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Effect of grinding wheel spindle vibration on surface roughness and subsurface damage in brittle material grinding

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ABSTRACT

The external interference and vibration can seriously affect the machining errors in brittle materials grinding process. This paper proposes a new model to analyze the relationship between surface roughness (SR) and subsurface damage (SSD) depth on the basis of grinding kinematics analysis and indentation fracture mechanics of brittle materials taking the wheel spindle vibration into account. The basic equations, for example, equations of grain trajectory and penetration depth are derived in new forms. Based on the basic equations above, the existing SR and SSD formulae are modified for further study. The effects of grinding and vibration parameters on SR and SSD are respectively analyzed in detail. Results show that both SR and SSD increase with the increase of table speed and vibration amplitude resulting in bad surface and subsurface quality. On the other hand, both the increasing grinding speed and decreasing vibration frequency can improve the quality of ground surface and subsurface with small SR and SSD. In addition, the increase of initial grinding depth and vibration initial phase increase the depth of SSD but have little effect on SR. The penetration depth and distance between grain's tip and finished surface are the two main factors considered to cause the different effect laws on SR and SSD among these parameters. Experiment is carried out to validate the rationality of proposed model. The effect trends of various grinding parameters on SR obtained by our model consist with measured experimental data. The typical subsurface crack system is clearly revealed through the experimental observation on SSD using SEM. Finally, the relationship between the two is fitted utilizing quadratic polynomial. Results show that the SSD depth is nonlinear monotone increasing with SR and the fitting accuracy is more or less affected by both grinding and vibration parameters.

1. Introduction

The interest in the use of brittle materials, for example, engineering ceramics and optical glasses, has increased a lot in the recent years due to their unique physical and mechanical properties such as low density, chemical stability, high hardness and strength at elevated temperature. Meanwhile, brittle materials are poor machinability because of their low fracture toughness. Although advances have been made in the near-net shape technology, as a method of choice for machining brittle materials, grinding is still one of the most efficient techniques. However, the ground brittle components are most likely to contain a deformed layer, surface/subsurface micro-cracks, phase transformation, residual stresses and other types of damage. Usually, there are two major forms of grinding damages. The first type is visible surface damage which is formed on the ground surface due to radial cracks; the other is invisible subsurface damage (SSD) that is formed below the affected grinding zone due to median and lateral cracks [1]. These damages may seriously alter the surface properties and cause strength degradation or even a catastrophic failure of brittle materials [2,3]. Thus, it would be essential to understand the mechanism of material removal and to assess the significance of the process parameters on the finished surface quality in order to obtain the ground brittle components with high surface quality, ultra-precision accuracy and low subsurface damage.

In fact, a large number of researches have been experimentally and theoretically conducted to study the exact nature and the manner of grinding-induced damages. Malkin and Hwang [4] studied the mechanism of material removal in ceramic grinding based on indentation fracture mechanics approach and machining approach. Xu and Jahanmir [5] investigated mechanisms of material removal and inspected subsurface damage utilizing the

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bonded-interface sectioning technique. Pei et al. [6] presented the observation of subsurface cracks in silicon wafers machined by surface grinding process based on cross-sectional microscopy methods. Experimental investigations of machining characteristics and removal mechanisms of advanced ceramics in high speed deep grinding were explored by Huang and Liu [7]. Zhang et al. [8] presented a research on diamond grinding of advance ceramics and found that damage depth was related to the properties of ceramic materials, especially their brittleness. Liao et al. [9] determined the size distribution of grinding-induced cracks to ceramic materials using simulation and statistical techniques. Ahn et al. [10] detected the subsurface lateral cracks at larger scale using the ultrasonic technique and the thermal wave measurement technique. In addition, they suggested that these techniques should be applied to investigate the small cracks developed during the grinding process while taking the effect of small cracks on service life of brittle component into account. Zhou et al. [11–13] did a lot of works on half-space contact problems with micro-defects such as inclusions, dislocations and cracks. The solutions might have potentially significant application in addressing challenging material science, in particular their wear and contact fatigue analysis. Agarwal and Rao [14] investigated the grinding characteristics, surface integrity and material removal mechanisms of SiC ground with diamond wheel on surface grinding machine. Their research linked the surface roughness (SR), surface and subsurface damages to grinding parameters, and then provided valuable insights into the material removal mechanism and the dependence of grinding-induced damage on grinding conditions. Li et al. [15] investigated the depth and morphology of SSD in fused silica samples ground with diamond grinding wheels and examined the factors possibly influencing the depth of SSD.

