*Review*

# A Review of Ultrasonic Vibration-Assisted Grinding for Advanced Materials

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**ABSTRACT:** Ultrasonic vibration-assisted grinding (UVAG), which superimposes high-frequency, micro-amplitude ultrasonic vibration onto conventional grinding (CG), offers several advantages, including a high material removal rate, low grinding force, low surface roughness, and minimal damage. It also addresses issues such as abrasive tool clogging, thereby enhancing machining efficiency, reducing tool wear, and improving the surface quality of the workpiece. In recent years, the rapid development of advanced materials and improvements in UVAG systems have accelerated the progress of UVAG technology. However, UVAG still faces several challenges in practical applications. For example, the design and optimization of the ultrasonic vibration system to achieve high-precision, large-amplitude, and high-efficiency grinding remain key issues. Additionally, further theoretical and experimental studies are needed to better understand the material removal mechanism, the dynamics of grinding force, abrasive tool wear, and their effects on surface quality. This paper outlines the advantages of UVAG in machining advanced materials, reviews recent progress in UVAG research, and analyzes the current state of ultrasonic vibration systems and ultrasonic grinding characteristics. Finally, it summarizes the limitations of current research and suggests directions for future studies. As an emerging machining technology, UVAG faces challenges in many areas. In-depth exploration of the theoretical and experimental aspects of high-precision, large-amplitude, and high-efficiency ultrasonic vibration systems and UVAG is essential for advancing the development of this technology.

**Keywords:** Ultrasonic vibration grinding; Advanced materials; Ultrasonic vibration system; Machining characteristics; Surface quality



## 1. Introduction

Advances in manufacturing technology and materials science have driven the widespread use of advanced materials with high hardness, wear and heat resistance in aerospace, medical devices and automotive manufacturing (e.g., titanium alloys, carbon fibre-reinforced composites for the aerospace industry, zirconium oxide bioceramics, silicon carbide semiconductor materials, *etc.*) [1,2]. In the aerospace field, the use of advanced materials such as titanium alloys, nickel-based high-temperature alloys, and ceramic matrix composites not only reduces structural weight and improves structural efficiency but also meets the requirements for the use of high-temperature parts and achieves high resistance to corrosion and long service life. In the automotive industry, the use of advanced materials helps reduce vehicle weight, lower fuel consumption, enhance power transmission, and minimize noise and vibration. In the medical field, titanium alloys and zirconia bioceramics are valued for their excellent biocompatibility, strong mechanical properties, and corrosion resistance. These materials are widely used in artificial joints, such as hip and knee replacements, orthopaedic implants, and dental implants.

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Advanced materials have excellent combined physicochemical and mechanomechanical properties and are also typically difficult to machine. For example, most advanced materials, such as titanium alloys and high-temperature alloys, are first manufactured by precision casting, and then the excess material is removed by machining operations [3]. In order to meet the needs of high-end fields, grinding as a precision machining process occupies an important position in the machining and manufacturing of critical precision parts of advanced materials. In order to improve the surface quality and shape or dimensional accuracy, grinding of parts is required. During the grinding process, each grit removes a small amount of material from the workpiece. This removal pattern helps to improve the work surface finish and shape or dimensional accuracy. However, advanced materials with high hardness and wear resistance are known to have poor grindability, resulting in high cost and low efficiency of current grinding methods [4]. Excessive grinding force, high grinding temperature and severe wear of abrasive tools usually occur when grinding advanced materials by conventional machining methods. Numerous scholars have continuously improved on the basis of traditional grinding and proposed some new special processing methods, among which UVAG has become a very important processing means. Ultrasonic vibration-assisted grinding refers to the application of high-frequency vibration on the grinding tool or workpiece to change the material removal mechanism, reduce the grinding force and grinding heat, and thus improve the quality of the machined surface [5].

At present, ultrasonic vibration-assisted grinding has been widely used in advanced materials such as ceramic materials, composite materials and high-temperature alloys. Therefore, it is necessary to conduct further research on the grinding mechanism and grinding effect of ultrasonic vibration-assisted grinding of advanced materials. The structure and parts of this review are shown in Figure 1. The main purpose of this paper is to systematically review and analyze the current status of ultrasonic vibration-assisted grinding technology in advanced material processing. This article provides a detailed discussion of the basic principles of ultrasonic machining, ultrasonic vibration systems, classification of ultrasonic vibration, ultrasonic machining characteristics, and machining effects, aiming to provide theoretical insights and practical references for future research and engineering applications.

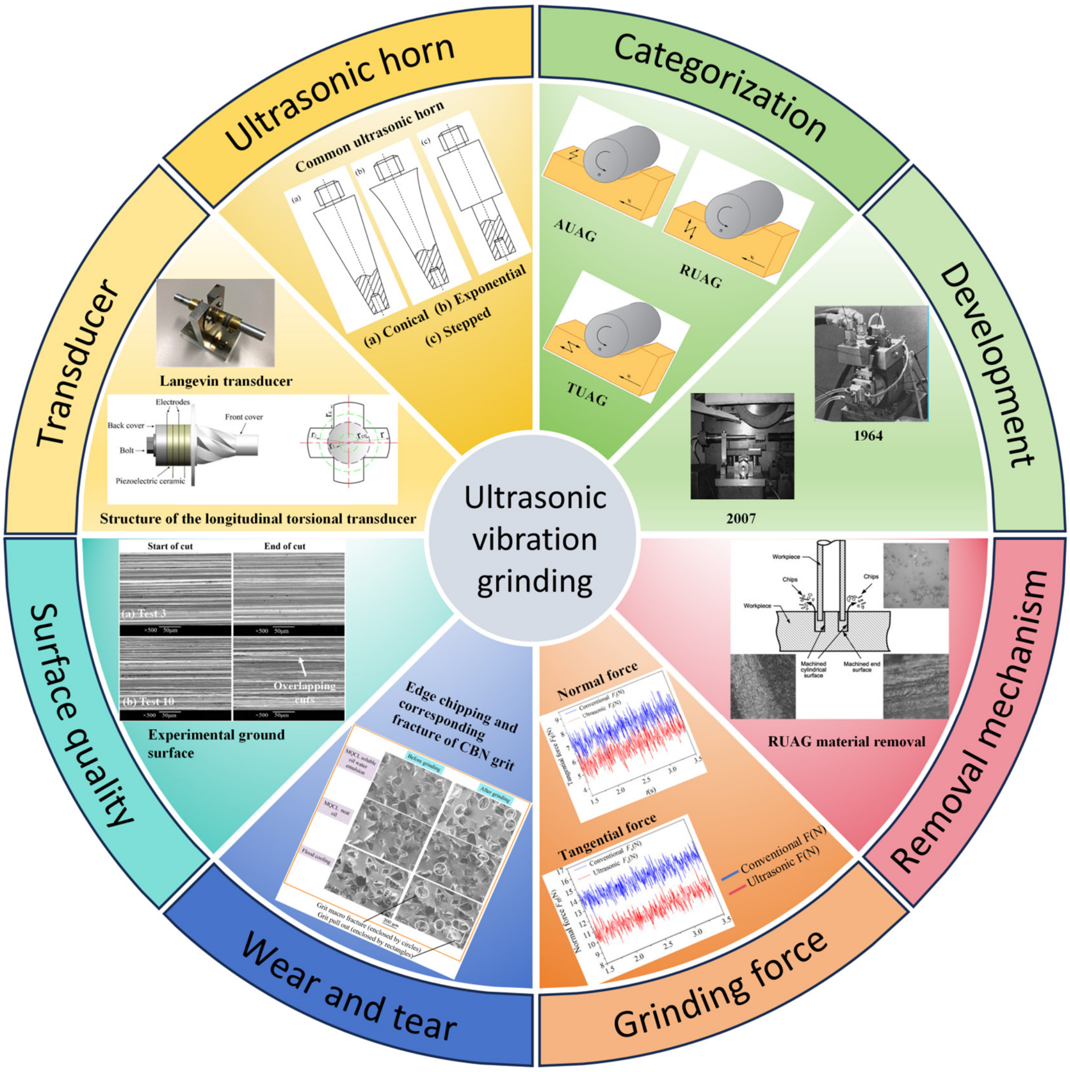


**Figure 1.** The main content of this paper.

## 2. Limitations of Conventional Grinding of Advanced Materials

In addition to its development, the rapid progress of advanced materials is another key factor driving the advancement of UVAG. Numerous studies have investigated the machining performance of various advanced materials, including optical glass (e.g., zirconia, quartz glass, sapphire crystal, and SiC), metal alloys (e.g., titanium alloys, Inconel 718, and aluminum alloys), and composites (e.g., CFRP and ceramic matrix composites) using UVAG. However, few studies have comprehensively classified and analyzed these materials based on their properties, vibration modes, and machinability. In addition, these materials are widely used in biomedical, optical, aerospace, and semiconductor applications due to their excellent physical, chemical, and mechanical properties. Research on advanced materials has revealed that existing studies have focused on cutting characteristics, cutting forces, surface quality and sub-surface damage. UVAG has significant advantages over CG, and UVAG can be an effective alternative for machining optical, semiconductor, aerospace and biomedical materials. Conventional grinding processes face many problems when machining advanced materials:

(1) The high cutting force generates significant heat accumulation during the grinding process, especially when grinding alloy materials, where the abrasive grains frequently undergo sliding, ploughing, and cutting actions. On one hand, the grinding force increases substantially due to the intense extrusion of the abrasive grains against the workpiece surface in a very short time. On the other hand, the energy dissipated during the grinding process is primarily converted into heat and transferred to the workpiece. However, the poor thermal conductivity of alloys exacerbates the formation of temperature gradients on the grinding surface, leading to thermal damage and deformation of the workpiece.

(2) Due to the significant work-hardening characteristics of the material, the wear rate of the tool during the grinding process increases substantially. At the same time, the material's relatively low surface hardness, poor surface tribological properties, and high chemical activity make it prone to adhering to the grinding wheel grits, which seriously limits the improvement of machining accuracy and the optimization of economic efficiency.

(3) Poor surface quality, the root cause of the grinding process in the surface layer of the temperature gradient, is significant, especially when the surface temperature is too high. It is very easy to trigger the grinding surface morphology deterioration, organizational transformation and other burns. When the grinding surface suffers from serious burns, it will further lead to the surface layer by the organizational transformation, plastic deformation and other induced residual stress, microcracks and other thermal damage defects, thus seriously affecting the final quality of the grinding surface.

According to Figure 2A, Guo et al. [6] found that the normal and tangential forces measured for processing TC4 alloy under normal grinding conditions were 5–21 N/mm and 3–14 N/mm, respectively, which were about 1.5 to 2 times that of 45 steels. Titanium alloy's high strength caused by material deformation resistance is one of the main reasons for the above phenomenon. Another important reason is that titanium alloy has a low modulus of elasticity (about half that of steel), which causes material deformation during the cutting process, thereby increasing the actual contact area between the abrasive particles and the workpiece, leading to higher friction. High grinding temperature is another significant feature of the grinding process of titanium materials. According to Figure 2C, Hood et al. [7] conducted a grinding study on two titanium alloys of γ-TiAl and BuRTi. When smaller grinding parameters are used, the two titanium alloys are able to obtain a machined surface without any burns and cracks, and at higher wheel speeds, all of the surface of the machined material appears to have varying degrees of burns, and in the case of the γ-TiAl machined surface, more extensive cracks appear on the surface. More extensive cracks appeared on the machined surfaces, and the increase in grinding depth and feed only exacerbated this result to some extent. According to Figure 2B, Li et al. [8] conducted a study on deep-cut grinding of (TiCp+TiBw)/Ti-6Al-4V using white alumina (WA), pink fused alumina (PA) and microcrystal corundum (SG) abrasive wheels. They found that the grinding force was highest with the WA wheel, followed by the PA wheel, and lowest with the SG wheel. Additionally, they observed significant adhesion to the grinding wheel when using the WA and PA wheels, while almost no material adhered to the SG wheel.

In traditional grinding, the inherent properties of titanium alloys, such as low thermal conductivity, high strength at elevated temperatures, and high elemental activity of titanium, result in challenges like high grinding temperatures, high grinding forces, low machining efficiency, and susceptibility to thermal damage (e.g., burns and microcracks) on the surface after grinding. Additionally, grinding wheel clogging and high machining costs are significant issues [9]. These factors severely hinder the development and application of titanium alloy precision parts. To bridge the gap between the growing demand for titanium alloy precision parts and the limitations of traditional grinding, a new specialized machining method is required; ultrasonic vibration-assisted grinding (UVAG) has emerged as a critical technology in this context. Further research is needed to explore the grinding mechanisms and effects of UVAG when applied to titanium alloys.

