully shaped. The results were shows that the material removal rate can be improved when increasing the moving speed of laser.

2.7. Laser Assisted Machining (LAM)

Patrick A. Rebro et al [13][15] has used laser-assisted machining (LAM) to machined on Al_2O_3 workpieces. Laser-assisted machining is a laser-assisted turning using a Nd:YAG laser. The obtained results applying these techniques give better surface quality, better surface roughness, larger material removal rate and moderate tool wear.

3. Major Findings on Machining of Alumina & Alumina Composites

Table 1. Literature Review

Ref No.	Mechanism	W/P Mtl & Its Dimensional Shape	Tool Mtl & Its Dimensional shape	Input Parameters	Output Parameters	Reported By & Year
1	Polishing/ Grinding/ Ultrasonic Machining	99.9%Al_2O_3 & ZrO_2 - Al_2O_3 (75.7% ZrO_2+ 4.2%Y_2O_3+20% Al_2O_3) Rectangular 300 μm thick	Polishing- diamond particle size of 6-1μm Grinding- wheel diamond particle size of 90μm	Amplitude of tool 20-40μm, Different W/P Mtls.	Ra, Strength, Defects –cracks, Optimization Using SEM & TEM	H.frei et al (1992)
2.	Ultrasonic Machining	Al_2O_3 Ceramic Tiles	Steel -Tubular Tool I.D-10mm, O.D.-8mm	Different W/P Mtls , Tool rpm-400, Amplitude-6-50μm	MRR,TWR, Ra-9μm, Production Rate	Henrik Dam et al (1995)

Ref No.	Mechanism	W/P Mtl & Its Dimensional Shape	Tool Mtl & Its Dimensional shape	Input Parameters	Output Parameters	Reported By & Year
3	Abrasive Waterjet Machining	Al_2O_3 AD-94 alumina plates – 5mm thickness.	AISI4340 steel & Al2024 aluminium	Abrasive particles - Ø 0.15-0.25 mm,Water Jet Pressure (MPa)-150-350, Types of mtl.	MRR-60-110mm^3/s, Thikness of fracture-1.5-2.1mm,RMS AE signal(0.1V/div)	GI SANG CHOI et al (1997)
4	Electro Discharge Machining	Al_2O_3+TiC+WC hot pressed plate	Copper solid circular shape	Voltage100-180, Current-4-24.8, Pulse on time-10-1800μs, Pulse off time-100-3200μs	MRR, TWR,Ra	J. H. Zhang et al (1997)
5	Electro-Chemical Discharge Machining	Al_2O_3 25mmX25mmX 3mm	Copper of Ø 2mm	electrolyte concentrations of 20%, 25% and 30% of NaOH, supply voltage-70 to 90V	MRR-(1-6×10^{-1}) mg/min, Overcut	B. Bhattacharya et al (1999)
6	Rotary Ball Burnishing Electrical Discharge Machining	Al_2O_3/6061Al Thickness 15 mm plate	Copper, ring shape Outer Ø 25.4–25.6 mm, Inner Ø19 mm	Non-load voltage (V) 60–120 ,Peak current(Ip)1–15 A, Pulse duration (ton) 1–650 ms, Pulse off time (toff) 1–650 ms	MRR-0.15-0.90mm/min, Ra-1.2- 3.5μm, ISR-55-92%	Biing Hwa Yan et al (2000)
7	Ultrasonic Machining	Al_2O_3/SiCw 3X4X36 (mm)	Mild Steel Ø5mm	power-250W, Frequency-16-25khz, Amplitude of vibration-5-20μm	MRR-0.60-1.65mm^3/min & Ra-0.4-0.8 μm	Tai-Chiu Lee and Deng Jianxin (2001)
8	Ultrasonic Machining	Al_2O_3 0.18×0.051×0.0095 m	Vibrating Tool	Force (N)72-466	Compressive Maximum (MN/m^2), Tensile stress(MN/m^2), Maximum shear stress(MN/m^2)	B. Ghahramani et al (2001)
9	Ultrasonic Machining	Al_2O_3/TiC,Al_2O_3/SiCw, Al_2O_3/TiB_2, Size- 3X4X36(mm)	Mild Steel Ø5	Power-250W, Frequency-16-25khz, Amplitude of vibration-5-20um	MRR-0.4-1mm^3/min, Ra-0.5-2μm	Deng Jianxin et al (2002)
10	Laser Machining (CO_2& Nd:YAG)	99.6% Al_2O_3 Substrate 108× 108×10 (mm)	Wavelength of CO_2 laser -10.6 mm, Dia of Focus spot -73 mm. wavelength of Nd:YAG laser -1.06 mm	Power of Nd:YAG laser - 53 W, power of CO_2 laser - 44 W	MRR- 0.15mm^3/s Ra- 60μm	Chwan-Huei Tsai et al (2003)
11	Abrasive Waterjet Machining	Al_2O_3 alumina tiles	Jet pressure (MPa) -0.3,Jet distance (mm)-0.5, Nozzle (mm)-Ø0.6, Abrasive flow rate (g/min)-2 Machining time (s)-20	Abrasive Particles-WA, GC, SD, Abrasive size (mm)-15–25μm	MRR-(0-0.010), surface appearance	Manabu Wakuda et al (2003)

