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Trends in Removal Machining Technology for Silicon Nitride Ceramics in ball bearings

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Abstract

As advanced technology develops, high-functional ceramics are attracting attention as high-performance parts materials due to their excellent physical properties such as high strength, heat resistance, wear resistance, functional surface, and corrosion resistance. However, ceramics are brittle materials and are very difficult to machining, so there are many restrictions on making shapes by machining. In order to meet the demand for high-functional ceramics, ultra-precision machining and high-efficiency machining technologies are required. Silicon nitride ceramics are highly regarded as functional precision parts, but the process of making parts with high reliability and precision is never easy due to their unique characteristics of ceramics, brittleness. This review focuses on the latest convergence research incorporating optimization technology as well as ceramic machining technology that induces ductile fracture and identification of the microstructure failure mechanism in relation to the trend of removal machining technology, focusing on silicon nitride ceramics. The development of ceramic removal machining technology is essential for all ceramic materials, not just silicon nitride ceramics, to be widely applicable as functional high-tech materials.

Keywords: Silicon nitride; Ball bearings; Surface roughness; ELID grinding

Introduction

Silicon nitride has a relatively low density, high strength and hardness, excellent oxidation resistance, and low thermal expansion coefficient. It is widely used as an industrial material for mechanical structures used in high temperature and wear-resistant environments such as gas turbine engines, aerial parts, and ceramic ball bearings. In particular, silicon nitride ceramic ball bearings are highly useful for electric vehicles and aircraft due to their excellent wear resistance and insulation, but they require high shape precision and surface roughness to reduce dynamic noise and vibration. However, manufacturing bearings and other structural silicon nitride ceramic parts incur high processing costs, and surface defects with high uncertainty occur during traditional grinding and finishing processes. These defects cause a lack of reliability and shortening of life, limiting the wide application of silicon nitride ceramics. Advanced machining techniques to overcome these limitations are needed to increase the application of bearing and structural ceramics. This paper aims to review relevant studies in order to provide insights for researchers in establishing research directions for the high-precision machining of silicon nitride ceramic ball bearings, which are receiving increasing attention as recent functional materials with high electrical insulation properties. The goal is to contribute to the advancement of high-quality component manufacturing.

Grinding techniques for Silicon Nitride

Inasaki in 1987 described the characteristics and machining principles of hard and brittle materials. He explained the basic principles of grinding considering material properties and presented examples of precision grinding. In addition, a method for achieving high-efficiency grinding of ceramics with high hardness and strong brittleness was pro-posed [1]. In 1992, K. Kitajima et al. evaluated the grindability of ceramic materials by measuring the grinding force, energy, temperature and wheel wear, and inspecting the grinding surface and SEM images of the grinding swart. It was confirmed that Al2O3 showed the lowest grinding force, energy, temperature, and wheel wear compared to SiC and Si3N4 under the grinding conditions with the same removal rate. On the other hand, SiC was the best in terms of surface roughness because no any bulge formed on the side edges of streaks. It was confirmed that the grindability of ceramics is related to the mechanical behavior of the material at the grinding temperature [2]. In 1996, H. Ohmori et al. discussed the principles of ELID grinding technology in their paper, along with presenting the results of ELID grinding applied to silicon nitride ceramics. This investigation also examined the impact of mesh size, grinding speeds, and feed rate on surface finish. The technology is anticipated to find broad applications in industries such as optics and semiconductors, including mirror finishing of silicon wafers, various fine ceramics, ferrite, and glass [3]. In 2003, M. Rahman et al. conducted a study aimed at comprehending the fundamental attributes of Electrolytic In-Process Dressing (ELID) grinding and its impact on surface finish.