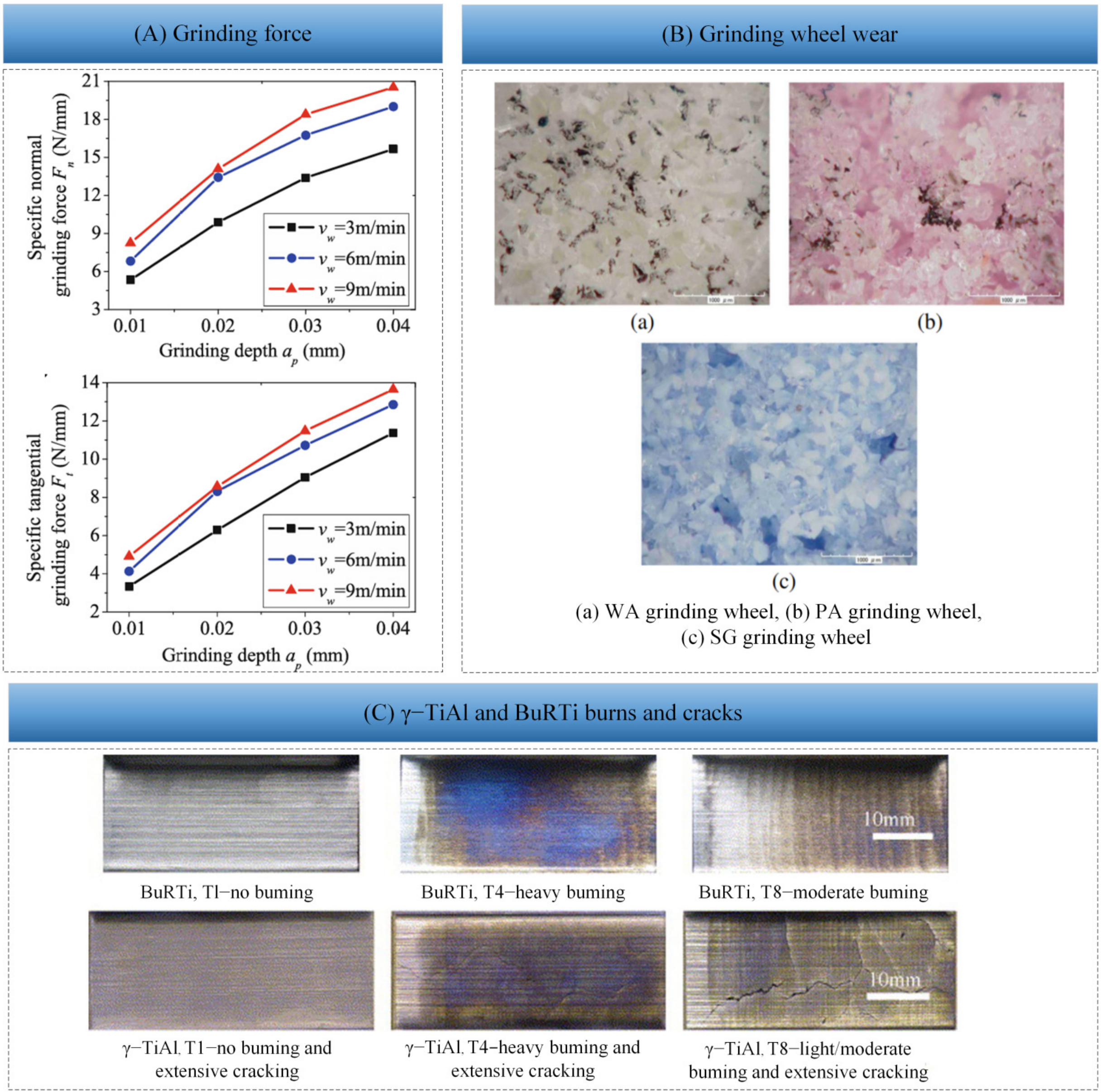


**Figure 2.** Current status of research on conventional grinding of titanium alloys [6–8].

## 3. Classification of Ultrasonic Vibration-Assisted Grinding

Ultrasonic vibration-assisted grinding machining technology is a composite machining method in which ultrasonic vibration is superimposed on the workpiece material removal process [10,11]. By changing the contact state between the abrasive grain and the workpiece, the machining efficiency and quality can be improved. In the ultrasonic-assisted machining process, the solidified diamond tool (electroplated or sintered diamond tool) is subjected to ultrasonic vibration while rotating at a certain speed, and the workpiece material is processed with a uniform feed or constant-pressure feed, which will force the abrasive grains in the tool to continually impact and scratch the surface of the workpiece, and to crush the workpiece material into very small particles for removal, so as to improve the machining efficiency. The rotational motion of the tool in ultrasonic vibration-assisted grinding increases the material removal rate, improves the accuracy of the machined workpiece, reduces the cutting forces and prolongs the tool's life [12].

### *3.1. One-Dimensional Ultrasonic Vibratory Grinding*

According to Figure 3, ultrasonic vibration-assisted grinding technology is currently categorized into one-dimensional and two-dimensional vibration methods. It is also classified based on the ultrasonic source, with distinctions made between workpiece ultrasonic vibration and tool ultrasonic vibration. In the workpiece ultrasonic vibration, according to the different vibration directions, its one-dimensional vibration can be divided into vibrations along the axial, the tangential, and the radial. Although the fundamentals of tool trajectories in conventional and ultrasonic vibratory machining are similar, the actual differences in abrasive grain trajectories between these two methods are significant. These differences have significant effects on the machining process and its results [13]. Currently, the results of many recognized studies confirm that these effects are generally positive. In other words, in most cases, the unique tool motion trajectory produced by ultrasonic vibratory machining contributes to improved machining quality. Some scholars have analyzed in detail the influence mechanism of three directions of ultrasonic vibration on the grinding process, kinematic properties, material removal, and surface generation. The three directions of ultrasonic vibration showed obvious differences in the reduction of grinding force, with tangential vibration showing the worst performance. In terms of the effect on surface roughness, axial ultrasonic vibration generates intersecting grinding traces with significantly lower surface roughness than normal grinding. And both radial ultrasonic vibration and tangential ultrasonic vibration will make the surface deteriorate to some extent. Wen et al. [14] further stated that radial ultrasonic vibration may deteriorate surface quality and increase surface roughness compared to axial ultrasonic vibration. Radial ultrasonic vibration is more effective in reducing the ultrasonic grinding force, but it slightly reduces the surface quality and is more suitable for grinding hard and brittle materials. For tangential vibration, it is mainly used for deep, slow feed grinding and other conditions of slow wheel speed, and will also deteriorate the surface quality to a certain extent, and need to make an appropriate selection of processing parameters. While axial ultrasonic vibration can effectively improve the surface roughness and also reduce the grinding force.

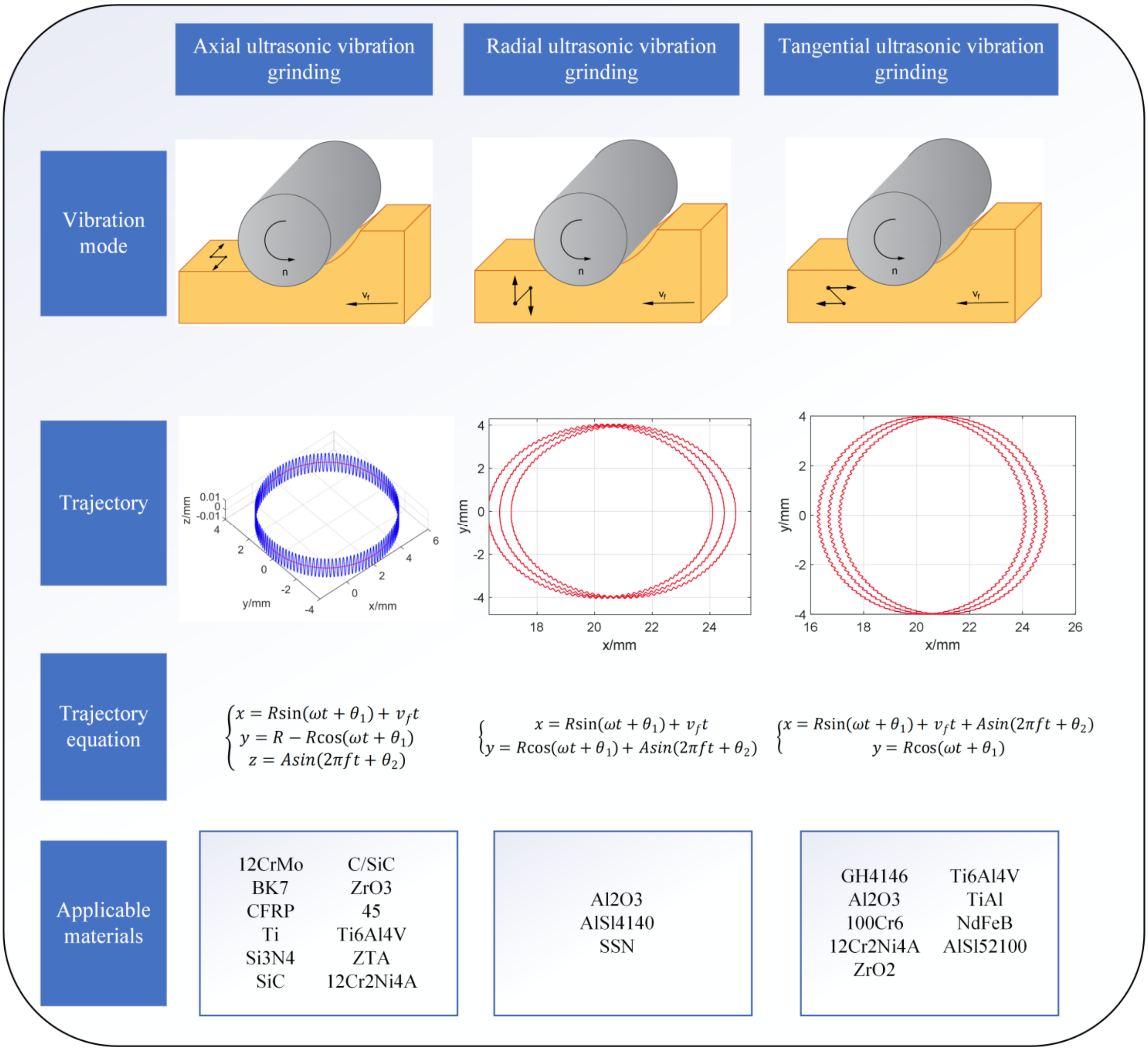


**Figure 3.** Classification of 1D ultrasonic vibration-assisted grinding [10–14].

### *3.2. Two-Dimensional Ultrasonic Vibratory Grinding*

Compared to sinusoidal ultrasonic vibration machining, two-dimensional ultrasonic vibration machining was born later. Two-dimensional vibration can be divided into two-dimensional elliptical ultrasonic vibration parallel to the surface of the workpiece and elliptical ultrasonic vibration parallel to the end face of the grinding wheel. The main value of two-dimensional elliptical ultrasonic vibration is to improve the material removal rate, but in terms of machining performance, elliptical ultrasonic vibration has a greater advantage. As shown in Figure 4, Wang et al. [15] used two-dimensional elliptical ultrasonic vibration for grinding fibre-reinforced composites (CFRP) and found that applying ultrasonic vibration to perpendicular and parallel workpiece surfaces altered the tool paths. This change in tool paths affected the chip formation process, resulting in reduced friction and frictional thrust components. Consequently, the friction generated during elliptical ultrasonic vibratory grinding was significantly lower than that produced during one-dimensional ultrasonic vibratory grinding [15–17]. In addition, elliptical ultrasonic vibratory grinding exhibits less cutting force or surface roughness during machining [18], lower tool temperature [19], and milder tool wear [20]. Liang et al. [21,22] found that applying ultrasonic vibratory grinding to the workpiece in both the axial and radial directions of the grinding wheel can simultaneously achieve efficient, high-quality, and low-damage machining of hard and brittle materials, based on a comprehensive consideration of the machining characteristics of axial vibratory grinding and radial vibratory grinding. Some scholars have applied axial and radial two-dimensional ultrasonic vibration to the grinding wheel and simulated the ultrasonic vibration grinding of three-dimensional surface micro-morphology. The ultrasonic grinding tests on monocrystalline silicon, compared with conventional grinding results, demonstrate that two-dimensional ultrasonic vibration significantly reduces surface roughness, lowers grinding force, increases the proportion of ductile material removal from the workpiece surface, and greatly improves surface quality. These findings confirm that two-dimensional ultrasonic vibration-assisted grinding can achieve more efficient and higher-quality processing of single-crystal silicon. Compared with one-dimensional ultrasonic processing technology, two-dimensional ultrasonic technology can further improve the effect of ultrasonic processing, which is also an important direction of current research.

