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Energy aspects and workpiece surface characteristics in ultrasonic-assisted cylindrical grinding of alumina–zirconia ceramics

Ali Zahedi [a,b,*], Taghi Tawakoli [a,1], Javad Akbari [b,2]

[a] Institute of Grinding and Precision Technology (KSF), Furtwangen University of Applied Sciences, Jakob-Kienzle-Strasse 17, 78054 Schwenningen, Baden-Württemberg, Germany

[b] Center of Excellence in Design, Robotics and Automation, School of Mechanical Engineering, Sharif University of Technology, 1458889694 Tehran, Iran

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ABSTRACT

Ultrasonic assisted grinding is a novel method for improving the grinding process of difficult-to-cut materials. In the present research a novel setup has been designed and manufactured for utilizing ultrasonic vibrations in external cylindrical grinding. The designed ultrasonic head vibrates a rotating workpiece in axial direction. An alumina–zirconia ceramic (AZ90) has been selected as the workpiece material. Energy aspects and workpiece surface characteristics of ultrasonic assisted cylindrical grinding (UACG) and conventional cylindrical grinding (CG) processes have been analytically modeled and corresponding grinding experiments have been performed. The combined kinematics of the cylindrical plunge grinding process and axial ultrasonic vibrations provide a unique surface treatment conditions, which leads to reduced peak heights and increased valley depths of the surface topography. The main axial vibration mode provides the overlap of the adjacent cutting traces and consequently smoothens the surface topography in cylindrical plunge grinding. It has been analytically and experimentally shown that, applying ultrasonic vibrations, grinding energy can be reduced up to more than 35% depending on the process parameters. The surface characteristics of the ground workpieces have been investigated in terms of four surface roughness parameters and the roundness error.

1. Introduction

Machining with undefined cutting edges has been shown to be promising especially in treating difficult-to-cut materials, and in different phases ranging from bulk material removal to finishing. Grinding is the most developed and well-known process in this category, where the material removal is done by a multitude of randomly positioned and shaped cutting grains held together in a bond material. The inherent complexity of the grinding process leads to difficulties in its analysis and consequently limitations in its applications. These challenges would be even more intensified for novel techniques introduced to the conventional process. Nevertheless the emergence of some novel materials which cannot be treated efficiently with other machining techniques, has made the role of the grinding salient.

Every edge of an abrasive grain is a potential cutting tool but only the edges instantaneously protruding from the bond material would be able to do the cutting action (static cutting edges). Topographical analysis of the grinding process has shown that, only a very small portion of the static cutting edges are involved in the cutting action (dynamic cutting edges) while the rest of them are engaged in rubbing and ploughing i.e. performing no material removal [1–4]. The ratio of the dynamic to the static cutting edges is reported to be in the range from 2% to 12% [1]. Hence, the major fraction of the grinding energy is consumed by rubbing and ploughing [2]. Any attempt to increase the ratio of the dynamic to the static cutting edges would lead to reduced grinding forces, lower temperatures, lower wheel wear and higher material removal rates. By changing the kinematics of the grain-workpiece engagement, applying ultrasonic vibrations in grinding can be favorable in this aspect [3]. Increased chip thickness, engagement velocity and grain depth of cut are the reported features of ultrasonic assisted grinding (UAG) [3]. The possibility of attaining high material removal rates, along with high geometrical freedom make UAG an interesting choice for grinding brittle/hard materials such as advanced ceramics [4]. Elastomechanical ultrasonic vibrations are generated by the transformation of electrical energy in

* Corresponding author at: Institute of Grinding and Precision Technology (KSF), Furtwangen University of Applied Sciences, Jakob-Kienzle-Strasse 17, 78054 Schwenningen, Baden-Württemberg, Germany. Fax: +49 7720 955779.
E-mail addresses: ali.zahedi@hs-furtwangen.de, azahedi@mech.sharif.edu (A. Zahedi), ta@hs-furtwangen.de (T. Tawakoli), akbari@sharif.edu (J. Akbari).
[1] Fax: +49 7720 3074208.
[2] Fax: +98 2166000021.

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piezoelectric or magnetostrictive converters [5]. The high frequency motion component induced in the grinding zone alters the material removal mechanism. Applying the method to different materials and different process kinematics has led to positive effects such as lower forces and temperatures, higher material removal rates and longer tool life [3,6–10]. There would also be beneficial environmental issues such as removal of the grinding fluid through the possibility of dry grinding [8].

Advanced ceramics have acquired a great importance in a wide range of industries owing to their outstanding properties such as heat, wear and corrosion resistance, and high strength to weight ratio. As the sintering process of ceramics is accompanied by shrinkage, a finishing machining process is always needed for high accuracy ceramic components. The need for a finishing process also arises with the requirement of complex geometries which cannot be generated by sintering [4,11]. The finishing process of ceramic parts is generally performed by grinding with diamond wheels [11]. Although practical, the grinding of ceramics is still costly owing to their high hardness, low machinability, and the high cost of diamond wheels. That is the reason why a better understanding of the ceramic grinding process has been the subject of research for decades and many modifications and improvements have been introduced in this field to optimize the time and costs, and retain the quality at the same time. The mechanism of ceramic grinding has been studied since the early 1970s [12–15]. The performed research in this time period were mostly concentrated on the brittle and ductile cutting regimes of ceramics. In the following decades, further research was carried out to control and optimize the material removal mechanism for better process outputs [16–18]. With the improvements in inspection, measurement and microscopy technologies, grindability [19], mechanical properties [20], finished surface quality [21–24], and the processing force/energy [25] of different ceramic materials have been studied. Some studies have also been aimed towards the predictive modeling of ceramic grinding processes using numerical [26–28], statistical [29,30] and analytical [31] approaches.

