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Development of a non-rigid micro-scale cutting mechanism applying a normal cutting force control system

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ABSTRACT

A micro/nano-scale cutting mechanism using a non-rigid tool holder has been developed. This mechanism, which relies on a control principle that is based on a technique for nano-cutting using an atomic force microscope (AFM), can be used to fabricate grooves with a constant cutting depth on the order of a few micrometers. A linear displacement sensor is used to measure the deformation of a flexible cantilever beam to which a single-crystal diamond tool is attached. This sensor, operated in conjunction with a feedback control system and piezoelectric actuator, can maintain a constant normal cutting force during the machining process. Unlike other nano-cutting systems, this system is attached to a common machine tool that increases its machining area to a couple of square centimeters, which is required for practical applications. Several experiments were performed using this cutting mechanism to assess its performance during the cutting process, especially when the grooves are fabricated on inclined or curved surfaces without a prior knowledge of the surface geometry.

1. Introduction

The development of micro-textured or "engineered" surfaces has increased because of the wide range of applications of such surfaces in various industrial fields, such as electronics, energy, optics, mechanical, tribology, and biology. Examples of these surfaces can be found in optical lenses, prism sheets for liquid crystal display (LCD) panels, surfaces with textures designed to produce the "lotus effect" to repel water, heat exchangers, etc. [1,2]. Micro-structures on mechanical components are frequently manufactured using lithographic and etching techniques; however these processes present some disadvantages including the necessity of sophisticated and expensive equipment, limitations on the materials where the technique will be implemented, geometrical limitations (of the structures to be fabricated and of the surface where the structures will be fabricated), and the use of hazardous chemicals, between others. In particular, elements with features such as moth-eye structures, for the suppression of the reflection on surfaces, result complicated to manufacture, especially when they are fabricated on non-flat surfaces [3,4]. Molding and imprinting is a good way to produce such micro-textured surfaces, however, the precision of the mold is one of the most important factors because it represents the quality of the molded product. Due to the fact that precision machining with diamond tools has been used increasingly in the manufacture of high-precision machined parts for advanced industrial applications, it represents an excellent candidate for micro-mold fabrication [5].

In recent years, several techniques that uses diamond tools have been developed for the fabrication of micro-structures and micro-grooves [6–12]. However most of these processes can be implemented only for the machining of flat surfaces and/or need ultra-high-precision motion mechanisms under strict environmental conditions and very complex control systems to obtain the required precision on the nano/micro-scale. This is principally because conventional cutting machines set the cutting depth by their feed mechanisms (hereinafter referred to as constant-feed cutting, CFC), so the preciseness of the part produced depends directly on the accuracy of the machine involved in its fabrication [13,14] (Fig. 1a). One solution to this inconvenience is to implement a constant-load cutting process (CLC) (Fig. 1b), where the main purpose is to control the normal cutting force applied to the tool in order to create micro-scale structures with constant cutting depth [13,14]. An example of a CLC process is the nano-cutting technique using the atomic force microscope (AFM) mechanism [15–19], however, because of the limited stroke of the piezo scanner used and the low cantilever stiffness, this process cannot be

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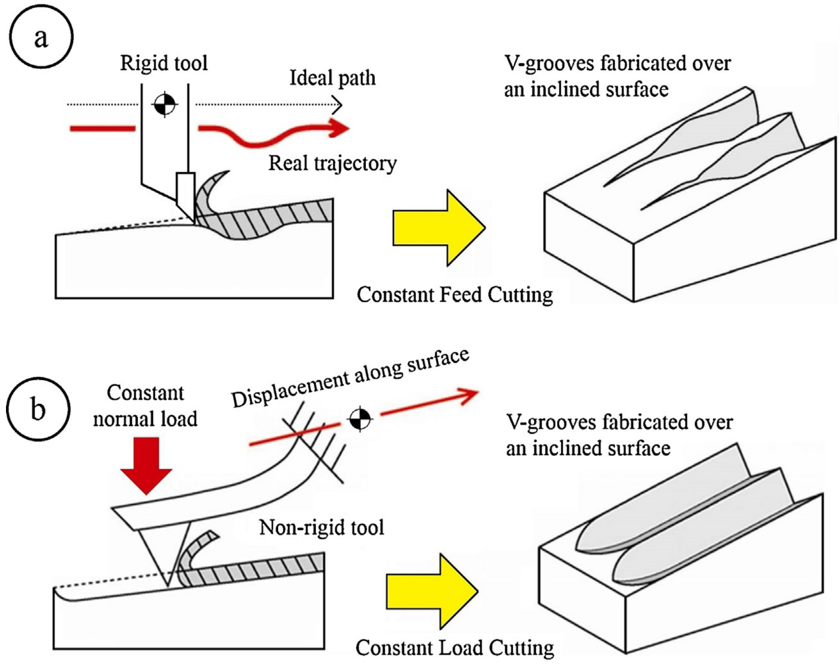