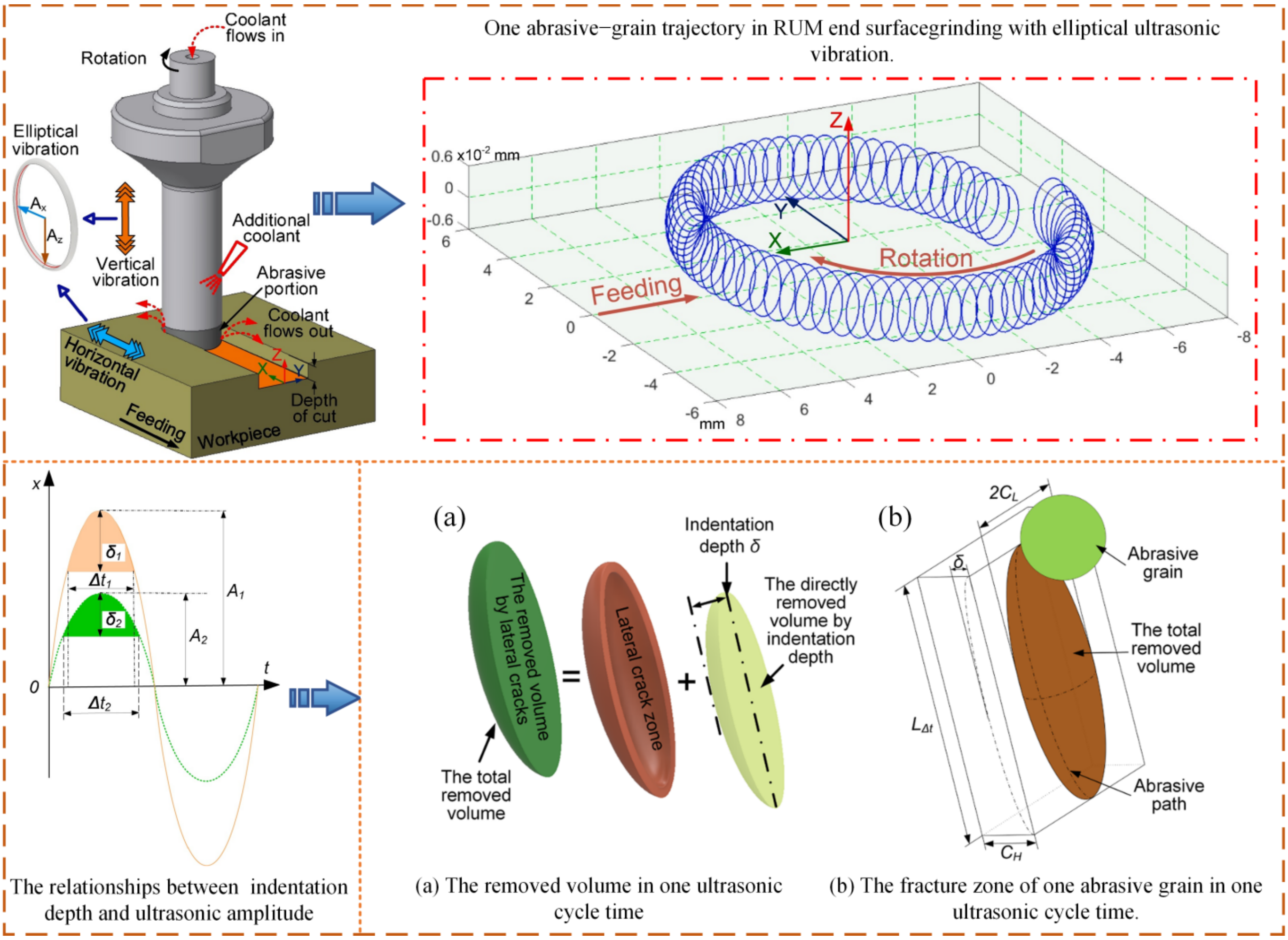


**Figure 4.** 2D elliptical ultrasonic vibration-assisted grinding [15].

Ultrasonic grinding processing inherits the advantages of traditional ultrasonic machining and grinding, while also offering unique benefits. First, it significantly reduces cutting force while increasing the material removal rate. Second, the combined effect of ultrasonic vibration and tool rotation effectively removes debris, preventing scratches on the processed surface, thereby improving both machining efficiency and accuracy. Third, the intermittent grinding action creates numerous micro-pits on the workpiece surface, which helps prevent workpiece adhesion during the friction process. Additionally, this action allows the coolant to more effectively reach the machining area, reducing the risk of tool wear due to high temperatures and extending tool life.

## 4. Ultrasonic Vibration System Research Status

The development of UVAG system is the key to realize the engineering application of UVAG technology. Ultrasonic vibration system is mainly composed of ultrasonic power supply, energy transfer device, transducer, ultrasonic horn and tool or workpiece. UVAG system has high precision, high reliability and applicability, which is conducive to the promotion of UVAG technology in the equipment manufacturing industry, and the current research focuses on the ultrasonic transducer and the ultrasonic horn [23]. At present, most of the ultrasonic vibration systems use the ultrasonic horn to drive the tool vibration, which often has the problems of low design accuracy, insufficient research on bending vibration, and poor tool vibration, which in turn affects the material processing.

### *4.1. Current Status of Ultrasound Transducer Research*

Ultrasonic transducers, according to the material, can be divided into simple structures, high conversion efficiency piezoelectric transducers and high stability, high radiant power per unit area, and complex process magnetostrictive transducers. With the continuous application of ultrasound technology and the emergence of electromagnetic force type, electrostatic type and other types of transducers currently used in ultrasonic processing in most of the 18~25 kHz medium and low-frequency transducers. Scholars have conducted a lot of research on various types of transducers in terms of frequency, structure, power, *etc.* Eriksson et al. [24] proposed a single-mode bending transducer consisting of a passive metal cap structure and piezoelectric sheet, which improves the conversion efficiency. Li et al. [25] proposed a novel longitudinal wave transducer using Halbach array arrangement with parameter optimization, and the proposed planar magnet array generates horizontal and vertical magnetic fields on the strong side. In addition, the array increases the flux density on the strong side to twice the flux density of a single permanent magnet, which significantly enhances the horizontal magnetic field and solves the problem of weak horizontally biased magnetic fields in conventional electromagnetic ultrasonic longitudinal wave transducers. As shown in Figure 5A, Li et al. [26] proposed an improved method for a helical slot longitudinal torsional ultrasonic vibration transducer by utilizing equivalent circuit theory and the material parameter equivalence method, taking into account the variation in stiffness. The model can determine the structural parameters of the transducer based on the resonance frequency and node position. The transducer was also subjected to finite element analysis, and the effects of the slot structural parameters on dynamic properties, such as vibration resonance frequency, frequency separation, and amplitude, were investigated. Finally, the excellent performance of the transducer was validated through experiments. The ultrasonic transducer will be affected by various factors such as self-heating, environment, and changes in load conditions in the process of use, and the realization of ultrasonic transducer resonance frequency tracking, keeping the frequency stable and controllable, and controlling the ultrasonic amplitude accurately and rapidly in a constant-frequency state, which is an important role in improving the quality of machining and expanding the ultrasonic technology. Zhang et al. [27] established an ultrasonic transducer impedance model using the electromechanical equivalence method, which can predict the frequency, conductance and electrical conductivity of the ultrasonic transducer. Kuang et al. [28] developed a drive measurement system capable of real-time monitoring of the operating parameters and states such as voltage, current, vibration amplitude, impedance amplitude and phase of the ultrasonic transducer in response to the resonance frequency shift and electrical impedance changes that are prone to occur in ultrasonic transducers, especially high-power transducers. As shown in Figure 5B, Hachisuka et al. [29] proposed an automatic resonant frequency control system for a stepped Langevin transducer, which consists of driving and controlling piezoelectric elements. The transducer's resonant frequency was adjusted to match the driving frequency by proportionally controlling the switching duty cycle of the Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) connected to the control piezoelectric element. The duty cycle and the optimum phase of the MOSFET switching were feedback-controlled and automatically adjusted by a system equipped with a lock-in amplifier. They confirmed that this system generated a non-sinusoidal waveform, specifically, a sawtooth wave and a trapezoidal wave. And they verified the effectiveness of a dynamic resonant frequency control system to match the resonant frequency of the transducer with the driving frequency. Du et al. [30] proposed a constant-frequency ultrasonic amplitude control method based on FPID and amplitude direct feedback, which was verified to be able to quickly and accurately control the vibration amplitude of the transducer, which is of practical significance for the application of ultrasonic vibration in the field of precision machining.

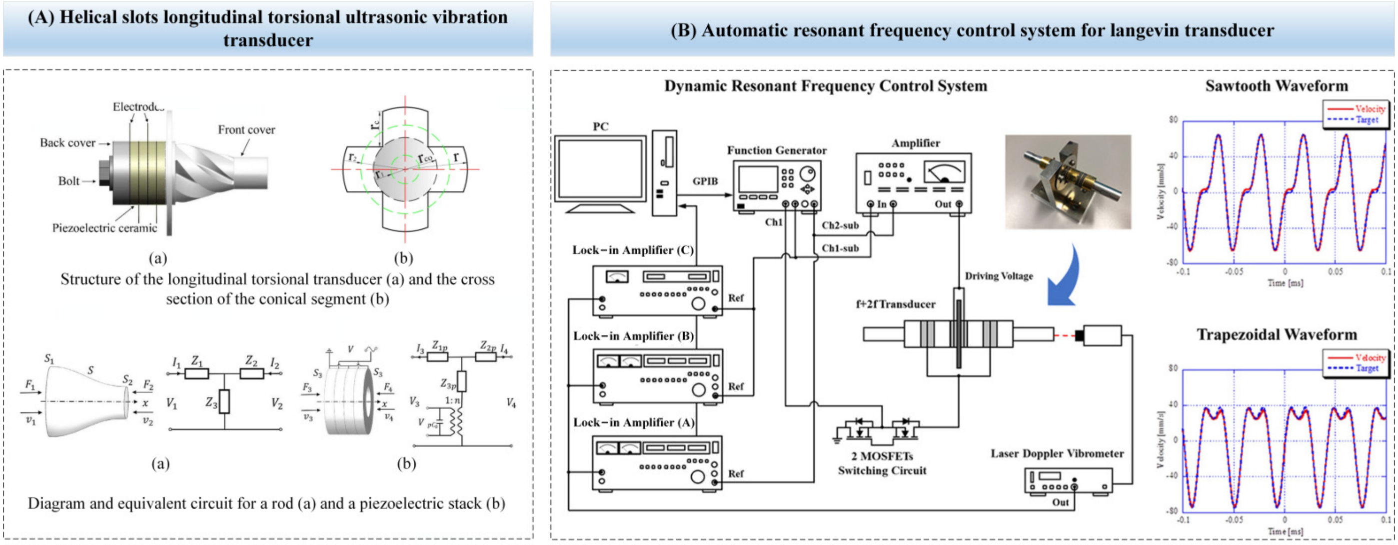


**Figure 5.** Research design of ultrasonic transducers. (**A**) Helical slots Longitudinal-torsional ultrasonic vibration transducer [26], (**B**) Automatic resonant frequency control system for Langevin transducer [29].

Because the transducer needs to match the resonance frequency with the amplitude change rod before processing, to change the frequency needs to replace the transducer, so for the complex frequency transducer, torsion transducer research is the current hot spot. In addition, high-power, large amplitude, high-performance transducer wafer material is also the focus of research in recent years.

## *4.2. Current Status of Ultrasonic Horn Research*

The ultrasonic horn, also known as the ultrasonic aggregator, plays a critical role in amplifying the amplitude of mechanical vibrations from 5 to 10 µm to about 100 µm, concentrating vibration energy, and enhancing the speed and transfer of energy. Improper design can negatively impact machining performance or damage the vibration system and generator. The shape or profile of the ultrasonic horn determines the amplification effect of vibration energy, which can be divided into a single ultrasonic horn and a composite ultrasonic horn. A common single ultrasonic horn is shown in Figure 6.

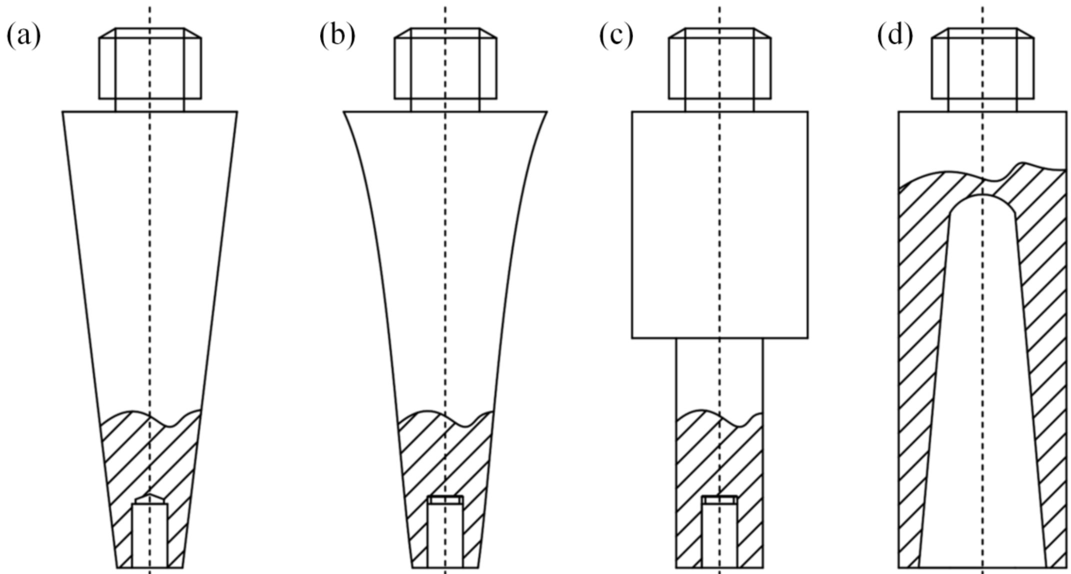


**Figure 6.** Common ultrasonic horn. (**a**) Conical, (**b**) Exponential, (**c**) Stepped, (**d**) Hollow Exponential [31].

