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Investigation on the effects of laser heating on surface quality of OFHC copper in diamond cutting process☆

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ABSTRACT

Due to the excellent electric and thermal conductivity leading to a high laser damage threshold, oxygen-free high conductivity (OFHC) copper is an ideal material for fabricating high power laser reflectors. However, in diamond machining of OFHC copper, the surface quality deteriorates dramatically with the increasing depth of cut resulting from the formation of surface delamination defects. The formation of these defects is suspected of being influenced by the ductility of OFHC copper, which is temperature dependent. In this research, laser heating was introduced into the diamond cutting process to investigate the influence of temperature on the formation of surface defects of OFHC copper. It was found that laser heating was beneficial to the improvement of the surface quality of OFHC copper at large depth of cut in diamond cutting process.

1. Introduction

Diamond machining is a well-developed method for fabricating high precision components, such as optical lens and high precision mold inserts, with machining accuracy in the order of 1 nm [1]. Surface quality of machined parts plays a vital role in their applications, especially in optical applications. There is a wide variety of factors that may affect the surface quality of machined parts, including cutting conditions [2], machine tool conditions [3,4], material properties [5,6] and vibration [7]. A comprehensive review of surface roughness generation in ultra-precision machining process can be found in Zhang's article [8].

Usually, nonferrous soft metals and some engineering plastics are adopted as workpiece materials in diamond machining. Oxygen-free high conductivity (OFHC) copper is such a material used in high power laser reflectors, as its excellent electric and thermal conductivity leads to a high laser damage threshold [9]. Much research has been done on the influence of material properties on cutting performance of OFHC copper in ultra-precision machining. Ding et al. [10] investigated the influence of microstructure on the cutting performance of polycrystalline copper. They concluded that the cutting force and surface roughness were strongly influenced by its crystallographic orientation. Wu et al. [11] conducted a similar experiment on single crystal copper and confirmed that the cutting force varied significantly when cutting along different crystallographic orientations. In addition, Brinksmeier and Schmütz [12] found that the quality of machined surface deteriorated markedly with the increasing of cutting depth from 0 to 10 μm in a plunge-cut experiment. Severe surface damage, often accompanied with significant fluctuation of cutting force, was found to occur occasionally in the region corresponding to the depth of cut larger than 2 μm. It was observed in our previous research [13] that the formation of surface delamination, normally occurring at large depth of cut, was the main reason for the deterioration of the machined surface quality in diamond micro-grooving process. The formation of these delamination defects was suspected to be influenced by the ductility of the workpiece material. The ductility of OFHC copper impacts on the formation of surface defects in diamond cutting process from two aspects. Firstly, a higher ductility usually leads to a larger chip compression ratio which corresponds to a larger cutting force. Secondly, a higher ductility tends to yield a higher degree of plastic deformation of the machined surface.

Laser assisted machining (LAM) has emerged as an alternative machining method over recent decades [14–16]. It is typically used to machine difficult-to-machine materials, such as hard alloys [17–20], ceramics [21,22], and semiconductors [23,24]. The common features of these materials are their exceptional hardness at room temperature and striking thermal softening behavior at high temperature. It is because of

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these characteristics that LAM method is helpful to improve the machinability of these difficult-to-machine materials. Compared to conventional machining methods, LAM contributes to the reduction of the cutting force [19,25,28] and tool wear [26–28] during the machining process. However, surface quality of the machined parts was not the main concern in these LAM attempts. Besides, most of the researches were performed on conventional lathes with low machining accuracy; while only a limited number of them were performed on ultra-precision lathes [24]. A remarkable difference between conventional machining and ultra-precision machining is the significance of the role of surface quality rather than machining cost. For materials that exhibit acceptable machinability in conventional machining process may no longer be the case when assessed by the criteria of surface quality in ultra-precision machining. OFHC copper can be considered as one of those materials with good machinability, both in conventional machining and in ultra-precision machining, when assessed by the criteria of machining cost. However, when assessed by the criteria of surface quality, the machinability of OFHC copper is somehow unsatisfactory in ultra-precision machining as the depth of cut increases and the super-mirror surface finish can no longer be sustained. Laser assisted ultra-precision machining OFHC copper becomes meaningful if it can improve the quality of the machined surfaces. The use of such heating is not to reduce the brittleness of the workpiece materials as in conventional LAM, but to suppress the formation of surface defects at a higher depth of cut.

In this research, the influence of laser heating on surface integrity of OFHC copper in diamond cutting process was investigated. Firstly, a laser assisted ultra-precision machining setup was designed and assembled. Secondly, the influence of laser heating on surface quality of OFHC copper was investigated in a diamond cutting experiment. To our knowledge, this is the first attempt in using laser to assist machining soft materials, and also one of the few researches using laser to assist machining in ultra-precision machining process.

