International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:2, No:5, 2008

Study on Ultrasonic Vibration Effects on Grinding Process of Alumina Ceramic (Al_2O_3)

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***Abstract*—**Nowadays, engineering ceramics have significant applications in different industries such as; automotive, aerospace, electrical, electronics and even martial industries due to their attractive physical and mechanical properties like very high hardness and strength at elevated temperatures, chemical stability, low friction and high wear resistance. However, these interesting properties plus low heat conductivity make their machining processes too hard, costly and time consuming. Many attempts have been made in order to make the grinding process of engineering ceramics easier and many scientists have tried to find proper techniques to economize ceramics' machining processes. This paper proposes a new diamond plunge grinding technique using ultrasonic vibration for grinding Alumina ceramic (Al_2O_3). For this purpose, a set of laboratory equipments have been designed and simulated using Finite Element Method (FEM) and constructed in order to be used in various measurements. The results obtained have been compared with the conventional plunge grinding process without ultrasonic vibration and indicated that the surface roughness and fracture strength improved and the grinding forces decreased.

***Keywords*—**Engineering ceramic, Finite Element Method, Plunge grinding, Ultrasonic vibration.

I. Introduction

NUMEROUS non-traditional methods such as electro-discharge machining (EDM) and laser machining, have been developed to process machine parts precisely and efficiently. However among these, Ultrasonic-Assisted Grinding (UAG), in which the machine tool (grinding wheel) or the workpiece is vibrated at ultrasonic frequencies, has been widely used especially for the machining of difficult-to-cut materials such as ceramics and glasses. The benefits include significantly increased rates of material removal, decreased grinding forces, reduced grinding wheel wear and improved surface finish. Vibration-assisted grinding was examined by Wang *et al.* and based on the fact that ground surface texture has dominant roughness in the cross feed direction [1], [2]. The results showed that the ground surface roughness improved both in feed and cross feed direction and the grinding forces decreased. UAG is regarded as one of the cost-effective grinding methods for advanced ceramics. In fact, it is a hybrid grinding process that combines the material removal mechanisms of diamond grinding and ultrasonic machining [3]. The effects of UAG control variables (rotational speed, vibration amplitude and frequency, diamond type, abrasive size, bond type, coolant and pressure, etc.) on its performance (removal rate, cutting force, surface roughness, etc.) have been investigated experimentally [4], [5]. G. Spur *et al.* did many experiments on creep feed grinding and face grinding [6]. Obtained results were comparisons between grinding forces, surface finish and radial wheel wear in grinding operation with and without ultrasonic vibration. A considerable improvement in all the three variables has been reported when the workpiece or grinding wheel is ultrasonically vibrated. Hanasaki *et al.* introduced a very low frequency modulation (30 Hz) of the workpiece during creep feed grinding [7]. The amplitude was in the range of 0-1.5 mm. The risk of surface burning and tempering was reduced with increased amplitude. Poletaev and Khrul'kov have used frequencies up to 400 Hz and the grinding experiments were carried out with hardened nickel alloy [8]. The experiments resulted in reduced cracking and surface burning. Moreover, Wu *et al.* studied on a new grinding technique named Ultrasonic Elliptic-Vibration Centerless Grinding, for grinding process of cylindrical-shaped workpieces [9], [10]. Ultrasonic assisted techniques are extensively used in several manufacturing and machining processes. It is well known that a high frequency modulation (>20 kHz) has the ability to decrease friction in the machining processes. This method was implemented in the grinding process by Nakagawa *et al.* [11]. Actually, up to 90 percent of the energy input in conventional grinding processes is converted to heat caused by friction. If the grinding wheel or workpiece were exposed to an ultrasonic actuation, the forces and temperature would decrease with consequence of possible increased material removal rates. All experiments with ultrasonic assisted grinding resulted in considerable reduction in grinding forces and a slight deterioration of the surface roughness.

The present paper discusses the results of a comprehensive investigation into the grinding of Alumina (Al_2O_3) fine ceramic workpieces which were undergone diamond plunge grinding using ultrasonic vibration. Obtained results have been compared with the available results of conventional plunge grinding process in three categories; normal and tangential grinding forces, surface roughness and fracture

Manuscript received April 30, 2008.
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strength. In this research, workpiece was vibrated at 20.53 kHz ultrasonic frequency along the grinding wheel radius (perpendicular to the axis of rotation). Considering the new experimental set up, this study has been examined a novel approach to ultrasonic grinding of Alumina ceramic. First, we describe the set of laboratory equipments which have been designed for this purpose and then results obtained are demonstrated and discussed.