The first ultrasonic horn appeared as the longitudinal vibration index-shaped ultrasonic horn used to increase ultrasonic power in the 1940s, and later, Eiji, Ryozo, and others proposed a variety of transducer structures which have continued to expand the range of industrial applications. For the design of the ultrasonic horn, the resonance of the tool is usually ignored, limiting the diameter of the connected tool, resulting in small amplitude and poor machining quality; therefore, the study of tool and ultrasonic horn resonance is crucial for the further development of ultrasonic vibration-assisted grinding. As shown in Figure 7A, Wang et al. [31] developed a large amplitude amplification factor ultrasonic horn with a cubic Bézier curve profile and developed a design program using multi-objective optimization algorithm and finite element analysis to optimize the displacement amplification of the horn. It has been experimentally proven that displacement amplification is 71% higher than that of traditional chain ultrasonic horns with the same length and end face diameter. Nad et al. [32] used fluctuation theory and finite elements to analyze the effect of the geometry of the ultrasonic horn on the ultrasonic machining process and the effect of the shape parameters of the ultrasonic horn, such as the aspect ratio δ, the tilt angle α, and the exponential function basis an on the intrinsic frequency. As shown in Figure 7B, Jagadish et al. [33] designed an ultrasonic horn with a longitudinally varying rectangular cross-section and conducted modal and harmonic analyses using finite element software to evaluate the design's feasibility. Additionally, an approximate mathematical model was developed to determine the amplification factor and equivalent stress of the ultrasonic horn. Comparison with existing ultrasonic horn designs revealed that the amplification factor of this new ultrasonic horn is higher than that of conical and exponential deformation horns, offering better performance and material removal rates while keeping the stress value below the durability limit of the horn material. As shown in Figure 7C, Singh et al. [34] used ANSYS to analyze the vibration patterns and natural frequencies of stepped and exponential-shaped ultrasonic horns made from aluminum and titanium alloys. The results showed that, for the stepped profile, the titanium horn produces higher natural frequencies for all six modes, while for the exponential profile, the aluminum horn produces higher frequencies than the titanium alloy. Some scholars have added a helical groove in the conical section of the conical composite amplifier ultrasonic horn and analyzed the effect of ultrasonic incident angle on the vibration mode and longitudinal torsion composite vibration torsion-longitudinal ratio through finite element analysis, which provided a theoretical basis for the design of composite amplifier ultrasonic horn. In terms of the design and optimization of ultrasonic horns, in addition to the studies by the above-mentioned scholars, some researchers who are focusing on the material selection of ultrasonic horns with a view to reducing their weight while maintaining their structural strength, thus improving the response speed and processing efficiency of the system. In addition, some researchers are exploring the design of multilayer structures for ultrasonic horns to achieve specific vibration modes and frequency characteristics through the combination of different materials.

In terms of the manufacturing process of ultrasonic horns, the development of precision machining technology has also had a significant impact on the performance of ultrasonic horns. For example, laser processing technology can be used to create complex microstructures on the surface of the ultrasonic horn, which can be used to regulate the distribution of vibration energy, thereby optimizing the processing effect. At the same time, the application of precision casting and 3D printing technology makes the design of the ultrasonic horn more flexible and allows for the rapid realization of complex-shaped ultrasonic horn prototypes. In terms of the performance test of the ultrasonic horn, researchers are also constantly exploring new test methods and evaluation standards. For example, laser Doppler vibration measurement technology can accurately measure the vibration mode and vibration amplitude of the ultrasonic horn, providing experimental data to support the design and optimization of the ultrasonic horn. In addition, through the simulation technology, the vibration characteristics of the ultrasonic horn can be simulated and analyzed on the computer so as to predict its performance before the actual manufacturing and reduce the cost of trial and error. In summary, the design and optimization of the ultrasonic horn is an important link in the ultrasonic vibration-assisted grinding system. Through the study of material selection, manufacturing process, performance testing and other aspects, the performance of the ultrasonic horn can be further improved, thus promoting the development of UVAG technology.

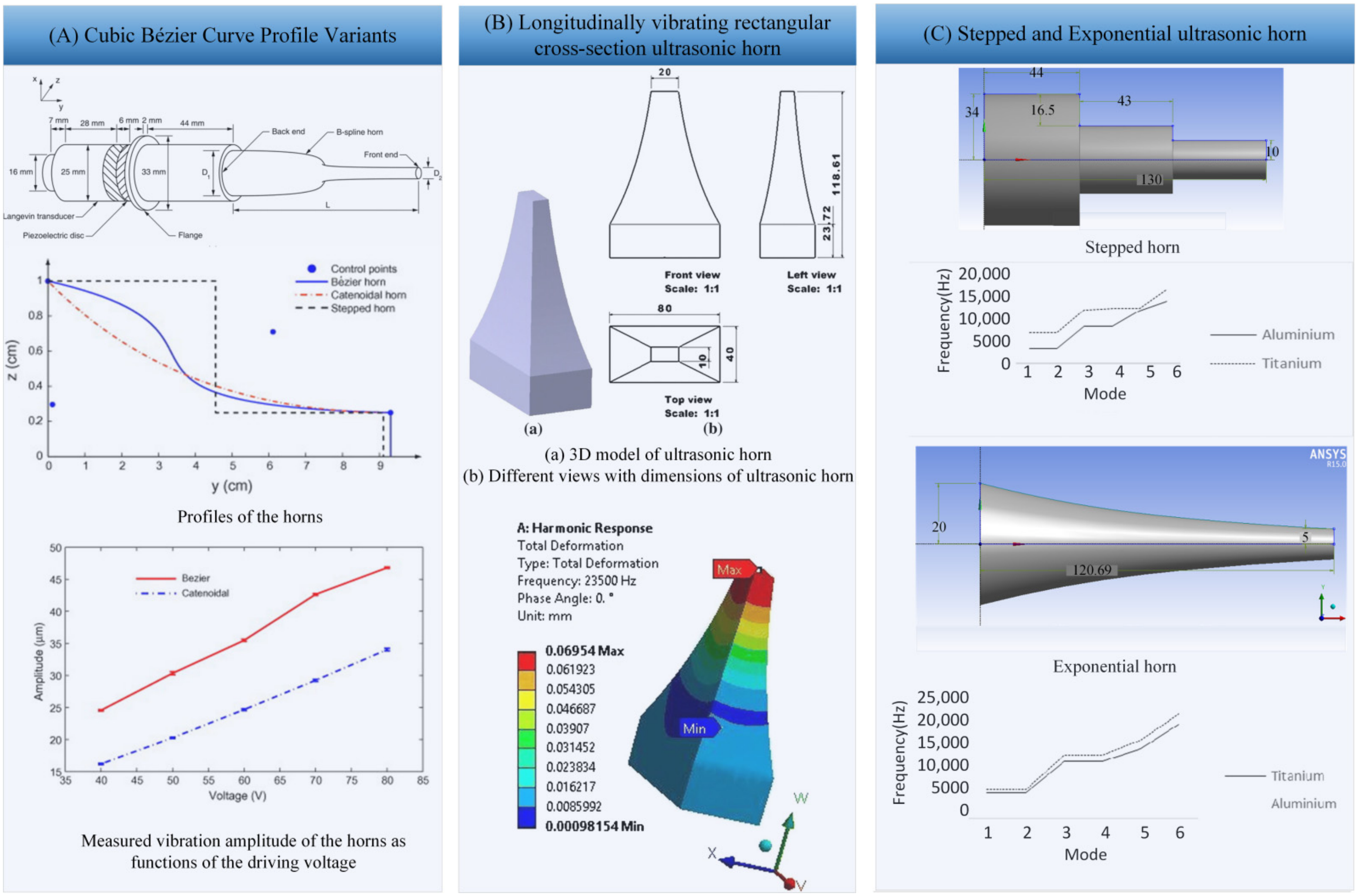


**Figure 7.** Research design of the ultrasonic horn. (**A**) Cubic Bézier Curve Profile Variants [31], (**B**) Longitudinally vibrating rectangular cross-section ultrasonic horn [33], (**C**) Stepped and Exponential Ultrasonic horn [34].

### *4.3. Discussion*

Overall challenges for the UVAG system include stable control of the output signal, improvement of the electromechanical conversion efficiency (transducer), and development of a multi-dimensional vibration system. Development of more advanced control algorithms to achieve accurate and stable control of the output signal of the UVAG system. This includes real-time monitoring and adjustment of the dynamic response of the transducer and amplitude-variable rod to ensure that the system maintains optimum performance under varying machining conditions. The tunability of the system's vibration parameters (frequency, amplitude) and the optimization of the mechanical structure play a large role in future improvements. Amplitude control and frequency tuning are key to ensure system stability. In addition, the development of multidimensional vibration systems is one of the focuses of future research. By designing and realizing multi-degree-of-freedom vibration systems, more complex vibration modes can be realized, which will improve the machining accuracy and efficiency and broaden the application range of UVAG technology.

## 5. Development of Ultrasonic Vibration-Assisted Grinding Technology

Wood et al. [35] in 1927 reported the use of ultrasonic vibration energy for material processing, by superimposing ultrasonic vibration in the suspended abrasive, improving the surface quality of the workpiece processing. In the 1950s, the Japanese scholar Junichiro Kuma began the earliest comparative systematic research on vibratory grinding and systematically put forward the theory of vibratory grinding [36]. British scholar P. Legge, in 1964, was the first to use sintered or electroplated diamond tools for rotary ultrasonic machining, overcoming the shortcomings of low machining speed and poor machining accuracy in deep-hole ultrasonic machining [37]. Komaraiah et al. [38] proposed a rotary ultrasonic machining method in 1991, in which the workpiece undergoes rotational motion while ultrasonic vibration-assisted machining is performed, and it was found that increasing the rotational speed of the workpiece can effectively improve the material removal rate of ultrasonic machining. In 2004, scholars from Akita Prefectural University and Tohoku University in Japan investigated ultrasonic elliptical vibration-guided centerless grinding technology, and a series of experimental studies were carried out [39]. Xiao Yongjun et al. developed a rotary ultrasonic-assisted grinding spindle structure in 2007, where the ultrasonic power supply outputs a high-frequency electrical signal, which drives the ultrasonic transducer vibration through the copper ring of the carbon brushes, and ultrasonic vibration can be realized at the same time as the grinding head rotates at a uniform speed. Singh et al. [40] improved the material removal rate by ultrasonic grinding pure titanium material in 2010, and found that the material removal rate increased with the increase of the ultrasonic power but also increased tool wear. Xiang et al. [41] in 2018 studied the wear behavior of CBN abrasive grains during ultrasonic high-speed grinding, and under high-speed grinding conditions, the wear volume of abrasive grains in ultrasonic vibration-assisted grinding was larger, mainly because the ultrasonic energy acted on the abrasive grains to produce a softening effect, which made the abrasive grains more prone to fracture. Zhao et al. [42] in 2020 investigated tangential ultrasonic vibration-assisted grinding of gears and established a grinding temperature model. The results showed that the use of ultrasonic vibration-assisted grinding reduced the temperature in the grinding zone by 38.7% and the grinding force by 71.3%, and it was also found that ultrasonic vibration-assisted grinding surfaces formed greater residual compressive stresses.

From the formulation of vibratory grinding theory in the 1950s and its extension to other vibration modes in the 1980s and 1990s, improved concepts, materials and methods were introduced [43,44]. The emergence of multiaxial flexible articulated structures at the beginning of the 21st century has fuelled the development of 2D/3D UVAGs [45,46]. In particular, the rapid development of UVAG in the last decade has led to further improvements in surface quality and material removal rates. Compared with CG, UVAG not only improves the machining accuracy and efficiency of general workpiece materials but also overcomes the problems caused by CG, such as excessive grinding force, severe tool wear, and low surface quality.

## 6. Ultrasonic Vibration-Assisted Grinding Characteristics

UVAG is a non-traditional machining technology. The cutting characteristic between the tool and the workpiece changes from continuous machining to periodic intermittent machining. This cutting characteristic not only changes the removal mechanism of the workpiece material but also has a certain effect on the cutting force, workpiece surface quality and tool wear. In order to explore the cutting characteristics of UVAG, many scholars have carried out in-depth studies and analyzed the effects of processing factors (grinding depth, cutting speed, *etc.*) and vibration factors (frequency f and amplitude A) on the cutting characteristics. As shown in Figure 8, this chapter aims to provide an in-depth understanding of ultrasonic vibration-assisted grinding (UVAG) by analyzing the current state of research on its machining characteristics and effects. This includes the material removal mechanism, grinding force, abrasive wear, and surface quality in ultrasonic grinding. The existing challenges and gaps in these research areas are also discussed, offering valuable insights for future studies on ultrasonic vibration-assisted grinding.

### *6.1. Ultrasonic Vibration-Assisted Grinding Removal Mechanism*

Ultrasonic vibration-assisted grinding processing applies high-frequency simple harmonic vibration to the tool or workpiece on the basis of ordinary grinding processing in order to change the removal mechanism of the material so as to realize vibratory cutting, which is a fundamental change in the removal mechanism of the material due to the change of the grinding characteristics compared with ordinary grinding [47,48]. Many scholars have studied the removal mechanism of ultrasonic vibration-assisted grinding.

