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High-efficiency and precision cutting of glass by selective laser-assisted milling

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ABSTRACT

As a hard and brittle material, glass is difficult to precisely cut with high efficiency. Although various attempts at ductile cutting of glass with high cutting depth have been reported, the low efficiency of the cutting process remains problematic. In order to achieve high-efficiency and precision cutting of glass, this paper proposes selective laser-assisted milling (SLAM). In this method, a fiber laser that has a wavelength out of the absorption band of glass is absorbed only into the small area where the black-body coating is put, and the selectively heated area is removed with a cutting tool. The experimental results of this study have demonstrated that SLAM reduces the arithmetic average of the roughness profile by 74% compared with conventional cutting. An observational analysis of the generated chips revealed that the application of SLAM changed the morphology of the chips from the crack type to the quasi-continuous type. These results demonstrate the feasibility of the high-efficiency and precision cutting of glass.

1. Introduction

Glass has been used in various applications such as in optical components, substrates in electronic devices, and chemical instruments. Recently, microfabrication on glass has received attention. An example is the use of microfluidic chips, which enables medical diagnoses, the development of new medicines, and chemical analyses to be conducted within extremely short time. They are prepared by fabricating micro flow channels, which have complicated configurations, on glass substrates [1]. During the application process, the precision surface has to be obtained with high efficiency. However, there are difficulties associated with the fabrication on glass. Etching is currently applied to the microfabrication of glass. In the etching process, the substrates are covered by a metal coating patterned by photolithography, and the non-coated area is selectively etched [2]. This process has beneficial effects when fabricating on a large scale. However, it is difficult to apply this process to the limited production of diversified products, because the cost of photomasks to create the metal coating is high. As a method for the replacement of etching, the fabrication of glass by cutting has been attempted [3]. If the cutting process is applied, the use of photomasks is not required, and the fabrication process becomes much simpler. However, glass is a hard and brittle material and is known to be difficult to cut.

It is known that glass can be cut in a ductile mode when the depth of cut is small, and in a brittle mode when the depth of cut increases and becomes larger than the critical depth of cut (d_c) [4]. d_c is known to be smaller than 1 μm, which is too small and inefficient to be put to practical use. Thus, the attempts to increase d_c and achieve the ductile mode cutting of glass with a large depth of cut have been reported. Schinker [5] conducted cutting experiments up to 100 m/s cutting speeds, and investigated the mechanism of ductile cutting of glass at elevated speeds. Moriwaki et al. [6] applied ultrasonic vibration to the glass cutting, and reported that d_c was increased to seven times of that obtained with the conventional method. Yoshino et al. [7] conducted scratching tests of glass under high hydrostatic pressure, and reported that d_c was increased.

The other reported method to achieve the ductile mode cutting with high efficiency is to use end mills. Matsumura and Ono [8] reported that the cutting depth could reach 10 μm when an inclined ball end mill was used as a cutting tool. The influence of the tool inclination on a brittle fracture was also investigated [9]. When end mills are used, d_c is dependent not on the cutting depth, rather on the feed per tooth. The mechanism of the crack generation in ball end milling is shown in Fig. 1(a). As shown in the schematic, cracks are generated when the feed per tooth exceeds d_c, which indicates

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Abbreviations: LAM, laser-assisted machining; SLAM, selective laser-assisted milling; SEM, scanning electron microscope; FIB, focused ion beam.

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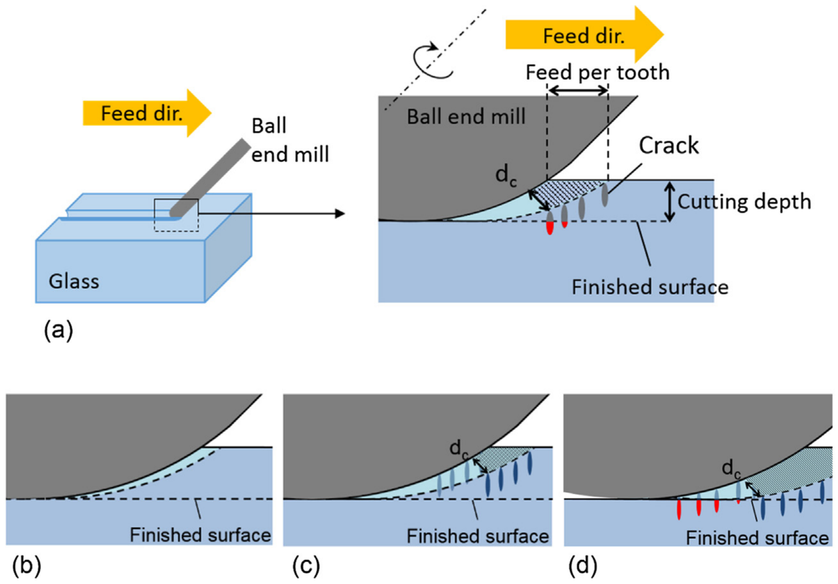