II. Design and Construction of the Ultrasonic Grinding Apparatus

In conventional ultrasonic machining processes, the cutting tool or workpiece is vibrated at frequencies between f = 20 to 40 kHz and the ultrasonic head which includes; ultrasonic transducer, horn and cutting tool or workpiece, is vibrated in longitudinal mode and set to be same to the resonant frequency. The oscillation amplitude obtained by the transducer is, however, very small and does not exceed 5μm in most cases. Hence, this oscillation must be amplified using an acoustic horn (also called a mechanical transformer, wave concentrator or acoustic amplifier) in order to be able to provide high cutting rates. Moreover, for maximum amplification and high efficiency, the acoustic horn must be designed to operate at resonant frequency, because the machining rate increases with increasing of oscillation amplitude [12]. Due to the complicated shape of the acoustic horn in this study and incapability of the available analytical methods to determine the horn contour, the FEM has been used for determination of geometrical dimensions of the acoustic horn. To obtain maximum amplitude, the length of ultrasonic head must be a multiple of λ/2 (λ is wave length). This matter is very important for generating static waves and should be considered precisely during the design and construction of ultrasonic head. As a result of producing the static waves and also fixed nodes, the oscillation amplitude will be calculable in every points of the motion. In addition, some other limitations and essential conditions in order to analyze of the ultrasonic head using FEM such as; types and optimum number of elements, choosing a reliable analytical soft ware, constructional limitations etc. must be examined. Mechanical properties of the components of the ultrasonic head are given in Table I.

TABLE I
MATERIAL PROPERTIES OF THE ULTRASONIC HEAD COMPONENTS

Part name	Material	Poisson Ratio (υ)	Density (ρ) (kg/m^3)	Elasticity Coefficient (GPa)
Horn & fixture	Steel (St37)	0.3	7870	207
Workpiece	Al_2O_3 Ceramic (99.7**%**)	0.22	3700	350

According to the results obtained from the modal analysis using FEM, for maximum amplification in oscillation amplitude, the ultrasonic head must be designed to operate at the resonant frequency of 20.4 kHz in longitudinal mode. The result observed by the finite element analysis of the ultrasonic head is shown in Fig. 1.

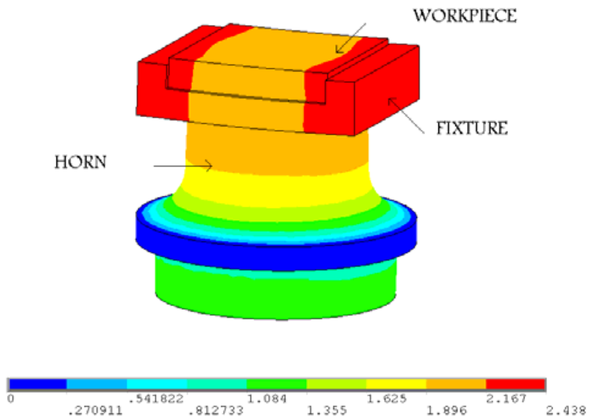

Fig. 1 Longitudinal displacement diagram of ultrasonic head obtained by FEM

To perform desirable experiments, the acoustic horn has been designed considering the ultrasonic vibration generator MSG 1200.IX made by MASTERSONIC Corp. with the following specifications:

- Range of frequency : 17.5 to 28 kHz
- Ultrasonic generator diameter : 40 mm
- Maximum produced amplitude : 2.5μm

The accuracy of the modal analysis has been verified by a Network Analyzer which indicated just 1.3% difference between the results obtained from the test and the finite element analysis.

In addition, since the ultrasonic head must be installed on the ultrasonic vibration generator, the resonant frequency of the ultrasonic head and the generator should be calculated together to find the actual resonant frequency of the whole system. Based on the results obtained from the measurements the best efficiency was gained at the resonant frequency of 20.53 ± 0.11 kHz. Manufacturing of the acoustic horn and fixture must be particularly accurate and precise, because the oscillation produced by the generator must be transferred to the other assembled parts completely without any dissipation of its energy or amplitude. Contact patches between horn-fixture, fixture-workpiece and horn-generator must be thoroughly polished and coincided to prevent from vibration damping as far as possible.