The investigation into ELID grinding revealed its high suitability for achieving nano-scale surface finishes on both metals and non-metals. The results demonstrated a noteworthy reduction in grinding force through the implementation of in-process dressing. The primary challenges encompass the absence of feedback mechanisms for regulating in-process dressing, the optimization of machining conditions, and the devel-opment of models for ductile mode grinding [4]. Conventional grinding technique is a very inexpensive process technology that produces materials in nanoscale form. M. Mar-tin-Gil et al. has applied a grinding process to evaluate the performance of silicon nitride ceramic electronic materials. Grinding technology was applied to reduce the surface particle size of silicon nitride ceramics used as cathodes in electrochemical cells from mi-crometer to nanometers. The effect of particle size manufactured through grinding on electrochemical properties was analyzed. it was confirmed that the electrochemical behavior of materials with nanometersized particles through grinding is increased by 34% compared to the existing materials, and the grinding surface affects the specific capacity of Si3N4. However, cycling behavior did not observe any noticeable changes through these nanotization [5]. In 2009, K. Katahira et al. described the highly efficient and precise Electrolytic In-Process Dressing (ELID) grinding method in their paper. They also discussed the ELID grinding process and the grinding characteristics of various ceramic materials. Their research findings indicated that ELID continuous grinding (ELID CG-grinding) can be effectively utilized to achieve improved surface roughness. The ELID grinding method can be employed to produce machined surfaces with desirable properties for hard AlN ceramics [6]. In 2016, W. Wijianto discussed silicon nitride ceramics in the context of their application to ball bearings. The surface finishing of ceramic bearings holds significant importance because silicon nitride, being a brittle material, has its strength limited by flaw sizes, particularly those present on the surface. Pores and surface flaws are the primary factors contributing to fracture initiation in silicon nitride ball bearings.

To minimize the surface flaws resulting from a coarse grinding process, it is recommended to reduce the material removal rate during the grinding process and eliminate grinding with coarse grit wheels [7]. In 2021, L. Yang et al. proposed a novel ELID power source with improved pulse generation and computer control for electrolysis time. This power source is designed to maintain a stable dressing current. It employs the superposition of large and small pulses to achieve periodic electrolysis and adjust the oxide layer state. The results demonstrate that the new ELID power source can sustain a stable grinding process and that the dressing current should be controlled based on the grinding wheel's grain size [8]. In 2022, S. M. Lee et al. applied the Electrolytic In-process Dressing (ELID) grinding processing method to silicon nitride ceramics used in ball bearings. The aim was to analyze and evaluate the surface processing characteristics and to investigate the influence of fracture toughness on surface processing. The results of fracture toughness and surface roughness tests indicated that silicon nitride ceramics with high fracture toughness exhibited excel-lent surface roughness when used for ball bearings. Therefore, it is inferred that an in-crease in the frequency of brittle fractures occurs when grinding materials with low fracture toughness, leading to an increase in surface roughness [9]. The remarkable excellence of ELID grinding as a machining technology capable of achieving surface quality and high efficiency on ceramic materials has been confirmed. To achieve even better improvements, it is necessary to understand and apply the fracture mechanism of ceramic materials, which would enable overcoming the limitations of brittle fracture observed in pro-cessing using fixed abrasive particles like grinding wheels with greater ease.