Since Giovanola and Finnie [16] first found that material removal in machining of certain glasses could be achieved in a ductile mode while the size of the cut was sufficiently small, several models have been presented to predict the ductile–brittle transition to prevent the fracture-based damage in machining of brittle materials. Bifano et al. [17] established a model to study the ductile–brittle transition in machining of brittle materials. Brinksmeier et al. [18] found out that constant penetration depth could give both ductile and brittle mode cutting depending on the ratio of feed rate to depth of cut which indicated the influence grinding kinematics along with depth of cut. Siva et al. [19] proposed a predictive model basing on fracture toughness to determine the critical undeformed chip thickness in the ductile–brittle transition of micro-machining of single crystal brittle materials. Gu et al. [20] proposed four grinding modes of brittle, semi-brittle, semi-ductile and ductile grinding mode during the study of BK7 glass horizontal grinding. Arif et al. [21] presented an in-depth analytical machining model and its experimental validation for various modes of material removal in milling process of brittle materials. The critical conditions for different modes of machining were determined with respect to the relationship between the radial depth of cut and the depth of subsurface damage. Mao et al. [22,23] carried out the systemic experiment to investigate the mechanical interactions between grains and workpiece produced by localized plastic flow in grinding. Neo et al. [24] reviewed and discussed the current state of research and development associated with mechanism of brittle–ductile transition, surface integrity and the factors influencing ductile regime machining (DRM) in details.

Although a wide variety of destructive and nondestructive evaluation techniques have been explored to evaluate the SSD depth, the measuring results may not entirely reflect the characters of all the brittle materials and sometimes only provide qualitative data [25]. In order to provide a simpler and more economic way for rapidly estimating the SSD depth during machining of brittle materials, several empirical and semi-empirical correlations between SSD and SR have been established indirectly [26,27]. Neauport et al. [28] demonstrated that there was a linear correlation between depth of SSD and SR with a proportionality constant. However, the precision of their method was very limited as the proportionality constant fluctuated in a relatively wide range. Lambropoulos et al. [29] developed a model to predict the ratio of SSD and SR through the applied load and the shape of the abrasives. Based on Lambropoulos' model, both Li et al. [30] and Lv et al. [31] proposed a nonlinear theoretical model to evaluate the relationship between SSD and SR through analyzing the stress field and the crack (median and lateral) systems induced by a sharp indenter. Zhou and Xi [32] proposed a new method to predict surface roughness using the stochastic distribution model of the grain protrusion heights to the kinematic analysis without considering the vibration of grinding wheel. Moreover, Yao et al. [33] also took the kinetic relationship between the grain and the specimen into consideration while analyzing the correlation between SR and SSD induced in grinding of BK7.

Recently, a specific-cutting-energy based model was proposed to predict the ductile–brittle transition point in terms of undeformed chip thickness in ultra-precision machining of brittle materials by Arif et al. [34] and was extended by Zhang et al. [35] for vibration-assisted machining (VAM) taking into account the vibration parameters in addition to the work-material intrinsic properties, tool geometry and machining parameters. With the aid of ultrasonic vibration, ground components with smaller surface roughness and lower subsurface damage have been obtained by Wang et al. [36]. Study has shown that ultrasonic vibration frequency and amplitude greatly influences on the material removal, grinding force, material thermal damage, the surface morphology and roughness. So the optimal matching of ultrasonic system and machine tool system is very necessary.

In practice, chatter problem always inevitably happens in machining processes due to the lack of dynamic stiffness of one or several elements of the system composed by the machine tool, the tool holder, the cutting tool and the workpiece material. Usually, there are three different types of mechanical vibrations in machining process, namely free vibrations, forced vibrations and self-excited vibrations [37]. It is worth mentioning that the spindle system vibration is one of the largest error sources in precision grinding and may be caused by factors such as the unbalance, eccentricity and elastic deformation of grinding wheel, rolling bearing defects, collision between elements, friction, chip formation mechanism and variable chip thickness [38–40]. Specifically, Alfares et al. [41] pointed out that the grinding depth was so small in brittle materials machining that even the slightest wheel vibration could have dramatically effects on surface quality, machining accuracy and subsurface damage. Due to these negative effects, chatter occurrence in machining process has been studied deeply. Especially, as an integral part of mechanical engineering, the research of relationship between surface roughness and vibration has become a topic of special interest. Takasu et al. [42] estimated an analytical model of surface roughness as a function of both the ratio of vibration amplitude to geometrical roughness and the phase shift of the vibration to work rotation. Their research made it clear that the roughness could be reduced by optimizing cutting conditions. An on-line measuring technique was developed by Jang et al. [43] for determining the correlation between surface roughness and cutting vibrations. Taking into account the effect of tool geometry, process parameters and relative tool–work vibration, Cheung et al. [44] presented a model-based simulation system for the analysis of surface roughness in ultra-precision diamond turning. Results showed that the surface roughness increased with increasing vibration amplitude and varied periodically with increasing frequency of vibration.