An Overview of Machining Process of Alumina and Alumina Ceramic Composites

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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 (Al2O3) 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 (Al2O3) 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]. Al2O3 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 Al2O3 & ZrO2 - Al2O3 using ultrasonic machining process & after that authors were found out for Al2O3 strengthening mechanism is depended on a direct correlation between roughness and strength: The lower, roughness the higher the strength. In case of ZrO2 - Al2O3 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 Al2O3 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 (Al₂O₃+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 Al₂O₃/6061Al 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 Al₂O₃ 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 Al₂O₃ 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 Al₂O₃ 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 Al₂O₃ 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

| 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%Al₂O₃ & ZrO₂ - Al₂O₃ (75.7% ZrO₂+ 4.2%Y₂O₃+20% Al₂O₃) 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 | Al₂O₃ 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 | $\text{Al}_2\text{O}_3$ 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-60-110 mm$^3$/s, Thickness of fracture-1.5-2.1 mm, RMS AE signal(0.1V/div) | GI SANG CHOI et al (1997) |
| 4       | Electro Discharge Machining | $\text{Al}_2\text{O}_3$+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 | $\text{Al}_2\text{O}_3$ 25mmX25mmX3mm | Copper of Ø 2mm | Electrolyte concentrations of 20%, 25% and 30% of NaOH, supply voltage-70 to 90V | MRR-(1.6×10$^4$) mg/min, Overcut | B. Bhattacharya et al (1999) |
| 6       | Rotary Ball Burnishing Electrical Discharge Machining | $\text{Al}_2\text{O}_3$/6061 Al 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-0.15-0.90 m/m, Ra-1.2-3.5 μm, ISR-55-92% | Biing Hwa Yan et al (2000) |
| 7       | Ultrasonic Machining | $\text{Al}_2\text{O}_3$/SiCw 3X4X36 (mm) | Mild Steel Ø5mm | Power-250W, Frequency-16-25kHz, Amplitude of vibration-5-20μm | MRR-0.60-1.65 m$^3$/min & Ra-0.4-0.8 μm | Tai-Chiu Lee and Deng Jianxin (2001) |
| 8       | Ultrasonic Machining | $\text{Al}_2\text{O}_3$ 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 | $\text{Al}_2\text{O}_3$/TiC,$\text{Al}_2\text{O}_3$/SiCw,$\text{Al}_2\text{O}_3$/TiB$_2$, Size- 3X4X36(mm) | Mild Steel Ø5 | Power-250W, Frequency-16-25kHz, Amplitude of vibration-5-20μm | MRR-0.4-1 mm$^3$/min, Ra-0.5-2μm | Deng Jianxin et al (2002) |
| 10      | Laser Machining (CO$_2$& Nd:YAG) | 99.6% $\text{Al}_2\text{O}_3$ 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 | $\text{Al}_2\text{O}_3$ alumina tiles | Jet pressure (MPa) -0.3, Jet distance (mm)-0.5, Nozzle (mm)-00.6, 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 | Al₂O₃ 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         | 3Al₂O₃-2SiO₂ 10.3 to 10.6 mm    | 1.5 kW CO₂ laser +60hp CNC 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      | Al₂O₃ 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         | Al₂O₃ 45×10× 10(mm)             | 25W (continuous wave) CO₂ 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         | Al₂O₃ 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,F ee d (mm/rev)-0.01-0.03 , Pulsed frequency (kHz)-30-50 | Ra (μm)-0.24-1.18, MRR (mm³/s) -1.5708-23.5619 | Chih-Wei Chang et al (2007) |
| 17     | Electro-Chemical Discharge Machining | Al₂O₃ 15×15×7mm³               | 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 Milling     | Al₂O₃ 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)-10 0-300, 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 Milling | $\text{Al}_2\text{O}_3$ 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 | $\text{Al}_2\text{O}_3$ 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 from discussion on analysis Strength, Weakness, Opportunities & Threats (SWOT).

4.1. Strengths

Advanced ceramic materials 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

![Bar Chart]

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

![Pie Chart]

6. Conclusion

1. The given literature review table 1 shows that machining of Al₂O₃ & Al₂O₃ 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.

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