Following the scientific research trends, and regarding the demand for high precision round ceramic parts in various fields such as optics and sensor/actuator industries, the present study is intended to investigate the effects of ultrasonic vibrations on the grinding energy and surface characteristics of ceramic parts in the cylindrical plunge grinding process. This study is in accordance with a concept introduced [32] for actuation of the workpiece in cylindrical grinding. When high finished surface quality is required, cylindrical grinding is usually performed with crossfeed which provides finer surfaces in comparison with plunge grinding owing to the overlapping of successive cutting traces [2]. However, the wheel would be non-uniformly worn which causes uncertainties in the final dimensions of the workpiece and also tends to crown the wheel [2]. Accordingly, a new method has been proposed to improve the workpiece surface in cylindrical plunge grinding while retaining the uniform profile of the grinding wheel. The design process is based on generating ultrasonic vibrations in the workpiece axial direction, while a radial vibration component of smaller amplitude would be also generated owing to the elasticity of the workpiece. As no torsional mode shapes of vibration are present near the working frequency range, no vibration component exists in the cutting direction along the periphery of the workpiece. The axial vibration component applied to the workpiece smoothens the surface topography as it leads to the overlapping of adjacent cutting traces. This combination of cylindrical grinding and ultrasonic vibration parameters provides a unique kinematics in comparison with the most well-known ultrasonic assisted machining processes. An important feature of the proposed method is that vibrating the workpiece rather that the grinding wheel introduces structural benefits such as longer machine tool and grinding wheel life. In addition to that, the method can be easily applied to a wide range of available machinery, wheel types and sizes, and workpiece materials with slight modifications. Up to the knowledge of the authors, no comprehensive study has been carried out on the grinding energy and surface characteristics in ultrasonic assisted cylindrical grinding process. According to the previously published research [32], a novel ultrasonic unit has been designed and optimized using a FEM commercial software, ANSYS. The unit has been manufactured and set into vibration using a MPI Mastersonics AMMM generator (1 kW) and a BLT transducer. Grinding energy and surface roughness models have been developed to investigate the effects of process parameters and predict the outputs of the UACG process. Cylindrical plunge grinding experiments have been performed on alumina–zirconia (90–10%) round bars to assess the effectiveness of ultrasonic assisted cylindrical grinding (UACG) process. The dimensional and form tolerances of the high precision round pieces are mostly dependent on their surface roughness and roundness. In addition to that, the waviness of the workpiece can lead to instabilities in the grinding process [5]. Therefore, in addition to the grinding energy, the surface characteristics of the ground workpieces have been also investigated in terms of surface roughness and roundness of the ground bars.

2. Ultrasonic unit design and manufacture

The underlying concept of ultrasonic assisted machining is the generation of elastic waves of favorable behavior in the system components and subsequently modifying the material removal kinematics. In the case of cylindrical grinding, axial and radial vibrations of the workpiece are preferable which cause the overlapping of individual cutting traces and intermittent cutting conditions, respectively. In order to optimize the design of the structure, harmonic and modal analysis features of ANSYS software have been used. As the transducer in use has its highest efficiency at frequencies near 20 kHz, the ultrasonic unit has been designed to have a mode shape of the same frequency with a vibration peak at the workpiece tip. Therefore, the whole system (transducer, sonotrode and workpiece) will consistently vibrate in a stable and desirable manner. Regarding light weight, acceptable strength, high machinability and high acoustic efficiency, aluminum alloy 7075 has been selected for the construction of the ultrasonic unit. The designed unit is composed of two parts: The main part, booster-sonotrode, provides the connection between the transducer and the workpiece, and the housing holds the vibrating system on the grinding machine spindle. Fig. 1 presents a schematic of the ultrasonic system. It is desirable to have a vibration node in the middle plane of the booster so that the housing will be as isolated as possible from the vibration chain (transducer, booster, workpiece). On the other hand, a vibration peak should be

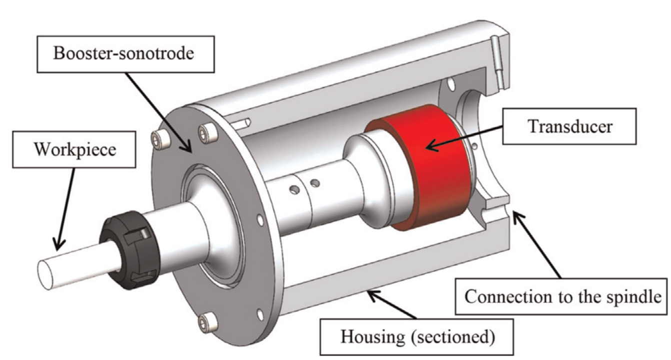

Fig. 1. Schematic of the ultrasonic system with components.