MFP Techniques for Silicon Nitride Ball Bearings

In 1996, N. Umehara et al. proposed a technique known as magnetic fluid polishing. Many studies on magnetic fluid grinding have been conducted focusing on the finishing process of silicon nitride ceramic bearing balls. developed a magnetic fluid grinding de-vice for roller finishing based on their experience with ball finishing devices. By applying it to Si3N4 rollers, excellent grinding surface, 5-10nm Ra was obtained, and at the same time, the effect of various abrasive materials and grain sizes on surface roughness and removal rate was studied with the aim of high material removal rate [10]. In 1998, H. S. Aum et al. conducted research focusing on developing a processing device for ceramic ball treatment using the magnetic fluid polishing method. As a result, a high-quality ceramic ball bearing processing device was successfully created. However, the challenge of enhancing the surface roughness of the treated ball remains unresolved. Future research will delve into this issue in detail, alongside efforts to enhance sphericity [11]. In 1998, M. Jiang et al. explored an alternative technology for finishing Si3N4 balls intended for use in hybrid bearing applications, employing the magnetic float polishing (MFP) process. The ultimate polishing of Si3N4 balls utilizing a softer abrasive like CeO2 yields a superior sur-face finish (Ra < 4nm, Rz < 0.04um) while maintaining an undamaged surface. The efforts was focused on increasing the batch size to enable the finishing of approximately a hundred balls per batch using next-generation equipment [12]. In 1999, R. Komanduri et al. proposed an alternative strategy for finishing ceramic balls, involving the integration of initial mechanical action with subsequent chemo-mechanical action. The magnetic float polishing (MFP) process can be considered a cost-effective method for finishing Si3N4 balls intended for bearing applications. A batch of balls can be completed within ap-proximately 16–20 hours, which is significantly shorter compared to the conventional polishing process that takes several weeks. The adoption of faster polishing times and the utilization of abrasives other than diamond would notably decrease the overall manufacturing costs of Si3N4 balls for bearing applications [13]. In 2000, K. Kida et al. investigated the surface crack growth behavior of a Si3N4 plate resulting from small pre-indentations during ball-on-plate contact. Cracks situated at the border of the contact area were observed, with minimal influence from fluid pressure due to "hydraulic pressure mechanisms." The growth behavior of these cracks was analyzed concerning calculated contact stresses and stress intensity factors under sliding-including-rolling contact and pure rolling contact conditions. The cracks were observed to propagate both parallel and perpen-dicular to the motion of the ball, indicating that their predominant propagation is driven by contact stresses at the border [14]. In 2003, B. Zhang et al. developed a magnetic fluid grinding method instead of the traditional V-groove lapping method with low productivity and applied it to silicon nitride ceramic balls. Based on a kinematic analysis of the spherical surface generation mechanism during polishing, it was suggested that ensuring uniform distribution of contact ground traces over the whole ball surface is key point in ultra-precision grinding of ceramic balls.

Dynamic analysis of the grinding system using four types of magnetic fluid supports was performed, and each performance was evaluated through a grinding experiment. Through such experiments, an attempt was made to analyze the ball grinding process in terms of mechanics to identify the mechanism of generating the spherical surface of the ball [15]. As stated in the review, while MFP is in-deed a technology capable of achieving an excellent surface for bearing balls, it has not provided a solution to the highlighted issue of excessive processing time that is often attributed to the limitations of the polishing process. In 2025, Kwak et al. conducted a study evaluating the surface roughness and material removal rate of ceramic bearing balls by simultaneously applying Magnetic Assisted Polishing (MAP) technology and met-al-bonded diamond wheels. The results confirmed that the pressing pressure of the wheel and its rotational speed significantly impacted surface quality. Using the #325 wheel, sur-face roughness was greatly improved during the first two hours, while with the #2000 wheel, lower rotational speeds and higher pressing depths (pressing pressure) were effective in enhancing the material removal rate. Notably, when a silicone pad was used, nano-level surface roughness (average 6.5nmRa, minimum 3.9nmRa) was achieved, meeting the G5 class specifications (<0.014μmRa) [16].

Hybrid Machining Techniques of Silicon Nitride

In 2006, N. Umehara et al. designed and constructed a novel apparatus intended for finishing large-sized or large-batch silicon nitride (Si3N4) balls using magnetic float polishing (MFP) technology for hybrid bearing applications. The developed magnetic float polishing apparatus, employing a self-aligning method, has proven to be effective in achieving polished surfaces for Si3N4 balls intended for bearing applications across a wide range of sizes. It is hoped that this information will contribute to making the polishing process for advanced bearing applications involving silicon nitride balls more precise and less reliant on artistic skill [17]. K. Mohammadali et al. conducted a study on La-ser-Assisted Micro-Grinding (LAMG) for silicon nitride in 2019. The experiments have shown that grinding force can be reduced by up to 60% compared to Conventional Micro-Grinding (CMG), and that the actual cutting depth using CMG was 30% lower than the nominal cutting depth, but when using LAMG, the total nominal cutting depth was removed from the material. However, the quality of the surface roughness, that is, the ground surface, was very inferior to CMG. As a result, LAMG can improve the efficiency and accuracy of the micro-grinding process by combining the micro-grinding and laser structure of a workpiece or grinding tool, but the quality of the ground surface is rather inferior to that of CMG [18]. Ultrasonic Assisted Grinding (UAG) is a convergence machin-ing technology that has long been attracting attention as effective in high-efficiency machining of hard-to-machining materials. B. Mohammad et al. presented a theoretical model in 2020 to predict the grinding force during ultrasonic application grinding for silicon nitride ceramics. Since ductile and brittle fractures coexist in the process of machining materials, it is meaningful to present a model considering their combination. The ex-perimental results showed that adding ultrasonic vibration to the grinding process re-duced grinding force by up to 64%, and that the suggested model presented based on both ductility and brittle cutting matched the experimental results well at an average error of 17.27%.