#### 6.1.1. Influence of Grinding Process Parameters on the Removal Mechanism

The ultrasonic vibration-assisted grinding removal mechanism is closely related to the grinding process parameters, and in the material removal rate and cutting force model for plastic materials, the rate of decrease of material removal rate increases with the increase of amplitude; the rate of material removal rate increases with the increase of tool rotational speed; the rate of material removal rate increases with the reduction of the number of working grits; the rate of material removal rate increases with the reduction of the diameter of abrasive particles [4]. As shown in Figure 9A, Cong et al. [49] investigated the grinding force prediction model for rotary ultrasonic machining of carbon fibre-reinforced composites. The chipping or spalling of the workpiece material could be seen from the machined surface and cutting interface. It can be concluded that the material removal mechanism in the RUM of CFRP is a brittle fracture. By analyzing the fracture zone of a single abrasive grain, the amount of material removal can be derived, revealing the influence of factors such as ultrasonic vibration frequency, amplitude, abrasive grain size, and abrasive grain distribution density on material removal. UVAG can increase the plasticity removal in the grinding process, and some scholars have investigated the percentage of plasticity removal in the ultrasonic vibration-assisted grinding process by carrying out ordinary grinding experiments and ultrasonic vibration-assisted grinding experiments and found that the percentage of plasticity removal in the grinding process increased after applying ultrasonic vibration assistance [50]. As shown in Figure 9B, Bhaduri et al. [51] found that grinding GH4169 nickel-based alloy with a deep cut using tangential ultrasonic vibration resulted in higher mechanical loads, leading to greater plastic deformation of the material under the same external force. Additionally, more overlapping grit marks were visible on surfaces produced with ultrasonic-assisted grinding. Some scholars conducted an experimental study on rotary ultrasonic machining of titanium alloys, and according to its assumptions on different sizes of abrasive grains as well as depth of cut, grinding wheel speed and other parameters, respectively, on hard and brittle materials as well as plastic materials, and verified the cutting force model and the material removal rate model established by using the law of conservation of momentum. In addition, the method of finite element simulation is an effective method to study the grinding removal mechanism, but the traditional algorithm has the problem of mesh distortion. The use of the Eulerian or Lagrangian algorithm can make up for the mesh distortion problem in the traditional algorithm, and the finite element simulation of three-dimensional single-grain grinding can be derived from the grinding process of the grinding temperature, contact stress and the change rule of the residual stress [52].

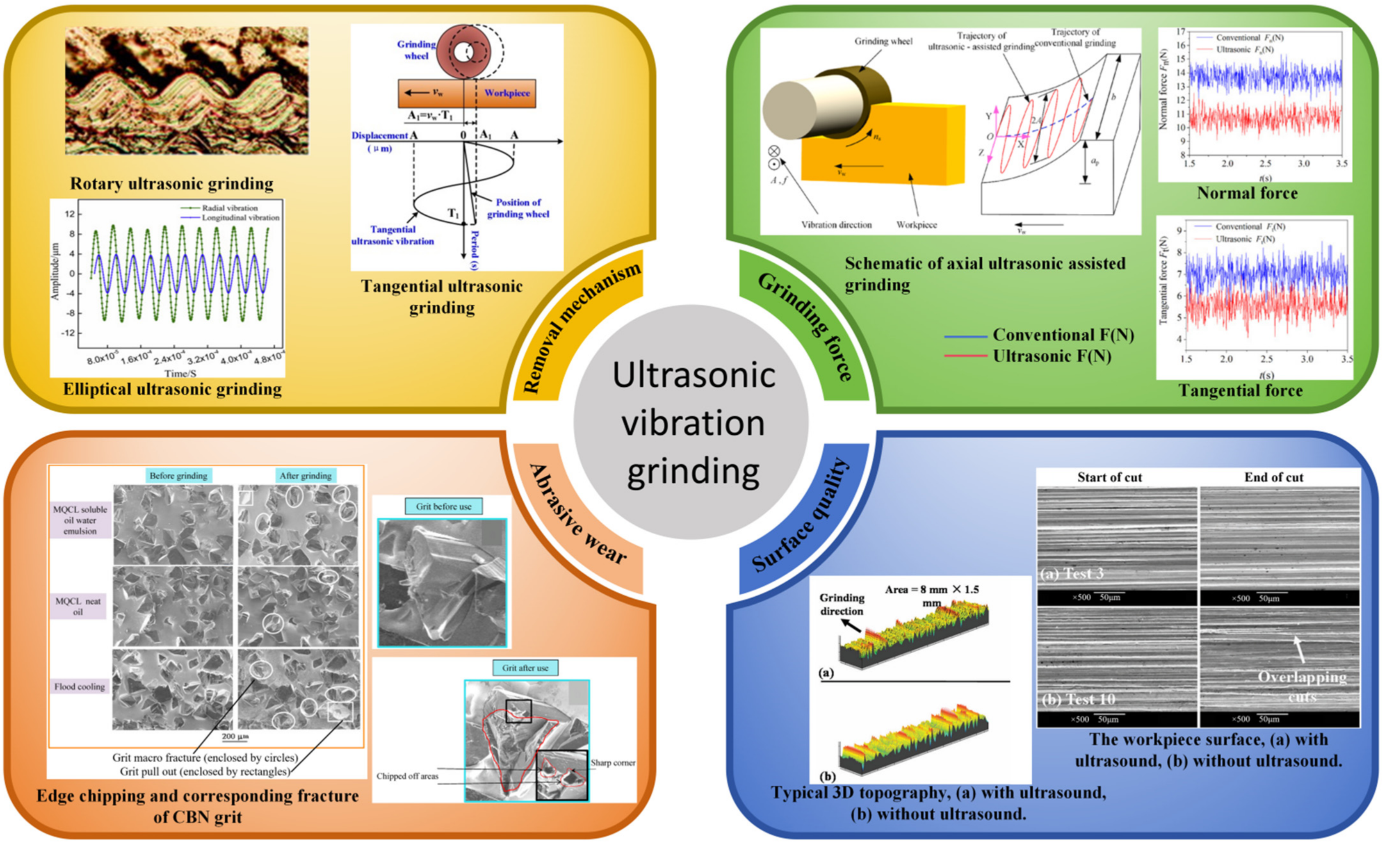


**Figure 8.** Ultrasonic vibration-assisted grinding characteristics.

### 6.1.2. Effect of Vibration Mode on the Removal Mechanism

The removal mechanism of ultrasonic vibration-assisted grinding (UVAG) is closely tied to the mode of applied ultrasonic vibration. Research by Yukio Tanaka et al. explored the impact of axial, radial, and tangential directions of the grinding wheel on the removal rate of stainless steel materials. The study revealed that all three directions enhanced the removal rate. Further investigation showed that axial ultrasonic vibration, combined with repetitive grinding action by a single grit, yielded better surface quality. In contrast, radial ultrasonic vibration resulted in poorer surface quality of the workpiece [53,54]. In the one-dimensional axial vibration grinding process, different numbers of abrasive grains distributed axially on the grinding wheel surface play a repetitive grinding effect on the workpiece; in addition, the two processing modes of side grinding and face grinding have different impacts on the surface quality of workpiece grinding, and the one-dimensional axial ultrasonic vibration is suitable for side grinding of alloy materials [55]. The axial ultrasonic vibration has wider grinding grooves and the reciprocating ironing effect on the workpiece surface, and because the direction of ultrasonic vibration is perpendicular to the workpiece grinding feed direction, it makes the abrasive grains have wider coverage, which reduces the height and width of the protrusions on the vertical cross-section of the workpiece and reduces the surface roughness of the workpiece [56]. Liu and Zhang proposed a material removal model of ultrasonic vibration elliptical machining, in which the trajectory of tool ultrasonic vibration is elliptical, and the mathematical model of grinding force was obtained, according to which it can be deduced that the cutting force of elliptical vibration rotary ultrasonic machining is much smaller than that of ordinary machining [57]. It is difficult to observe the ultrasonic motion trajectory of abrasive particles at a macro level, but this problem can be overcome through simulation methods. As shown in Figure 9C, Zhao et al. [58] simulated the motion trajectory of abrasive particles under different ultrasonic vibration modes using simulation software, and validated the results through experiments. Electron microscopy was used to observe the abrasive particle grinding trajectory on the surface during elliptical ultrasonic vibration-assisted grinding (UAEVG) and conventional grinding (CG). When the grinding depth was increased, the plastic deformation ratio of the material under UAEVG was significantly higher than that under CG, leading to improved surface topography. The surface roughness increased with the grinding depth and feed rate, while the surface compressive stress decreased with increasing grinding depth. Therefore, it can be concluded that UAEVG expands the plastic deformation domain, enhancing the surface integrity and fatigue strength of Nano-ZrO2 ceramics to some extent. In terms of ceramic materials, different ultrasonic vibration modes will have different effects on the material. Some scholars used tangential, axial and radial ultrasonic vibration-assisted grinding to carry out experimental research on the removal mechanism of the material based on the brittle deformation of the ceramic material to the plastic deformation of the conversion conditions and analyzed the effect of applying ultrasonic vibration in different directions on the brittle material removal conditions and efficiency.

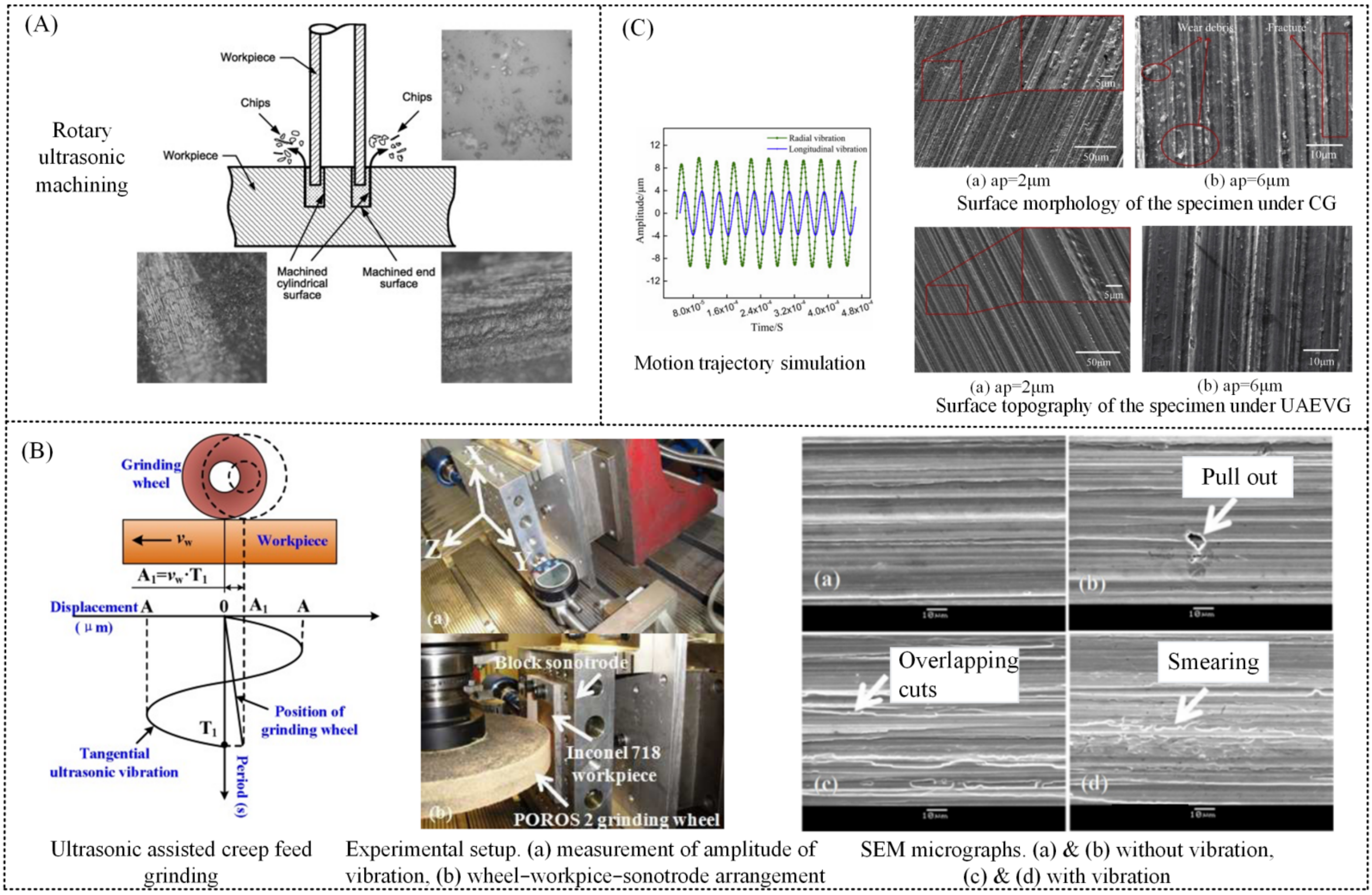


**Figure 9.** Ultrasonic grinding removal mechanism. (**A**) Rotary ultrasonic grinding [49], (**B**) Tangential ultrasonic grinding [51], (**C**) Elliptical ultrasonic grinding [58].

### 6.1.3. Discussion

In summary, in the previous research on the removal mechanism of UVAG, different vibration modes and different grinding parameters were studied and analyzed for the material removal mechanism; in addition, a large number of research works have analyzed the machining process by ultrasonic grinding by means of actual machining tests and finite element analysis. There are very few studies on the removal mechanism of advanced materials by ultrasonic vibration-assisted grinding from the perspective of microscopic two-adjacent abrasive grains and small grinding heads instead of conventional grinding wheels.

### *6.2. Ultrasonic Vibration-Assisted Grinding Force*

In the grinding process, grinding force is one of the important parameters to characterize the grinding process, which not only affects the quality of workpiece surface processing but also has a greater impact on the service life of grinding tools. Therefore, the grinding force in the grinding process and its influencing factors have become a hot spot in current research.