2. Experiment

2.1. Installation of experimental setup

In order to investigate the laser heating effect on the machining performance of OFHC copper in the diamond cutting process, a special purposely-built laser assisted diamond cutting equipment was set up. In this equipment, a fiber laser unit was incorporated into the Optoform 30 (Precitech) ultra-precision lathe, and a video microscope was used to assist in adjusting the relative position between the laser spot and the diamond tool.

Fig. 1 shows the design drawing of the laser assisted diamond cutting machine. The laser beam was designed to focus on a point on the workpiece surface in front of the cutting tool. Both the size and the position of the laser spot could be adjusted by a three-axis motion platform on which the laser output unit was mounted. The video microscope was used to assist in adjusting the relative position between the diamond tool and the laser focal area. Fine adjustment of the relative position between the laser spot and the diamond cutting tool was realized by this method. Fig. 2 shows the actual laser assisted diamond cutting equipment. In this equipment, the spindle of the ultra-precision lathe was fixed and did not rotate during the experimental process. Only straight cutting experiment was performed in this research.

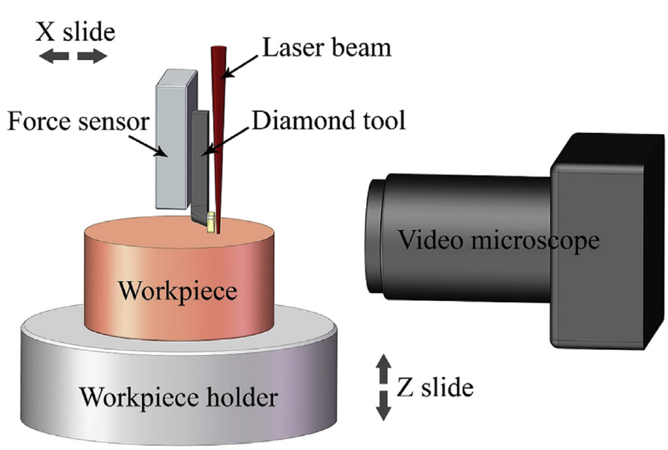

Fig. 1. Design drawing of the laser assisted diamond cutting machine.

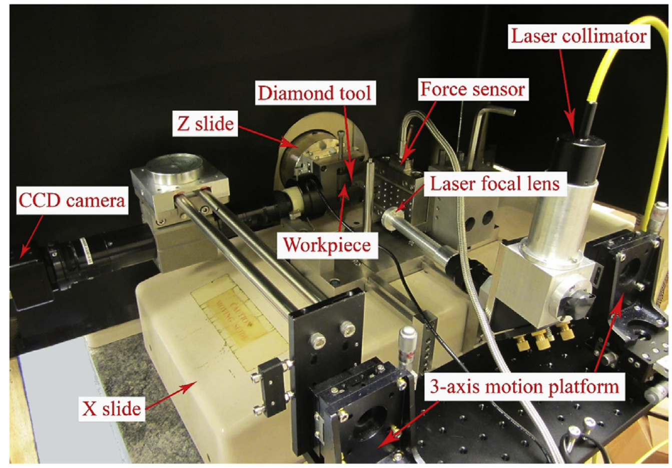

Fig. 2. Laser assisted diamond cutting experimental setup.

2.2. Alignment of laser and diamond tool axis

For the LAM experiments, the distance between the laser spot and the machine tool is an important parameter since it influences the temperature distribution in the cutting area. In LAM at the macroscale, there is no difficulty in adjusting the laser tool distance, because the sizes of the laser spot are typically in the range of millimeters which are large enough to be seen by the naked eye. However, for the LAM at the microscale, both the machine tool tip and the laser spot are too small to be identified by naked eye, which makes it impossible to do tool laser alignment using conventional methods. With the assistance of a video microscope, this problem was readily solved. Fig. 3 shows the schematic diagram of the video microscope assisted laser tool alignment method from the side view.

As shown in this diagram, the corner of the workpiece was intentionally cut off to form a chamfer with an angle of θ. The positions of the diamond tool tip and the laser spot center were marked as A and B, respectively. L and d were the vertical and horizontal components of the distance between point A and point B. From the view of the video microscope, point A and point C were in the same position. The distance between B and C, marked as L, could be measured from the video microscope. Thus the laser tool distance d was calculated as

$$d = L * \tan\theta \quad (1)$$

The laser collimator was mounted on a three-axis motion platform which enabled the laser beam position to be adjusted independently from the diamond tool. By adjusting the measured length L, a desirable tool laser distance d was obtained. Fig. 4 shows the actual image of laser spot and diamond tool which was taken by the video microscope.

2.3. Experimental process

A taper cutting experiment with the assistance of laser heating was conducted. The cutting depth increased continuously from 0 to 20 μm with an inclination angle of approximately 0.057°. The cutting speed was set as 10 mm/min. A cylindrical shaped commercially available