In addition, it was confirmed that the ultrasonic vibration frequency does not affect the grinding force, and the grinding force decreases nonlinearly as the amplitude in-creases [19]. Longitude torsional ultimate grinding (LTUG) has been developed as a machining method to achieve high-quality and high-efficiency machining of hard-to-machining ceramic materials. However, it is difficult to accurately implement a high-quality processed surface due to random factors such as irregular shape, protrusion height, inter-particles spacing on the grinding wheel, and precise and accurate control of ultrasonic vibration. Z. Zhang et al. proposed a stochastic algorithm for the height (HRMS) of materials that remain on the surface with complex surface properties caused by various random factors during LTUG processing for silicon nitride ceramics. In addition, the ground surface was analyzed to set a prediction model for surface roughness and 3-D surface shape. Simulation and experimental results have shown that the HRMS algorithm and prediction model can realistically predict the general characteristics of process parameters and ground surfaces, and the consistency of the surface roughness prediction model was very high at 0-14.07% [20].

Optimization of Machining Process

Recently, process optimization has been attempted for high-quality machining of rough materials such as silicon nitride ceramics. As a first example, in 2017, J. Juntao et al. used a neural network model to optimize the grinding process. They built a BP neural network model between grinding process parameters such as spindle speed, cutting depth, feed rate, grit size of diamond particles, grit concentration, and binder types, and ground surface conditions. Due to the complex nonlinear relationship between the ground surface and grinding process parameters, calculations by standard BP algorithms and improved BP algorithms in terms of momentum are not converged, so an improved BP algorithm based on Powell method was proposed to calculate the weights and thresholds [21]. In addition, there is a case of developing a neuro fuzzy inference system prediction model for MQL process optimization. It is confirmed that the use of nanofluids in the MQL process greatly reduces grinding force and helps improve both tool life and surface quality. In 2019, Y. Dambata et al. presented a theoretical model for predicting grinding force and surface quality in the grinding process of advanced engineering materials, as silicon nitride.

An adaptive Neural Fuzzy Inference System (ANFIS) prediction model has been proposed to analyze and predict the effects of each process variable on grinding force, surface and subsurface quality [22]. In 2020, X. L. Xiao et al. proposed a novel finishing method called clustered magnetorheological finish (CMRF) to enhance the surface finish of silicon nitride ($Si3N4$) balls with ultra-fine precision. The modeling and simulation of CMRF displayed visualized traces and distributions of contact points using various polishing parameters. The distribution of contact points in different sections revealed uniform distribution when the machining gap, rotation speed, and eccentricity of the polishing plates were appropriately chosen [23]. The research on process optimization, as de-scribed, is gaining attention as a technology that can contribute to realizing the full potential of machining techniques up to their maximum limits. The recent significant ad-vancements in technologies such as artificial neural networks and AI are expected to play a substantial role in achieving process optimization for manufacturing.