Fig 1. (a) Mechanism of crack generation in ball-end milling. Crack generation by cutting with (b) extremely low feed rate, (c) low feed rate, and (d) high feed rate.

that the ductile mode cutting with large cutting depth is achieved when the feed per tooth is smaller than d_c. However, for the ductile mode cutting, the feed rate is limited to a small value since the feed per tooth has to be small. Currently, the feed rate of the milling of glass is limited to 0.5 mm/min [8]. Even though the cutting depth is approximately 10 μm, efficient machining is not achieved when the feed rate is too small. For these reasons, it is necessary to use a method that can achieve the cutting of glass with a large cutting depth and high feed rate.

Fig. 1(b–d) show the mechanism of the crack generation when the feed rate is changed in ball end milling. When the feed per tooth is smaller than d_c, no cracks form and a surface with a smooth finish is obtained, as shown in Fig. 1(b). When the feed rate is increased and the feed per tooth exceeds d_c, cracks form, as shown in Fig. 1(c) and (d). However, cracks can be removed by the following tooth and the smooth surface can be obtained if the generated crack does not reach the finished surface, as shown in Fig. 1(c).

Therefore, there are two possible approaches for achieving the precision cutting of glass with large cutting depths and high feed rates. The first approach is to increase d_c, which depends on the material properties. The second approach is to decrease the depth of the generated cracks to prevent them from reaching the finished surface. d_c can be expressed as follows [10]:

$$d_c = bE\frac{K_{IC}^2}{H^3}, \tag{1}$$

where K_{Ic} is the fracture toughness, H is the hardness, E is the Young's modulus of the material, and b is a constant that is dependent on the tool geometry. It is known that K_{Ic} increases, H decreases, and E increases when the temperature of the fused silica, which is one of the glass materials and a promising material for the microfluidic chips, increases. The temperature dependences of K_{Ic} and E were investigated by Shinkai et al. [11]. The temperature dependence of H was investigated by Schuh et al. [12]. This indicates that all the material properties of fused silica help to increase d_c when the temperature is increased. Thus, utilizing heat while cutting glass is an appropriate method for increasing d_c.

Furthermore, the increase in K_{Ic} indicates that the extension of the cracks is interrupted. Even if the cracks are generated during the cutting process, the depth of the cracks is decreased, and they can be prevented from reaching the finished surface when the temperature is increased. Thus, utilizing heat enables both of the possible approaches to be achieved simultaneously. However, heating the whole workpiece reduces the accuracy of the cutting because of the thermal expansion of the workpiece and the machine tool.

Laser-assisted machining (LAM) is a method in which a workpiece is heated locally by a laser beam, and then the heated zone is selectively removed by a cutting tool [13]. Laser-assisted machining has been applied to many kinds of hard-to-machine materials such as Inconel alloys [14] and ceramics [15], and its effectiveness has been proved. However, LAM is difficult to use on glass because of the transparency of glass. Glass can absorb two main types of laser beams. The first is a laser beam with a wavelength of over a few micrometers. This wavelength excessively heats the material because the diameter of the laser beam is large owing to the diffraction limit; as a result, a precision surface cannot be obtained. The second is an ultrashort pulse laser beam, which creates a smaller heat-affected zone; this, however, means that the material cannot be heated efficiently.

In this work, we propose selective laser-assisted milling (SLAM). In this method, a fiber laser that has a wavelength out of the absorption band of glass is absorbed only into the small area where the black-body coating is put, and the selectively heated area is removed with a cutting tool. The schematic is shown in Fig. 2.

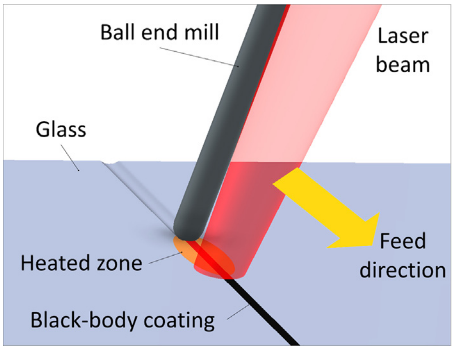

Fig. 2. Selective laser-assisted milling.