#### 6.2.1. Influence of Different Advanced Materials on Grinding Forces

Ultrasonic vibratory grinding force is closely related to the processed material, and many researchers have investigated the machinability of different advanced materials using UVAG, but few studies have comprehensively classified and analyzed the materials from the perspectives of material properties, vibration modes and machinability. Through the ultrasonic-assisted grinding tests on 100Cr6 and 42CrMo4 steels with alumina grinding wheels and cubic boron nitride (CBN) grinding wheels, respectively, scholars found that ultrasonic vibration can effectively avoid thermal damage to the surface of the workpiece and reduce the grinding force, with the reduction of normal grinding force of up to 60% to 70%, and the reduction of tangential grinding force of up to 30% to 50% [59]. Through the ultrasound-assisted creep feed grinding test on nickel-based high-temperature alloys, compared with ordinary creep feed grinding, the ultrasonic vibration effect can significantly increase the number of effective cutting edges on the surface of the grinding wheel, and the normal and tangential grinding forces of the test alloys were reduced by 23% and 43%, respectively, and the surface roughness was reduced by 45% [60].

Many scholars have studied the ultrasonic vibration-assisted grinding force by establishing a mathematical model of ultrasonic grinding force and numerical simulation, which can effectively predict the trend of the grinding force. As shown in Figure 10, Xiao et al. [61] developed a cutting force model for ultrasonic vibration-assisted transverse grinding based on the removal mechanism of the ceramic ductile-brittle transition in ultrasonic vibration-assisted side grinding (UVASG). To simplify the modeling process, a single diamond grain was first modeled and approximated as a rigid octahedron of equivalent size. Next, the undeformed chip thickness under ultrasonic vibration was analyzed. Subsequently, cutting force models for both the ductile and brittle regions were derived separately, and the total cutting force model was determined by summing the two. The final cutting force model was obtained by considering all diamond grits in the grinding area and accounting for the overlapping and interference effects between abrasive grains. The accuracy of the mathematical model was validated through experimental verification. Obikawa et al. [62] established the ontological relationship of titanium alloy materials under force-heat coupling and revealed the chip deformation and stress field distribution of the cutting process by combining the changes in strain, strain rate, and temperature. Unyanin and Khunsainov developed a grinding force model for ultrasonic vibration-assisted grinding by expressing the grinding force as four components related to plastic deformation and friction behaviour [63]. Y.B.Wu et al. [64] deduced a calculation model for the average chip section area of axial ultrasonic vibration-assisted grinding and ordinary grinding from the cutting arc length of a single abrasive grain and analyzed the reduction rate of axial ultrasonic grinding force compared with that of ordinary grinding force. They analyzed the effect of each grinding parameter and ultrasonic vibration parameter on the reduction rate of the grinding force, but they lacked the friction analysis in the grinding process.

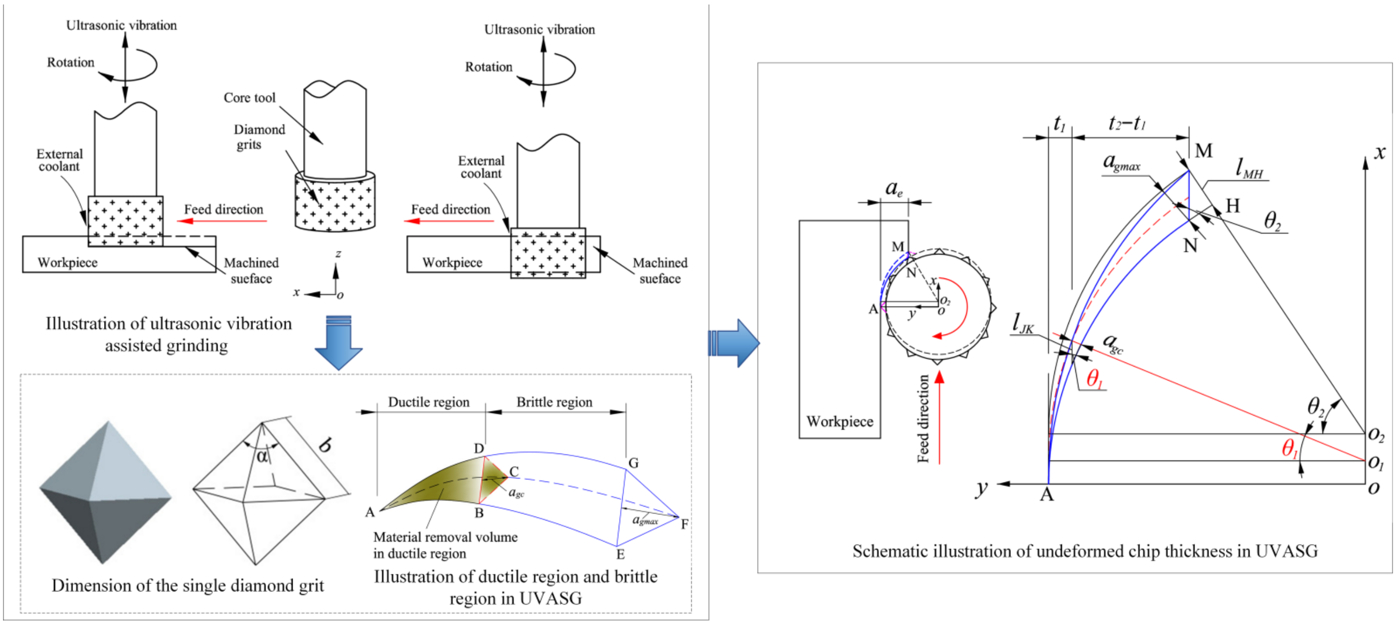


**Figure 10.** Schematic illustration of undeformed chip thickness in UVASG [61].

### 6.2.2. Influence of Process Parameters and Vibration Mode on Grinding Forces

The ultrasonic vibration grinding force is closely related to the machining parameters and the mode of applied ultrasonic vibration. Different process parameters will have different effects on the grinding force. Through the use of different process parameters on ceramic materials grinding force change rule of the experiment, was found that the grinding force with the increase of ultrasonic frequency and the grinding speed and reduced, with the increase of feed depth and feed speed and increase. Wang et al. [65] established a grinding force model for axial ultrasonic vibration-assisted grinding of ceramic materials based on the relationship between the equations of motion of the abrasive grains, the critical load for ceramic material crushing, the transverse crack width, the longitudinal crack depth, and the rate of material removal. They found that the grinding force decreases with increasing amplitude, frequency, and grinding speed and increases with increasing grinding depth and feed rate. The accuracy of the model was verified through ultrasonic assisted high-speed grinding single particle grinding experiments. Lei et al. [66] investigated the effect of different grinding parameters on the grinding force. The results show that the normal force is always larger than the tangential force under the same parameters and the grinding force increases with the increase of workpiece linear speed. The maximum errors between experimental and simulated values are about 23% and 34%, respectively, and the trends of both changes with time are basically the same. As shown in Figure 11, Zhang et al. [67] investigated the effect of different fibre orientations on the grinding force of two-dimensional woven carbon fibre-reinforced silicon carbide matrix composites (2D-Cf/SiC). They found that the grinding force in conventional grinding is higher than that in ultrasonic-assisted grinding. Significant fluctuations in the grinding force were observed, which can be attributed to the brittle nature of the Ceramic Matrix Composites during the removal process, as well as the uneven distribution of fibre content and orientation. The normal force, tangential force, and surface roughness in ultrasonic vibration-assisted grinding were reduced by approximately 20%, 18%, and 9%, respectively, compared to conventional grinding. The grinding force in ultrasonic-assisted grinding decreases with increasing spindle speed and ultrasonic amplitude but increases with greater grinding depth and feed rate.

### 6.2.3. Discussion

It can be seen that ultrasonic vibration-assisted grinding has great advantages in reducing the grinding force [68]. Many researchers have studied the machining performance of different advanced materials using UVAG, by establishing a mathematical model of ultrasonic grinding force, studying the ultrasonic vibration-assisted grinding force by numerical simulation, and experimentally exploring the effects of different machining parameters and ultrasonic vibration modes on the grinding force. However, with the application of more and more complex curved structures, traditional grinding wheel grinding is difficult to process them effectively due to the influence of size, so it is necessary to carry out research related to ultrasonic grinding on small grinding heads.

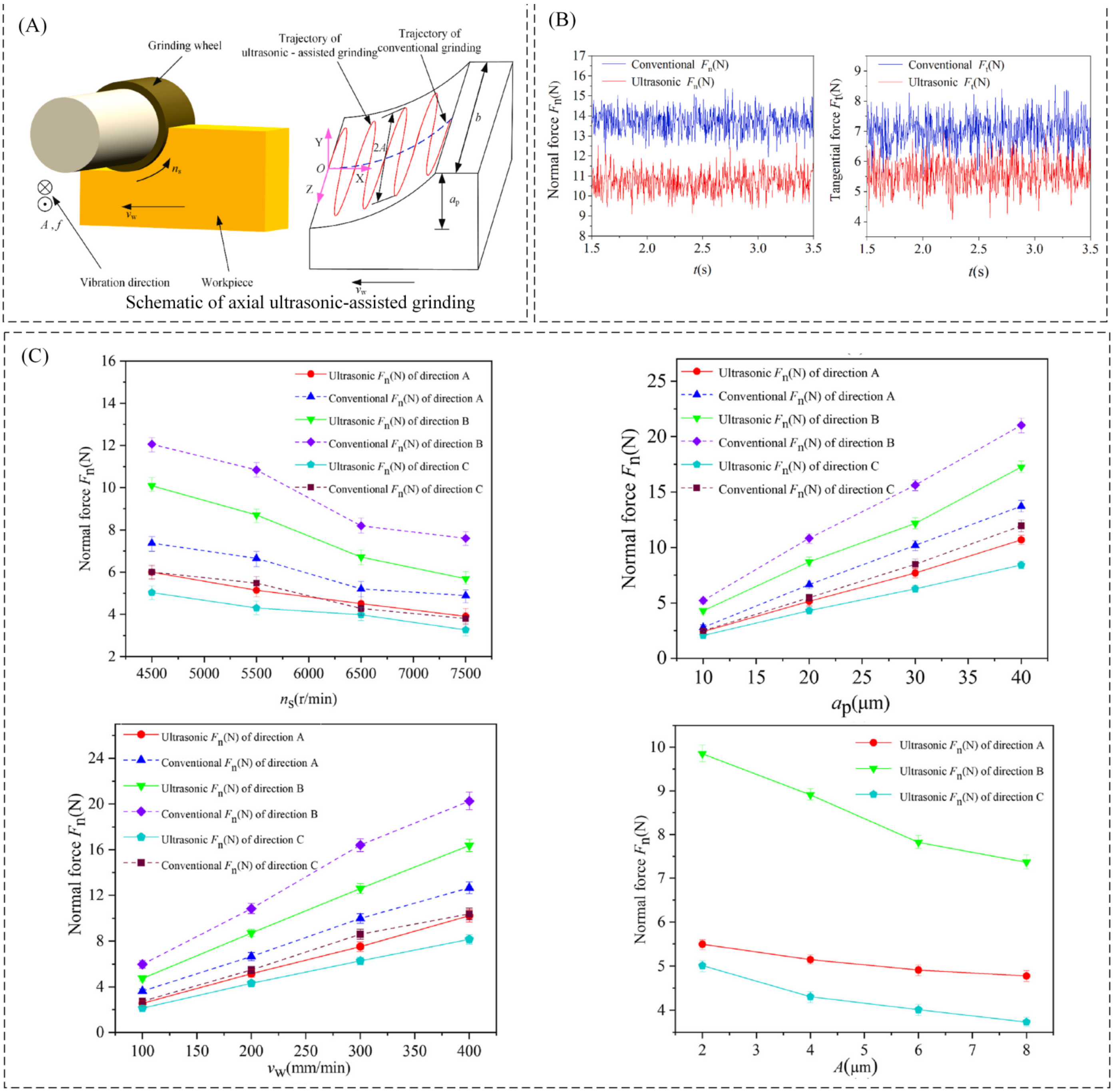


**Figure 11.** Ultrasonic grinding forces and surface roughness [67]. (**A**) Schematic of axial ultrasonic-assisted grinding, (**B**) Comparison of force signals between CG and UVAG, (**C**) The influence of processing parameters on grinding force.

### *6.3. Ultrasonic Vibration-Assisted Grinding Abrasive Wear*

Abrasive wear is the result of mechanical, physical and chemical interactions in the grinding process and can have a serious impact on grinding productivity and product quality. Therefore, many scholars have carried out a lot of research on the wear mechanism of abrasives in the grinding process, with a view to improving the machining performance and service life of abrasives.