Ref No.	Mechanism	W/P Mtl & Its Dimensional Shape	Tool Mtl & Its Dimensional shape	Input Parameters	Output Parameters	Reported By & Year
12	Multipass abrasive waterjet machining	Al_2O_3 87% alumina ceramic slabs of 12.7mm thick	Nozzle Ø-1.02mm Orifice Ø-0.39mm Nozzle Length-76.2mm, Standing Distance-4mm, Abrasive mass flow rate:8.33gm/s	Water Pressure-345-380Mpa Nozzle transverse speed(mm),Nozzle Transverse Direction-one & alternating	Kerf Profile, kerf taper-3.5-8 degree, Surface roughness-7-20.4µm, Depth of cut-3-12mm	J.wang et al (2003)
13	Laser Assisted Machining	$3Al_2O_3$–$2SiO_2$ 10.3 to 10.6 mm	1.5 kW CO_2 laser +60hpCNC Turret	Power (W) -170, Time-(s)-13, Dia D (mm)- 4.30, Length- (mm)-2.16 Feed- (mm/rev) -0.010 Speed-(rpm) -800 Dia-d(mm) -0.50	Find out Tool life, Surface integrity	Patrick A. Rebro et al (2004)
14	Rotary Ultrasonic Machining	Al_2O_3 32 ×32 ×6.35(mm)	Diamond core drills O.D-9.54& I.D.-7.82 mm	Spindle speed 17-- 50(rev/s), Feed rate 0.09-.15 (mm/s),Ultrasonic vibration-Power supply A: 35%-50%;	Cutting force, MRR, chipping Thickness, and chipping size	Z.C. Li et al (2005)
15	Laser Assisted Machining	Al_2O_3 45×10× 10(mm)	25W (continuous wave) CO_2 laser TNMG1604 CBN Tool	Laser power (W) 25, Laser beam diameter (mm) 1.0,Laser-tool lead (mm) 1.0, Depth of cut (mm) 0.05, Feed rate (m/min)-0.5- 1.0	Cutting force-10-50N, Ra(µm)-2.98-4.12	Chih-Wei Chang et al (2007)
16	Laser Assisted Machining	Al_2O_3 Ø15mm & 65mm length	Beam spot diameter of 0.54 mm, A focal length of 40 mm, CBN Tool	Depth of cut (mm) -0.2- 1 Rotational speed (rpm)-1000-2000,Feed (mm/rev)-0.01-0.03 , Pulsed frequency (kHz)-30-50	Ra (µm)-0.24-1.18, MRR (mm^3/ s) -1.5708-23.5619	Chih-Wei Chang et al (2007)
17	Electro-Chemical Discharge Machining	Al_2O_3 15×15×7mm^3	A spring fed diamond embedded cylindrical abrasive tool electrode of Ø1.5mm	Voltage, X1 (V)-60-120,Duty factor, X2 (%)-0.48- 0.96, Electrolyte conductivity, X3 (mmho/cm) - 275-375	Dimensional accuracy and surface integrity	Sanjay K. Chak et al (2007)
18	Electrical Discharge Millling	Al_2O_3 Rectangular shape	Steel, Assisting electrode material red copper	Pulse time 500ms pulse off-time- 400 ms, peak current-25A Positive polarity, Machining fluid water-based	MRR(mg/min)-100-300, Ra(µm)-6-10	Y.H. Liu et al (2008)