Study on Grinding Wheel

Materials with high hardness and strong brittleness, such as ceramics, require metal binder diamond tools with excellent bonding strength and high hardness because they seriously wear of particles and easily pull out of particles from tool during grinding. Metal binder of wheels are generally based on alloys composed of Fe, Co, Ni, Cu, Sn, Zn, or Cr, but binders with high heavy metal concentrations are hazardous to the environment and threaten the health of operators. J. Peng et al. proposed and compared two metal binders, NiAl and FeAl, which are environmentally friendly and light based on intermetallic bonding. To confirm the tribology behavior of NiAl and FeAl for Si3N4 ceramic balls, the effect of sintering temperatures on the microstructure and mechanical properties of NiAl and FeAl was investigated, and the grinding performance of sintered diamond tools was also compared. The relative density of sintered NiAl was higher than that of FeAl, while the Vickers hardness and flexural strength of NiAl were lower than that of FeAl, and in the wear resistance experiment, NiAl showed higher wear resistance to compared to FeAl. On the other hand, FeAl-binding diamond tools showed a higher grinding rate than NiAl-binding diamond tools due to enhanced self-sharpening ability. It has been con-firmed that both NiAl and FeAl-based diamond wheels can be effectively used to grinding of silicon nitride ceramics [24].

Loading phenomenon in grinding process increases grinding resistance and interferes with the protrusion of grinding particles to induce brittle destruction of ceramic materials, which is the main cause of deterioration of the ground surface and chipping. S. Serge et al. conducted a study on silicon nitride by conducting touch-dressing and laser-structuring on grinding tools to analyze differences with non-dressed tool and non-structured tool and compare their effects. It was confirmed that touch-dressing affects cutting power and surface roughness during micro-grinding ac-cording to the overlap ratio and speed ratio of the dressing. Through experiments, it was confirmed that touch-dressed tool improves the ground surface by reducing the grinding force and the chattering pattern. It was confirmed that the laser-structured tool increased the material removal rate by up to 98%, greatly improved the geometric accuracy of the processed workpiece, and also increased the tool life [25]. While tool development is often perceived as a subset of machining technology advancement, it holds a significance as one of the most practical and directly applicable solutions in the manufacturing field.

Conclusion

High-quality machining of ceramics requires very difficult technologies, but more advanced technologies are emerging due to understanding the material removal mechanism and accumulating various experimental data. Ceramic materials will continue to be developed as high-tech materials, and high-efficiency high-quality machining technologies can be solved by optimizing grinding processes, developing advanced grinding wheels, developing advanced hybrid machining technologies, and developing a dedicated machine for ceramics and so on. The remarkable development of AI technology, coupled with high-quality material removal machining, is expected to be one of the solutions for effectively machining these hard-to-machine materials, such as ceramics.