III. Experiments

The affecting variables in this study, which are cutting depth and feed rate in plunge grinding with and without ultrasonic assistance, are listed in Table II. The measured parameters also include surface roughness, fracture strength and grinding force. The results of experiments were analyzed by three-factor factorial method. Each kind of grinding experiments related to one of the mentioned variables, has been repeated three times therefore considering the number of variables and test runs, 18 different kinds of experiments and totally 54 tries have been made separately on 54 different Alumina workpieces.

TABLE II
EXPERIMENTAL CONDITIONS

Variable	*Unit*	*Value*
Vib. Freq.	kHz	20.53
Depth of Cut	µm	2.5, 5, and 7.5
Feed Rate	m/min	1, 3, and 6

The grinding wheel which was installed on a horizontal surface grinding machine (NAGASE Corporation, model SGH-600T), was a diamond grinding wheel of type AC5C 125/100 A2 4 B2-01. Grinding forces in both normal and tangential directions were measured by means of a dynamometer (Kistler Instrument Corporation, type 9-255-B) fixed on the machine table as shown in Fig. 2. The Alumina workpiece is clamped at the horn tip. The ultrasonic head is mounted on the dynamometer using a stand as shown in Fig. 2. Therefore the ultrasonic head oscillates perpendicular to the machine table. Measuring the maximum amount of grinding force has been desirable. Surface roughness of the ground workpieces was also measured by a roughness tester of type TR200 made by Time Group Corporation. Besides, three-point bending fracture strength test was done on the ground workpieces using a tensile-testing machine of type Asmler HCT 25-400 made by Zwick / Roell Corporation.

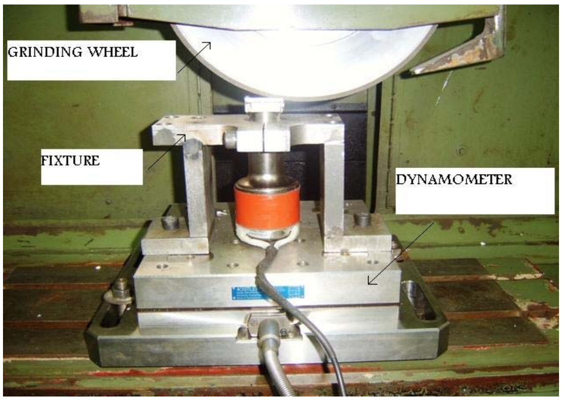

Fig. 2 Illustration of the experimental equipment

IV. Results and Discussion

A. Ultrasonic Vibration Effect on the Normal Grinding Force

The average effect of adding ultrasonic vibration to the conventional grinding process on the normal grinding force has been demonstrated in Fig. 3. Approximately, 23% reduction in the amount of normal grinding forces, when the workpiece was ultrasonically vibrated, has been observed.

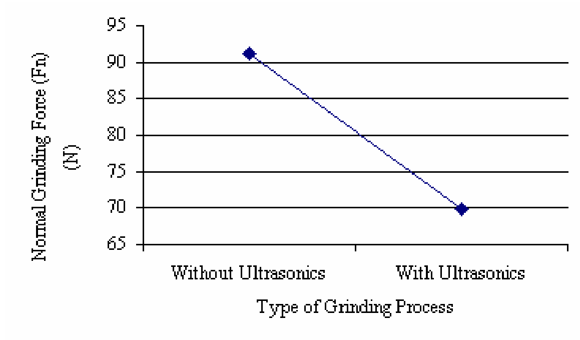

Fig. 3 Ultrasonic vibration effect on the reduction of normal grinding force

Two reasons can be stated for reduction in the normal grinding forces in ultrasonic grinding:

1. Ultrasonic vibration provides a self-sharpening action to the diamond grinding wheel and always causes to keep it sharp, therefore tool pressure and thereby the normal grinding force will be reduced.
2. Besides the tangential relative motion between the workpiece and diamond wheel, a vertical motion will also be produced between them when ultrasonic vibration is applied. Ultrasonic vibration makes it easier for the diamond grits to penetrate into the surface of the workpieces and promotes much more brittle fracture-mode machining and this is why a significant reduction of normal grinding force could be achieved.

The effect of variations of the cutting depth on the normal grinding force has been plotted in Fig. 4. As it can be inferred from the diagram, although the normal grinding force variation follows the same trend with raising the cutting depth in both the operations, ultrasonic vibration causes to fall the normal grinding force at any particular depth of cut.