Ref No.	Mechanism	W/P Mtl & Its Dimensional Shape	Tool Mtl & Its Dimensional shape	Input Parameters	Output Parameters	Reported By & Year
19	Electrical Discharge Millling	Al_2O_3 Rectangle shape	Steel & Assisted electrode Mtl red copper, shape-Circular wheel	Pulse duration-50-500µs, Peak Voltage- 100-200, Peak Current- 25A, Feed speed (mm/min)-0.5-3, Rotational Speed(r/min)-250-1500	MRR 120-350 mg/min, Ra-8-12µm	Y.H. Liu et al (2008)
20	Abrasive Waterjet Machining	Al_2O_3 ceramic tiles 150×100×12.7mm.	76.2-mm-long carbide nozzle (or mixing tube) of 0.762mm in Dia	Traverse speed (mm/s)-0.67-1.17, Standoff distance (mm)-2-5,Water pressure (MPa)-310- 410, Abrasive mass flow rate (g/s)-7.6- 9, Compensation angle(degree)-0-5	kerf taper Angle-(1-5°)	D.K. Shanmugam et al (2008)

4. SWOT Analysis on Machining Process of Alumina & Alumina Composites

Based on the literature survey of machining process of alumina & alumina composites the following points were drawn form of discussion on analysis Strength, Weakness, Opportunities & Threats (SWOT).

4.1. Strengths

Advanced ceramic material have superior properties such as high hardness and strength at elevated temperatures, chemical inertness, high wear resistance, low thermal conductivity, high strength to weight ratio, high corrosion resistance, oxidation resistance, lower thermal expansion coefficient, low density, high-temperature stability, light weight, high compressive strength, a stronger electromagnetic response than that of metals and good creep resistance due to this it is used as wide application.

4.2. Weakness

1. Ceramics are known as very difficult-to-machine materials. The main factors that cause ceramics to be difficult to machine are their high hardness, non-electrical conductivity and brittleness.
2. Ceramic components often to meet high demands for dimensional accuracy and surface quality.
3. Due to different material removing processes the various machining methods lead to different type material damage.
4. The tougher the material, the greater is the tool wear & lesser is the machining rates.
5. The ceramic material is more brittle in nature due to this the greater is the tendency for removal of debris by fracture.

4.3. Opportunities

1. Mechanical industries ceramic uses such in making seals, valves, aerospace, ballistic armor, ceramic composite automotive brakes, diesel particulate filters, a wide variety of prosthetic products, bearings, water pump seals, the adiabatic material of catalytic converters, roller followers, rotors, and cutting tools.
2. Electronic application such as substrate in hybrid circuits, piezo-ceramic sensors and next generation computer-memory.
3. Biomedical is making components such as artificial joints, bones, and teeth.

4.4. Threats

The characteristics of machining-induced damage depend also on the properties of the machined ceramic due to this reason it is impossible for machined ceramic material by using conventional machining process for that purpose only non-conventional process is only beneficial.

1. Conventional machining of ceramic is not only difficult but also costly attempt
2. Most of the ceramic parts shaped by sintering processes cannot meet the requirements of accuracy and surface quality. Therefore the machining and surface finishing of parts become necessary

5. Results & Observations

The Bar Chart Shows that numbers of papers published with respect to their Machining process. The Pie Chart shows that percentage of research conducted in different machining process on alumina ceramic materials.