References

1. Inasaki I (1987) Grinding of Hard and Brittle Materials, CIRP Annals 36(2): 463-471.
2. Kitajima K, Cai G Q, Kurnagai N, Tanaka Y, Zheng H W (1992) Study on Mechanism of Ceramics Grinding, CIRP Annals 41(1): 367-371.
3. Ohmori H, Takahashi I, Bandyopadhyay B P (1996) Ultra-Precision Grinding of Structural Ceramics by Electrolytic In-Process Dressing Grinding, Journal of Materials processing technology 57(3-4): 272-277.
4. Rahman M, Kumar A S, Lim H S, Fatima K (2003) Nano finish grinding of brittle materials using electrolytic in-process dressing (ELID) technique, Sadhana 28: 957-974.
5. Martín-Gil M, Rabanal M E, Várez A, Kuhn A, García-Alvarado F (2003) Mechanical grinding of Si3N4 to be used as an elec-trode in lithium batteries, Materials Letters 57(20): 3063-3069.
6. Katahira K, Ohmori H, (2009) Nano level surface finishing technology of advanced ceramics, Építöanyag 61(4): 114-117.
7. Wijianto W (2016) Application of Silicon Nitride (Si3N4) Ceramics in Ball Bearing, Media Mesin: Majalah Teknik Mesin 15(1): 17-25.
8. Yang L, Ren Ch, Jin X (2021) Experimental Study of ELID Grinding Based on The Active Control of Oxide Layer, Journal of Materials processing technology 210(13): 1748-1753.
9. Lee S M, Kim H N, Ko J W, Kwak T S (2022) Effect of Fracture Toughness on Surface Roughness in ELID Grinding of Silicon Nitride Ceramics for Ball Bearings, Journal of the Korean Society of Manufacturing Process Engineers 21(12): 94-99.
10. Umehara N, Komanduri R (1996) Magnetic fluid grinding of HIP-Si3N4 rollers, Wear 192(1-2): 85-93.
11. Aum H S, Roh B O, Lee S W, Jang T S (1998) Development of Machining Apparatus for Ceramic Ball Bearing, Transactions of the Korean Society of Mechanical Engineers A 22(3): 545-553.
12. Jiang M, Komanduri R (1998) On Finishing of Si3N4 Balls for Bearing Applications, Wear 215(1-2): 267-278.
13. Komanduri R, Hou Z B, Umehara N, Raghunandan M, Jiong M, et al. (1999) A “Gentle” Method for Finishing Si3N4 Balls for Hybrid Bearing Applications, Tribology Letters 7: 39-49.
14. Kida K, Ogura K (2000) Surface crack growth behavior on Si3N4 under ball-on-plate contact in the near border of contact area, A Hen/ Transactions of the Japan Society of Mechanical Engineers, Part A, 66(645): 901-908.
15. Zhang B, Nakajima A (2003) Dynamics of magnetic fluid support grinding of Si_3N_4 ceramic balls for ultraprecision bearings and its importance in spherical surface generation, Precision Engineering 27(1): 1-8.
16. Han S Y, Lee S M, Kim H N, Ko J W, Kwak T S (2025) Application of Magnetic-Assisted Polishing Using Metal-Bonded Grinding Wheels for Machining Silicon Nitride Ball Bearings, materials 18(3): 677.
17. Umehara N, Kirtane T, Gerlick R, Jain V K, Komanduri R (2006) A New Apparatus for Finishing Large Size/Large Batch Silicon Nitride (Si_3N_4) Balls for Hybrid Bearing Applications by Magnetic Float Polishing (MFP), International Journal of Machine Tools and Manufacture 46(2): 151-169.
18. Mohammadali K, Sergey S, Babak S, Amir D, Bahman A (2019) Laser-assisted micro-grinding of Si3N4, Precision Engineering 60: 394-404.
19. Mohammad B, Saeid A (2020) Mathematical model to predict cutting force in rotary ultrasonic assisted end grinding of Si_3N_4 con-sidering both ductile and brittle deformation, Measurement 156: 107586.
20. Zhang Z, Shi K, Huang X, Shi Y, Zhao T, et al. (2022) Development of a probabilistic algorithm of surface residual materials on Si3N4 ceramics under longitudinal torsional ultrasonic grinding, Ceramics International 48(9): 12028-12037.
21. Jing J, Feng P, Wei S, Zhao H (2017) Investigation on surface morphology model of Si_3N_4 ceramics for rotary ultrasonic grinding machining based on the neural network, Applied Surface Science 396: 85-94.
22. Dambatta Y S, Sayuti M, Sarhan A D, Hamdi M, Manladan S M, et al. (2019) Tribological performance of SiO2-based nanofluids in minimum quantity lubrication grinding of Si_3N_4 ceramic, Journal of Manufacturing Processes 41: 135-147.
23. Xiao X L, Li G X, Mei H J, Yan Q S, Lin H T, et al. (2020) Polishing of Silicon Nitride Ceramic Balls by Clustered Magnetorheological Finish, Micromachines 11(3): 304.
24. Peng J, Zhang F, Huang Y, Liu J, Li K, et al. (2021) Comparative study on NiAl and FeAl intermetallic-bonded diamond tools and grinding performance for Si_3N_4 ceramic, Ceramics International 47(23): 32736-32746.
25. Serge S, Bahman A, Ali Z (2023) Impact of the touch dressing and laser structuring of electroplated grinding pins on mi-cro-grinding of Si_3N_4, CIRP Journal of Manufacturing Science and Technology 41: 44-54.