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Trends of Removal Machining Technology of Silicon Nitride Ceramics

Seung Min Lee and Tae Soo Kwak*

Gyeongsang National University, Korea

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***Corresponding author:** Tae Soo Kwak, Gyeongsang National University, Korea Email: tskwak@gnu.ac.kr

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. Therefore, 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.

Mechanism of Ceramics Grinding

I. 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 proposed [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 swat. It was confirmed that Al_2O_3 showed the lowest grinding force, energy, temperature, and wheel wear compared to SiC and Si_3N_4 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].

Application of Grinding Techniques for Silicon Nitride Ceramics

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. 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 device for roller finishing based on their experience with ball finishing devices. By applying it to Si_3N_4 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 [3]. 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 [4]. Conventional grinding technique is a very inexpensive process technology that produces materials in nanoscale form. M. Martin-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 micrometer 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 nanometer-sized particles through grinding is increased by 34% compared to the existing materials, and the grinding surface affects the specific capacity of Si_3N_4. However, cycling behavior did not observe any noticeable changes through these nanotization [5].

Optimization of Grinding 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 [6]. 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 [7].

Hybrid Grinding Techniques of Silicon Nitride

K. Mohammadali et al. conducted a study on Laser-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 [8]. Ultrasonic Assisted Grinding (UAG) is a convergence machining 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 experimental results showed that adding ultrasonic vibration to the grinding process reduced 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 increases [9]. 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 has 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% [10].

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

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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 Si_3N_4 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 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 confirmed that both NiAl and FeAl-based diamond wheels can be effectively used to grind silicon nitride ceramics [11]. The 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 between 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 according 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 [12].

Conclusion

As we have seen, 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 is expected to be one of the solutions for the effective machining of these hard-to-machining materials like ceramics.

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