#### 6.3.1. Influence of Process Parameters and Vibration Mode on Wear of Abrasives

UVAG can significantly reduce abrasive wear, and different ultrasonic vibration modes and grinding parameters have a close relationship on abrasive wear through the experiments found that for metal-based sintered abrasives, relative to the ultrasonic grinding process, the abrasive wear of abrasive end face and bond friction wear is more serious in ordinary grinding [69,70]. Rotary ultrasonic vibration-assisted grinding can significantly reduce the wear of abrasive tools. Some scholars, through the rotary ultrasonic grinding compared with ordinary grinding, research on rotary ultrasonic processing SiC material removal rate on the tool wear, the surface roughness of the influence of the law, the ultrasonic vibration can significantly reduce the grinding force and tool wear, when the depth of grinding for 0.05 mm, rotary ultrasonic grinding material removal rate is the largest and the material removal rate of rotary ultrasonic grinding is maximum and the tool wear is minimum [71]. In rotary ultrasonic grinding of titanium alloys, tests were carried out by testing tools with different abrasive grit sizes, different abrasive concentrations and different bonding agents and observing the morphology of abrasive grains on the end faces of the tools before and after the tests. The results showed that the wear conditions of rotary ultrasonic grinding titanium alloy abrasives were mainly gritted abrasion, grit shedding, grit rupture and bond breakage and that bond rupture and grit shedding were more severe at the end face edges of the tool than at the centre of the tool [72]. In the experiment of rotary ultrasound-assisted grinding of lead oxide ceramics, by analyzing the surface morphology of the tool before and after the test, it was found that ultrasonic vibration made characteristics such as increased wear and self-sharpening correction of the tool [73]. In the grinding of titanium alloys, Attia et al. [74] conducted a study on the grinding wheel wear of Ti-6Al-4V alloy by electroplated diamond grinding wheels and found that the radial wear of the grinding wheel became more and more serious with the increase of the depth of grinding; at the same time, the increasing degree of the grinding wheel wear also led to the increase of the specific energy of grinding titanium alloys. In addition, under the same grinding conditions, the wheel durability of plated diamond grinding wheels for grinding titanium alloys was higher than that of plated CBN grinding wheels. Param Singh et al. [75] studied wheel wear during ultrasound-assisted microfine EDM grinding of Ti-6Al-4V alloy and found that the introduction of ultrasonic vibration helps to improve the flushing effect on the chips in the grinding area, which results in a reduction in the degree of adhesion on the surface of the grinding wheel, an improvement in the quality of machining of the work piece's internal holes, and a decrease in the rate of wheel wear with the increase in the ultrasonic power.

#### 6.3.2. Wear Processes and Wear Mechanisms

It is important to study the process and wear mechanism of abrasive wear during ultrasonic vibration. The grinding of different workpiece materials and the use of different ultrasonic vibration modes have different effects on the wear mechanism of abrasive wear. In the experiment of grinding silicon carbide materials, the primary forms of wear on diamond grinding wheels include abrasive grain crushing, abrasive wear, grain shedding, and adhesive wear. In the early stages of wear, the predominant forms are abrasive grain crushing and grain shedding. The main form of wear in the normal wear stage is abrasive wear, the main form of wear in the rapid wear stage is abrasive grain shedding and adhesive wear, and in the case of impact, abrasive grain crushing and abrasive grain shedding are the main forms of wear. In elliptical ultrasound-assisted grinding technology for processing carbon fibre composites, the introduction of ultrasonic vibration makes the abrasive tool produce a large acceleration, which can reduce the resin adhering to the abrasive grains and thus improve the clogging of the abrasive tool [76]. In the test of ultrasonic vibration single-grain high-speed grinding of ductile iron, the abrasive wear forms of abrasive grains mainly include crushing wear, abrasive wear, corrosive wear and removal wear, and the abrasive wear forms of abrasive grains under ultrasonic-assisted grinding are mainly shear wear and abrasive removal wear, while micro-crushing wear and a small amount of abrasive wear are predominantly found in normal grinding. Scholars have found through the study of the wear mechanism of diamond tools in the rotary ultrasonic elliptical cutting of CFRP materials that, relative to ordinary grinding, the tiny breakage of diamond grits during rotary ultrasonic elliptical grinding will lead to rapid wear of the tools, while the rotary ultrasonic grinding force is also smaller [77]. As shown in Figure 12a, when using an electroplated CBN grinding wheel to grind titanium alloy at high grinding speeds under different cutting fluid environments (water-based soluble oil emulsion in minimum quantity cooling lubrication (MQCL), flood cooling mode, and neat oil in MQCL), the wear type of the electroplated CBN grinding wheel is abrasive grain fracture. The primary cause of abrasive grain fracture is thermal stress impact during grinding. Additionally, as observed in Figure 12b, thermal stress may also contribute to or promote edge cracking. These sharp edges can concentrate stress under the grinding force, leading to crack initiation and propagation, ultimately resulting in grain fracture. The effect of grinding speed on surface redeposition is shown in Figure 12c. It can be observed that at low grinding speeds, redeposition is smaller. At lower speeds, the time available for heat dissipation is longer than at higher speeds, which helps reduce the adhesion of abrasive particles, thereby lowering the level of redeposition. As shown in Figure 12d, the changes in redeposition of accumulated material removal for different fluids are displayed. The surface generated using pure oil shows minimal redeposition, while the use of water-based emulsion results in significant redeposition [78].

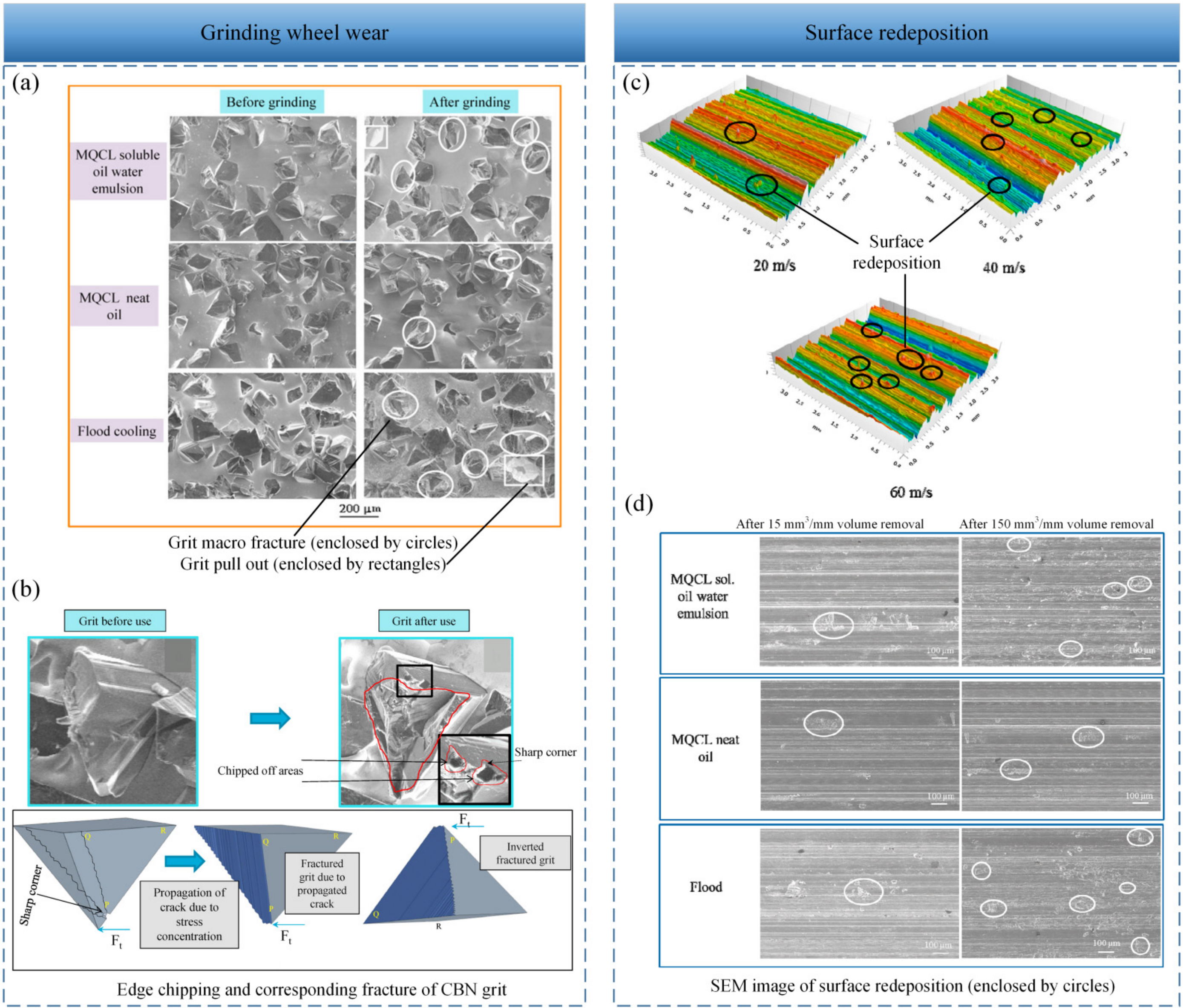


**Figure 12.** Ultrasonic vibration-assisted grinding wheel wear and surface integrity. (**a**) Conditions before and after the grinding wheel at 40 m/s grinding speed, (**b**) Edge chipping and corresponding fracture of cBN grit, (**c**) Surface redeposition at different grinding speeds under flood cooling environment, (**d**) SEM images after removal of different volumes at 40 m/s under different conditions [78].

6.3.3. Discussion

In summary, scholars have carried out some research on the form and mechanism of abrasive wear in the grinding process by reducing the grinding heat and grinding force in the machining process and the use of lubrication methods so as to reduce the occurrence of tool wear and adhesion. However, most scholars studying tool wear methods basically use the observation of tool wear morphology before and after the experiment to study the wear mechanism, qualitatively analyzed the wear of abrasive tools in ultrasonic grinding machining of specific materials, and the research on the prediction model of abrasive tool wear generated in ultrasonic vibration-assisted grinding of advanced materials is still relatively small. Therefore, it is necessary to study abrasive wear and its prediction models for specific machining modes.

*6.4. Ultrasonic Vibration-Assisted Grinding of Surface Quality*

Surface quality has a direct impact on the performance of the workpiece, affecting its strength and wear resistance. At present, for the study of grinding surface quality, scholars are mainly focused on the surface defects, surface roughness, surface residual stress, surface micro-morphology and micro-hardness of these aspects.

### 6.4.1. UVAG Processing Effect

UVAG can significantly reduce the surface roughness of the workpiece relative to CG. As shown in Figure 13A, tangential UVAG experiments were conducted on Inconel 718. Figure 13B presents the representative 3D morphology of the workpiece surface ground with and without ultrasonic assistance, respectively. When ultrasonic vibration is used, the average surface roughness (Sa) is typically lower. This may be due to an increased frequency of overlapping cuts compared to processing under normal grinding conditions, as illustrated in Figure 13C. Additionally, greater levels of smearing and side flow/ploughing of the workpiece material were observed when operating with ultrasonic vibration, suggesting an increase in plastic deformation [60]. The surface morphology of the workpieces obtained by UVAG versus CG differed from that of the ultrasonically ground surfaces with a unique groove texture, which provides better friction properties and surface strength [55]. In addition, the formation of this groove texture is also related to the precise control of the grinding parameters, including the grinding speed, the grinding pressure, and the use of the grinding fluid. By finely adjusting these parameters, the surface treatment effect of UVAG technology can be further optimized, resulting in a more uniform and detailed groove texture on the surface of the workpiece, thus meeting the needs of higher-standard industrial applications. Jiang et al. [79] investigated the mechanism of surface texture formation during ultrasonic vibration-assisted grinding, analyzed the effect of the superposition of adjacent abrasive grains, defined the characteristic parameters characterizing the surface topography, and quantitatively described the surface topography. Ultrasonic vibration also increases the lateral flow of the material during the cutting process, which makes it easier to achieve plastic removal of the material. At the same time, ultrasonic vibration reduces the tensile stress in the shear zone during the material removal process, which reduces the extension of cracks on the surface of the workpiece and effectively reduces the surface defects [80]. When using ultrasonic vibration-assisted grinding of titanium alloys, the use of ultrasound can effectively avoid the adhesion of titanium elements and abrasive grains, which plays a positive role in the improvement of surface quality [81]. Some scholars have taken the UVAG trajectory as the entry point to study the influence of the interference between the abrasive grain movement trajectory and the neighbouring trajectories on the grinding surface. Under the condition of rotary ultrasonic grinding, the scratch trajectory of the grinding wheel abrasive grains is sinusoidal, and the sinusoidal trajectories of the neighbouring abrasive grains on the grinding wheel are interleaved with each other in the machining process, which reduces the maximum tangential thickness of abrasive grains, and thus reduces the surface roughness of the grinding surface. However, as the grinding parameters become larger, the sinusoidal trajectories of the abrasive grains gradually converge to the linear trajectories of normal grinding, which weakens the overlapping effect between the abrasive grain trajectories and reduces the processing effect of rotary ultrasonic grinding.

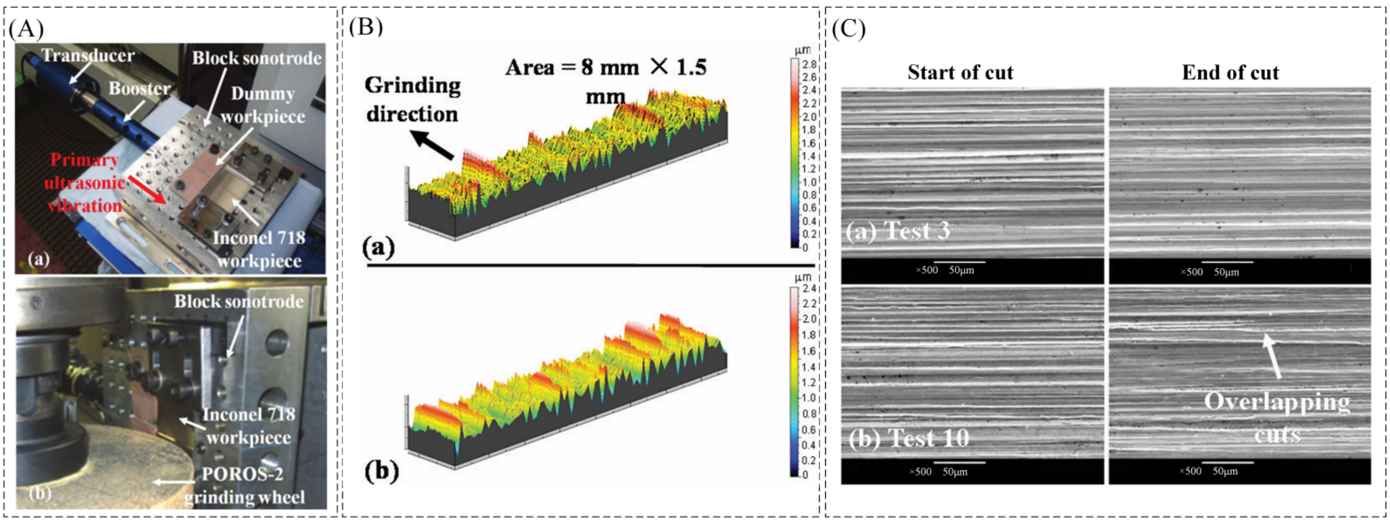


**Figure 13.** Surface topography analysis of ultrasonic vibratory grinding [60]. (**A**) Experimental setup, (**a**) block sonotrode and transducer arrangement, (**b**) machine configuration. (**B**) Typical 3D topography, (**a**) with ultrasound, (**b**) without ultrasound. (**C**) Scanning electron microscope micrographs of the workpiece surface, (**a**) with ultrasound, (**b**) without ultrasound.