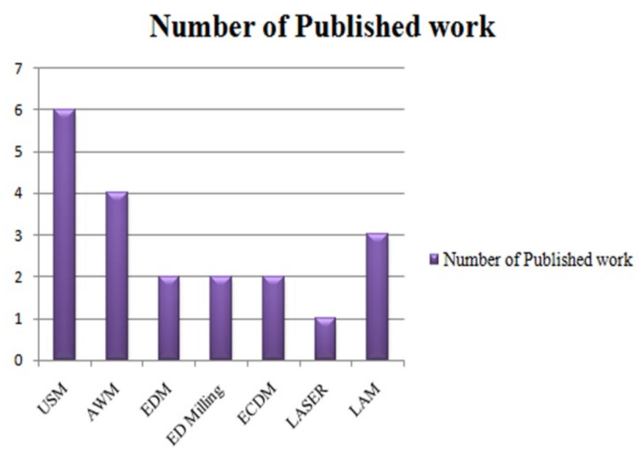

Figure 1. Distribution of the collected research papers for machining on Alumina ceramic materials

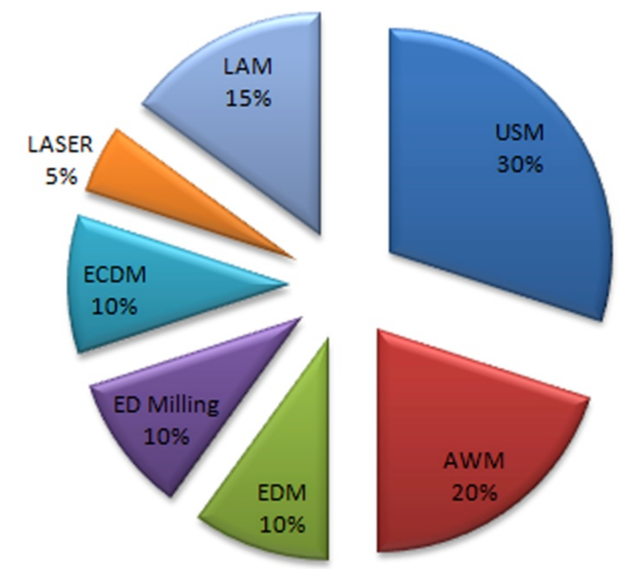

Figure 2. Percentage of Research conducted in different machining process on Alumina ceramic materials

6. Conclusion

1. The given literature review table 1 shows that machining of Al_2O_3 & Al_2O_3 composites by different machining process mechanism such that uses 30% of Ultrasonic Machining process, 20% of Abrasive Water-jet Machining process, 15% of Laser Assisted Machining process, 10% of Electro Discharge Machining process, 10% of Electro Discharge Milling & 10% of Electro Chemical Discharge Machining Process & 5% of Laser Machining.

2. Maximum authors put efforts to find output responses such as MRR, TWR, Ra & some of them find out Cutting force, Dimensional accuracy , Analysis of Depth of cut, Tool life ,surface integrity & also comparing different material results.

3. The review reveals that different authors use different machining process by taking different work-piece & tool materials & also taking different input & output parameters to find out optimum results.

Acknowledgements

This paper is a revised and expanded version of a paper entitled ‘A Review on machining process of alumina and alumina composite ceramics’ presented at International Conference on Industrial, Mechanical and Production Engineering: Advancements and Current Trends (ICIMPACT) held during 27th to 29th November 2014 in MANIT, Bhopal, India.