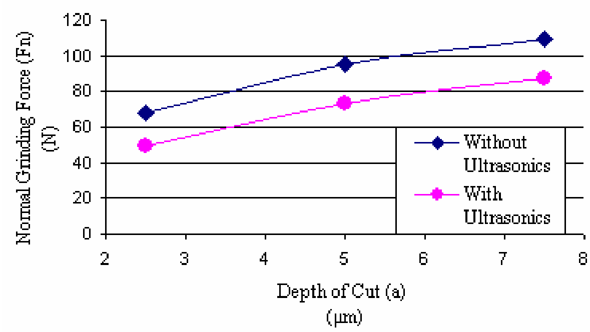

Fig. 4 Effect of cutting depth on the normal grinding force

Fig. 5 shows the percentage of reduction in normal grinding force due to applying the ultrasonic vibration to the grinding operation, against the increase of cutting depth. Almost the percent reduction in the normal grinding force linearly reduces with the increase of cutting depth. This matter could be explained considering the amplitude of the ultrasonic vibration. It can be clearly seen from the Fig. 4 that the normal grinding force increases with the increase of cutting depth. In the depth of cuts lower than 5.2µm, when the workpiece is ultrasonically vibrated, the diamond grits are not continuously in contact with the workpiece. In this stage of ultrasonic grinding, the only factor that affects the normal grinding force will be the normal contact force between the workpiece and wheel resulting from the non-continues contact between them or in other words, will be the force resulting from the ultrasonic vibration. The effect of that force will increase with the increasing of cutting depth. With raising the cutting depth more than 5.2µm the initial pressure, resulting from penetration of abrasive particles into the surface of the workpiece, increases. Therefore an initial static force, which is added to the resulting force of ultrasonic vibration, will be produced. The sum of the two discussed forces (initial static force and ultrasonic vibration force) cause the normal force to increase in the ultrasonic grinding process.

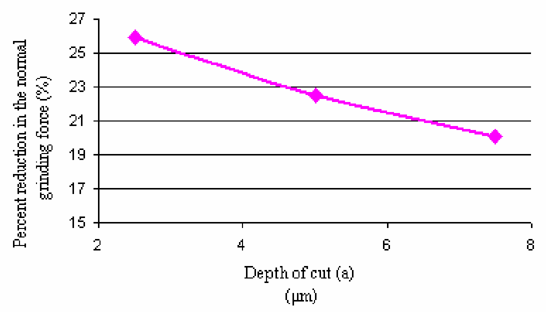

Fig. 5 Percentage of reduction in normal force versus the cutting depth in the ultrasonic grinding

B. Ultrasonic Vibration Effect on the Surface Roughness along Grinding Direction

The average effect of applying ultrasonic vibration on the surface roughness along the grinding direction has been shown in Fig. 6. By using ultrasonic vibration, the surface roughness can be reduced by 8% on average. Considering the results obtained from the factorial analysis, the main factor, which has the greatest effect on the surface roughness, is normal grinding force and therefore, by using ultrasonic vibration surface roughness will decrease with reduction in the normal grinding force.

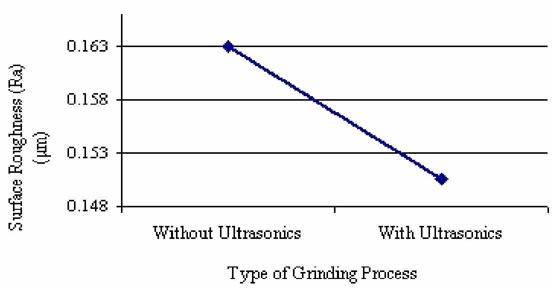

Fig. 6 Reduction of surface roughness as a result of ultrasonic vibration

The variation of the surface roughness versus the feed rate, in both ultrasonic and conventional grinding, has been illustrated in Fig. 7.

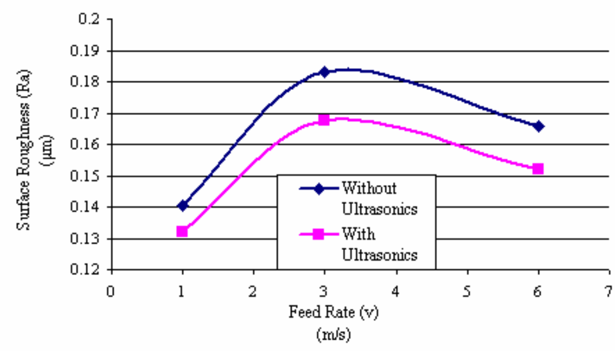

Fig. 7 Surface roughness does not show a unique trend with increasing the feed rate

Although there is not a unique trend in the graph, by ultrasonic vibration assistance, the surface roughness will decrease in all feed rates. The size of a chip, which is produced by an abrasive grit, increases with increasing the feed rate. As a result, the surface roughness will increase with increasing the size of chips.