### 6.4.2. Predictive Modelling of Surface Quality

By establishing a prediction model for the surface quality in the ultrasonic vibration process, the surface quality of the workpiece after machining can be effectively predicted. The neural network algorithm has significant superiority in predicting the surface roughness and grinding force, and some scholars take the grinding process parameters as inputs and output the grinding roughness and grinding force, and their test results are basically the same as the prediction results [82]. Kanakarajan et al. [83] used silicon carbide grinding wheels to grind aluminium oxide ($Al_2O_3$) ceramics and evaluated a surface roughness prediction model based on the comparison of experimental results with regression analysis. Scholars have investigated the high-frequency vibration effect in ultrasonic grinding of hard and brittle materials, considering the combined influence of the elastic-plastic stress field. Based on the establishment of a nonlinear relationship between the workpiece surface roughness and subsurface crack propagation depth and incorporating the inertial force of abrasive particles, working angle, and dynamic fracture toughness of the workpiece material, a new model for rotary ultrasonic machining has been developed. This model provides insights into the surface formation process in rotary ultrasonic machining. Nguyen et al. [84] proposed a numerical method based on random field transformation for efficiently generating grinding wheel morphology, and the results showed that the generated morphology has the same probabilistic features and self-correction function as the original morphology. Zhang et al. [85] proposed a probabilistic algorithm for predicting surface morphology and surface roughness in longitudinal torsional ultrasonic grinding. As shown in Figure 14, Chen et al. [86] proposed a simulation model and surface roughness prediction method for the surface topography of grinding, taking into account the ultrasonic vibration of the workpiece and the shape of the grains. And established an equation for the change of the surface of the abrasive grain trajectory with time. Subsequently, a new simulation model for the surface topography of the grinding process is proposed by dividing the workpiece into a grid and calculating the minimum value of all remaining grains at each grid point. Finally, experimental validation was carried out to discuss the effect of ultrasonic vibration amplitude on surface roughness. The simulation results show that the results obtained by the proposed method are consistent with the experimental results, thus proving the effectiveness of the method. Liu et al. [87] proposed an adaptive fuzzy inference system combined with a genetic algorithm to predict the grinding surface quality of YG3 cemented carbide with a root-mean-square relative error of 4.13%.

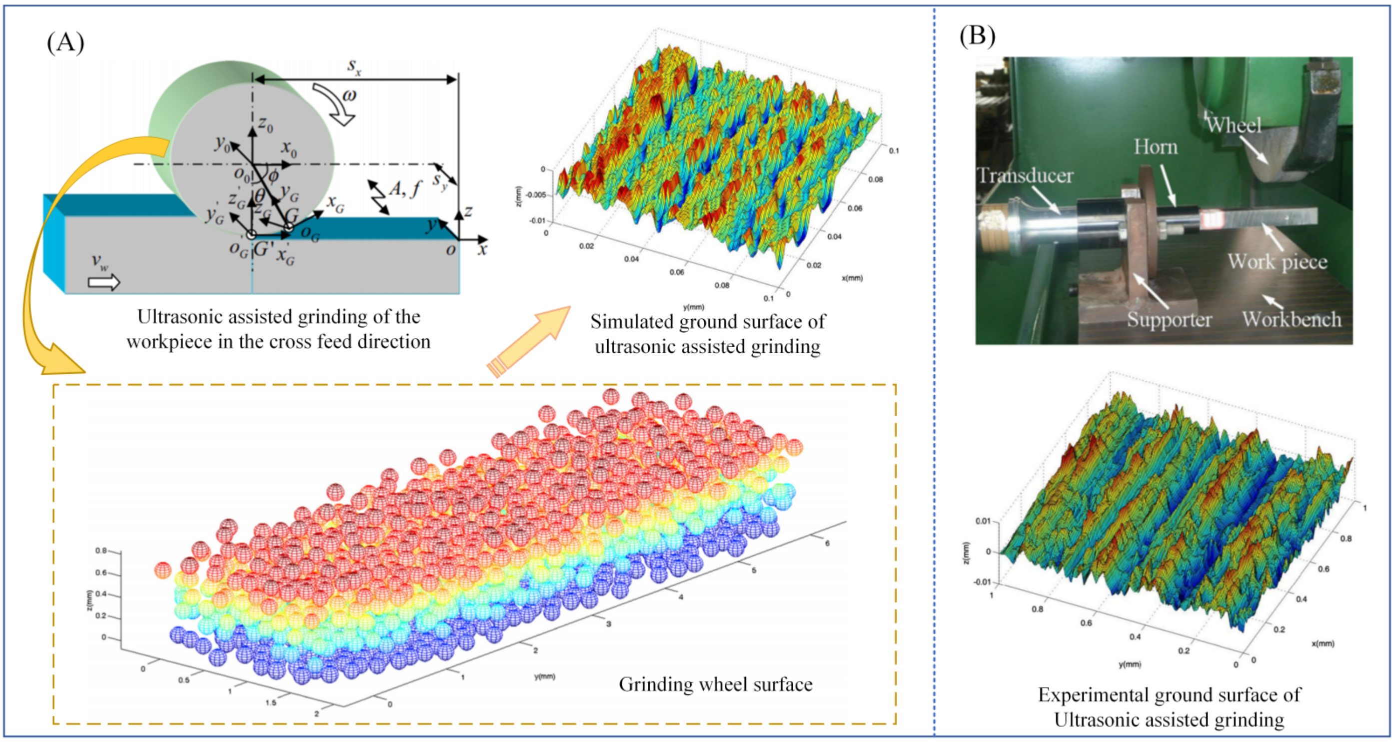


**Figure 14.** Surface topography of ultrasonic grinding [86]. (**A**) Simulation, (**B**) Experiment.

6.4.3. Surface Residual Stress

Surface residual stress is one of the criteria for evaluating the effectiveness of grinding, and residual stress inside the workpiece can affect the service life of the workpiece to some extent. Compared with compressive stress, which is effective in improving the service life of the workpiece inside the workpiece, in ceramics and high-temperature alloy materials, the residual stress can produce certain deformation, reduce the tolerance, decrease performance, and even cause phase transformation inside the workpiece material [88,89]. The increase in grinding temperature leads to a decrease in the yield strength of the material, an increase in plastic deformation, and an increase in the residual tensile stress generated by the grinding heat, which affects the properties of the workpiece; whereas the residual compressive stress generated by the mechanical stress is conducive to the improvement of the surface fatigue strength. Through the above section, we know that the establishment of mathematical models can predict the grinding force and grinding heat, and further can also be derived from the surface residual stress model. With a single grain as the object of study, we can analyze the motion characteristics of the abrasive grain under the action of axial ultrasonic vibration, derive the cutting deformation force calculation expression, establish the axial ultrasonic vibration-assisted grinding of the surface residual stress model, and can be experimentally verified that ultrasonic vibration can reduce the tangential grinding force and the intensity of heat source, thus reducing the grinding temperature and affecting the formation of surface residual stresses. Meanwhile, the scratch load can be reduced by the ultrasonic vibration-assisted grinding process, and with the increase of the scratch depth, the residual stress is changed from tensile stress to compressive stress as measured by Raman spectroscopy [90]. The influence of different processing parameters on the surface residual stress is also different. Some scholars, through a combination of single-factor test and finite element simulation method, found that with the increase of spindle speed, the surface residual stress gradually decreases; with the increase of ultrasonic amplitude, the surface residual stress is firstly increasing and then decreasing [42].

#### 6.4.4. Discussion

In summary, the service life of the workpiece is reflected in the requirements for surface quality, and a number of scholars have simulated the surface morphology of different machining methods and predicted the surface roughness after actual machining. Compared with CG, the application of ultrasonic vibration changes the contact relationship between the tool and the workpiece, and the relative trajectory becomes more complex. As a result, the surface topography is improved to some extent, and functional surface textures can be generated. In addition, the application of ultrasonic vibration increases the material removal rate and reduces the surface roughness. However, the relationship between the ultrasonic vibration parameters and the machining process parameters on the surface quality of the workpiece needs to be further investigated. Therefore, it is necessary to specifically analyze the surface quality after ultrasonic vibration-assisted grinding of advanced materials through a combination of simulation and experimentation.

## 7. Summary

This paper reviews the current research on ultrasonic vibration-assisted grinding (UVAG) and examines the state of research in various areas, including conventional grinding of advanced materials, UVAG technology, ultrasonic vibration systems, material removal mechanisms, grinding forces, abrasive tool wear, and grinding surface quality. Based on the information gathered so far, the large-scale application of UVAG still faces challenges. However, machining efficiency can be improved, and the surface roughness of the machined material can be reduced to the micro-nanometer scale by appropriately adjusting machining parameters and utilizing different ultrasonic vibration modes. Furthermore, the rapid development of advanced materials has contributed to the advancement of UVAG technology. The following conclusions can be drawn from this review:

(1) Traditional grinding methods for advanced materials often suffer from issues such as excessive grinding forces, high grinding temperatures, and significant abrasive wear, which hinder the development and application of precision components made from these materials. Therefore, new specialized processing methods are needed, with ultrasonic vibration-assisted grinding (UVAG) emerging as a key technique. Further research is required to explore the grinding mechanisms and effects of UVAG when applied to advanced materials.

(2) The ultrasonic vibration system is mainly composed of an ultrasonic power supply, energy transfer device, transducer, ultrasonic horn and tool or workpiece. Currently, most ultrasonic vibration systems utilize the ultrasonic horn to drive tool vibration. However, these systems often suffer from low design accuracy, insufficient research on bending vibration, and poor tool vibration, which negatively impacts material processing. The main challenges facing the UVAG system include stable control of output signals, improving the efficiency of electro-mechanical conversion (transducer), and developing multi-dimensional vibration systems. The tunability of vibration parameters (frequency, amplitude) and optimization of the mechanical structure are crucial for future advancements.

(3) In terms of the material removal mechanism in ultrasonic grinding, previous research has primarily focused on the material removal processes of conventional grinding wheels under different vibration modes and grinding parameters. Additionally, a significant amount of research has analyzed the ultrasonic grinding process through actual machining tests and finite element analysis. However, few studies have investigated the removal mechanism

of ultrasonic vibration-assisted grinding of titanium alloys from the perspective of microscopic interactions between adjacent abrasive grains and small grinding heads, as opposed to conventional grinding wheels.

(4) In the study of ultrasonic grinding force, many researchers have used UVAG to study the machining performance of different advanced materials by establishing a mathematical model of ultrasonic grinding force, studying the ultrasonic vibration-assisted grinding force by numerical simulation, and experimentally exploring the effects of different machining parameters and ultrasonic vibration modes on the grinding force. However, with the application of more and more complex curved structures, traditional grinding wheel grinding is difficult to process effectively due to the influence of size, so it is necessary to carry out research related to ultrasonic grinding on small grinding heads.

(5) Most of the scholars in the field of abrasive wear have used experimental methods to observe the abrasive wear morphology and to qualitatively analyze the abrasive wear in ultrasonic grinding of specific materials. Abrasive wear is affected by a variety of factors, and by establishing a prediction model for abrasive wear, it is possible to analyze the effect of different processing parameters on the wear rate of abrasive tools, so it is necessary to study the abrasive wear and its prediction model for a specific processing method.

(6) In terms of surface quality, many scholars have carried out surface topography simulation studies by establishing surface topography prediction models for different ultrasonic machining methods and effectively predicted the surface roughness after actual machining. However, there is still a need to explore how the ultrasonic vibration parameters and machining process parameters affect the surface quality of workpieces. There is an urgent need to comprehensively and specifically analyze the surface quality under the ultrasonic vibration-assisted grinding advanced material process through a combination of simulation and experimental verification.

## Author Contributions

Conceptualization, L.Z. and Q.L.; Methodology, C.L. and Y.Z.; Software, C.L. and Y.Z.; Validation, X.S., Q.L. and S.Q.; Formal Analysis, X.S.; Investigation, C.L., Y.Z. and Q.L.; Resources, Y.Z., X.S. and Q.L.; Data Curation, D.W. and W.S; Writing—Original Draft Preparation, C.L. and Y.Z.; Writing—Review & Editing, L.Z.; Visualization, Q.L.; Supervision, L.Z.; Project Administration, L.Z.; Funding Acquisition, L.Z.

## Ethics Statement

Not applicable.

## Informed Consent Statement

Not applicable.

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## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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