REFERENCES

[1] H Frei., G Grathwohl. Microstructure and strength of Advanced Ceramics after machining. ceramics International ,19,93-104, 1993

[2] Henrik Dam, Per Quist, Mads Peter Schreiber. Productivity surface quality & tolerances in ultrasonic machining of ceramics, Journal of Material Processing Technology, 51,358-368,1995

[3] Gi Sang Choi, Gi Heung Choi. Process analysis and monitoring in abrasive water jet machining of alumina ceramics. International Journal of Machine Tools & Manufacture, Vol -37, no.3, 295-307, 1997

[4] J. H. Zhang·, T. C. Lee band W. S. Lau Study on the electro-discharge machining of a hot pressed aluminum oxide based ceramic. Journal of Materials Processing Technology, 63, 908-912, 1997

[5] B. Bhattacharyya, B.N. Doloi, S.K. Sorkhel. Experimental investigations into electrochemical discharge machining (ECDM) of non-conductive ceramic materials. Journal of Materials Processing Technology, 95, (145-154), 1999

[6] Biing Hwa Yan, Che Chung Wang, Han Ming Chow, Yan Cherng Lin. Feasibility study of rotary electrical discharge machining with ball burnishing for Al_2O_3/6061Al composite. International Journal of Machine Tools & Manufacture, 40, 1403–1421, 2000

[7] Tai-Chiu Lee, Deng Jianxin. Ultrasonic erosion of whisker reinforced ceramic composites. Ceramics International, 27, 755–760, 2001

[8] B. Ghahramani, Z.Y. Wang. Precision ultrasonic machining process a case study of stress analysis of ceramic (Al_2O_3). International Journal of Machine Tools & Manufacture, 41, 1189 - 1208,2001

[9] Deng Jianxin, Lee Taichiu. Ultrasonic machining of alumina based ceramic composites, Journal of the European Ceramic

Society, 22,1235–1241,2002

[10] Chwan Huei Tsai, Hong Wen Chen. Laser milling of cavity in ceramic substrate by fracture-machining element technique. Journal of Materials Processing Technology, 136, 158–165 , 2003

[11] Manabu Wakuda, Yukihiko Yamauchi, Shuzo Kanzaki. The cutting performance in multipass abrasive waterjet machining of industrial ceramics, Journal of Materials Processing Technology, 132 ,177–183,2003

[12] J.wang , D.M. Guo. The cutting performance in multipass abrasive waterjet machining of industrial ceramics Journal of Materials Processing Technology, 133,371–377 , 2003

[13] Patrick A. Rebro ,Yung C. Shin, Frank P. Incropera Design of operating conditions for crackfree laser-assisted machining of mullite International Journal of Machine Tools & Manufacture 44, 677–694,2004

[14] Z.C. Li, Y. Jiao, T.W. Deines, Z.J. Pei, C. Treadwell Rotary ultrasonic machining of ceramic matrix composites feasibility study and designed experiments. International Journal of Machine Tools & Manufacture, 45, 1402-1411,2005

[15] Chih-Wei Chang, Chun-Pao Kuo Evaluation of surface roughness in laser-assisted machining of aluminum oxide ceramics with Taguchi method. International Journal of Machine Tools & Manufacture, 47,141-147,2007

[16] Chih-Wei Chang, Chun-Pao Kuo. An investigation of laser-assisted machining of Al_2O_3 ceramics planning. International Journal of Machine Tools & Manufacture,47,452-461,2007

[17] Sanjay K. Chak, P. Venkateswara Rao. Trepanning of Al_2O_3 by electro-chemical discharge machining (ECDM) process using abrasive electrode with pulsed DC supply. International Journal of Machine Tools & Manufacture,47,2061-2070,2007

[18] Y.H. Liu, X.P. Li, R.J. Ji, L.L. Yu, H.F. Zhang, Q.Y. Li. Effect of technological parameter on the process performance for electric discharge milling of insulating Al_2O_3 ceramic. Journal of Matl. Processing Technology , 208 , 245–250,2008

[19] Y.H. Liu, R.J. Ji, X.P. Li, L.L. Yu, H.F. Zhang, Q.Y. Li. Effect of machining fluid on the process performance of electric discharge milling of insulating Al_2O_3 ceramic. International Journal of Machine Tools & Manufacture,48, 1030–1035,2008

[20] D.K. Shanmugam, J. Wang, H. Liu. Minimisation of kerf tapers in abrasive waterjet machining of alumina ceramics using a compensation technique. International Journal of Machine Tools & Manufacture,48,1527-1534,2008