The variation of the surface roughness against the depth of cut has been also plotted in Fig. 8.

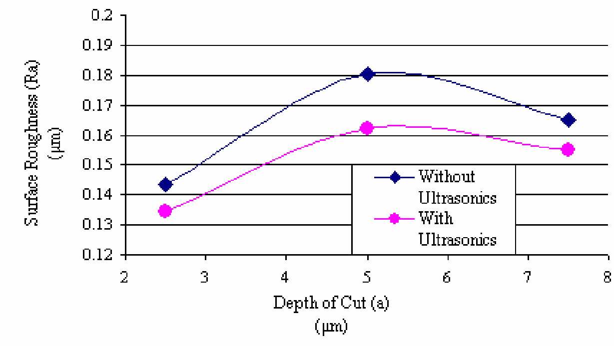

Fig. 8 Surface roughness variation versus the depth of cut

With increasing the cutting depth (<5.2µm), the length of surface micro cracks, which are produced as a result of increasing the normal grinding force, will be longer and then the surface roughness will increase. On the other hand, in deeper depth of cuts (>5.2µm), the abrasion and bluntness of the diamond grits makes some improvement in the surface roughness. As it could be understood from the diagram, the dominant factor on the variation of surface roughness in the depth of cuts lower than 5.2µm is the increasing of the micro cracks' length and in the deeper cuts is the abrasion of the abrasive grits.

C. Ultrasonic Vibration Effect on the Fracture Strength

Fig. 9 shows the required amount of force to fracture the workpieces after the grinding operation. In each case, both feed rate and depth of cut are indicated (separated by a comma). Except for two cases, the required force to fracture the workpieces which had been ground by ultrasonic vibration assistance was higher than the conventional grinding process. With a precise look on the surfaces of workpieces that have been ground ultrasonically, two near notches were found along the grinding direction. In the two mentioned workpieces, which the fracture strength in ultrasonic grinding was lower than non-ultrasonic grinding, fracture started from a crack which was exactly located on those notches.

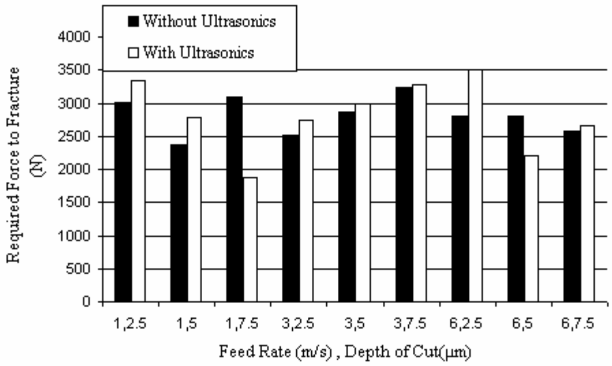

Fig. 9 A comparison between the required amounts of force to fracture the workpieces in both the grinding processes

Regarding the measured forces (except for two mentioned cases), about 10.3% improvement in the fracture strength can be observed. In best cases which there were not any notches on the surface of workpieces, this improvement increased up to 25%. The reduction in the fracture strength after grinding results from under layer micro cracks which damage the surface of material and their length depends mostly on the amount of normal grinding force. By using ultrasonic vibration the normal grinding force will decrease and as a result, the surface damage and fracture strength will decrease too.

V. Conclusion

In this study, a new grinding technique applying ultrasonic vibration along the radius of the grinding wheel was proposed. A compact ultrasonic unit composed of an ultrasonic transducer, acoustic horn and their respective holders was designed and constructed and then installed on a dynamometer surface to measure the normal and tangential grinding forces. During horizontal grinding, the workpiece was vibrated ultrasonically at the resonant frequency in the vertical direction. Performance of the unit, including the percent reduction in the normal and tangential grinding force and also improvement in the surface roughness and fracture strength has been investigated. The results described below has been confirmed the validity of the proposed new grinding technique, and demonstrated that the designed and constructed unit performed well. The results can be summarized as follows:

1. The results of the grinding test showed that the surface roughness of Alumina workpieces was improved by 8% when ultrasonic vibration was applied.
2. The assistance of ultrasonic vibration in the grinding operation reduced the total grinding force. For Alumina (Al_2O_3), particularly, the reduction reached about 22%.
3. The fracture strength of Alumina workpieces, which had been ground using ultrasonic vibration, was improved by approximately 10% on average.

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