Fig. 1. Comparison between (a) constant-feed cutting (CFC) and (b) constant-load cutting (CLC) principles and their results.

applied for practical cutting. Other mechanisms that uses cutting force control systems have been developed [20–22]; however, they are mainly focused on the machining in the nano-scale regime, and on the compensation of tool wear or tool deflections during the cutting process.

For that reason, based on the AFM nano cutting technique and combined with the advantages of using diamond tools, a non-rigid cutting mechanism for micro-scale machining and a large cutting area was introduced in [23]. The system consists on a single crystal diamond tool that is mounted to a single cantilever beam, and by means of the optical lever method, it is possible to estimate the total cutting force by measuring the torsion and bending of the cantilever beam (the cutting direction must be perpendicular to the longest side of the cantilever). In the same paper [23], a variation of this mechanism was briefly described, in which, by implementing a parallel leaf spring cantilever system and a linear capacitive displacement sensor, the deformation of the cantilever beam caused by the normal component of the cutting force can be estimated and used to implement the FFBC. In this paper, several cutting experiments performed using the cutting mechanism that uses the linear displacement sensor are described. Those experiments were focused principally in its capacity to fabricate grooves with constant cutting depth on surfaces with inclined and curved surfaces, without the necessity of having prior knowledge of the geometry to be manufactured or the requirement of a complex machining control system. Additionally, some cutting experiments performed on glass are presented to observe the behavior of CLC mechanism on brittle materials.

2. Setup of the CLC mechanism for micro grooving

2.1. Design of the cutting mechanism

A schematic illustration of the mechanism developed is shown in Fig. 2. The cutting mechanism consists of a single-crystal diamond tool chip (with a cutting angle of 90[°]) that is mounted at the free end of a parallel-leaf spring cantilever beam. A displacement sensor and a piezoelectric actuator (PZT) are part of the FFBC system required to maintain a constant normal cutting load.

The sensor selected for measuring the deformation of the cantilever is a Lion Precision 5-mm cylindrical linear displacement capacitive sensor. In typical capacitive sensing applications, the probe or sensor is one of the conductive objects, and the target object is the other. The sizes of the sensor and the target are assumed to be constant, as is the size of the material between them. Therefore, any change in the capacitance is a result of a change in the distance between the probe and the target. The electronics are calibrated to generate a specific voltage change for a corresponding change in capacitance that represents a specific change in distance [24]. The sensitivity s of the sensor is 2.5 [μm/V], and the sensor is able to measure variations of under 15 [nm]. To ensure the capacitive sensor functions correctly, it is positioned in a working range that varies between 50 and 100 [μm] from the target plate, using a simple positioning system illustrated in Fig. 2.

Because of the nature of the sensor, which can only detect linear displacements, the cantilever was designed to exhibit a linear deformation when a load is applied to the diamond tool; for that reason, the mechanism developed has parallel-leaf spring cantilever beam. The cantilever and the sensing system are mounted on a linear guide that is connected to a piezoelectric actuator (PZT) and allows a fine displacement of the tool in the Z direction. The PZT has a 120 [μm] stroke. All the components previously described are mounted together and are considered the *CLC mechanism*. To provide motion to the system, and for the fabrication of micro-grooves in a work area of several square centimeters, the cutting mechanism is mounted on a three-axis machine tool. One advantage of the cutting mechanism developed is that the feedback control system is capable of compensating part of the geometric errors of the motion system such as axis misalignments or errors in the path of the tool. Fig. 3 illustrates both the CLC mechanism and the machine tool on which it is mounted.

2.2. Cantilever stiffness

One of the most important aspects considered in the design process was the stiffness of the cantilever beam on which the diamond tool is mounted. As mentioned previously, a parallel-leaf spring cantilever was used because the sensor could only detect linear

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