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An ultrasonic elliptical vibration cutting device for micro V-groove machining: Kinematical analysis and micro V-groove machining characteristics

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Abstract

Micro V-groove machining characteristics of an ultrasonic elliptical vibration cutting (UEVC) device have been experimentally investigated and compared with the conventional micro V-grooving. From the initial experiments performed on ductile material such as aluminum and brass with a single crystal diamond cutting tool, it was found that the cutting force was significantly decreased and the formation of burrs at the machining boundaries was greatly suppressed in the UEVC. The elliptical vibration of the cutting tool was achieved using two parallel stacked piezoelectric actuators with assembling metal structures. Kinematical analysis of the UEVC system has shown that the manipulation of the cutting tool path is possible by changing dimension of the mechanism, phase difference, and relative magnitude of the voltages applied to the piezoelectric actuators.

Keywords: Ultrasonic elliptical vibration cutting (UEVC); Single crystal diamond cutting tool; Burr; Piezoelectric actuator; Phase difference

1. Introduction

The demands for precision and micro-machining technologies that enable to produce mechanical components of micrometer scale and mechanical features such as V-grooves and cavities of micrometer scale have drastically increased with the advance of semiconductor manufacturing industry, micro-electro-mechanical systems (MEMS), bio-technology (BT), and nano-technology (NT). But the conventional machining technologies such as turning, milling, and drilling appear to have reached to the point where the speed at which the conventional machining technologies advances cannot keep up with the demands of industries requiring micro-machining technologies. In an effort to meet these demands, non-conventional machining technologies that include micro-electrical discharge machining, laser machining, electro chemical machining and, etc. have been proposed, but applications of these technologies have been limited because of lack of machinable workpieces, thermal distortion of machined surface, need for the pre-machining of an electrode, high cost and high energy requirements, and so on.

A new surface machining technology that is based on the conventional cutting but has advantages such as high productivity, low-cost and high degree of freedom in machining is needed. Therefore, a new machining method using ultrasonic vibration as a means for precision machining was proposed, but has primarily been applied to machining micro-holes which are created by micro-chipping caused by vibrating abrasive slurry at an ultrasonic frequency with a machining tool, and making it colliding with the workpiece [1]. Other application of the ultrasonic vibration to the precision machining includes reduction of the cutting force by vibrating a cutting tool in the cutting direction. But most of the efforts are geared toward enhancing the surface roughness, not toward the realization of a new kind of precision micro-machining [2–4].

Shamoto and Moriwaki [5] proposed a novel vibration cutting method termed as “the elliptical vibration cutting (EVC)” in which a cutting tool attached to piezoelectric actuators circles along an elliptical path and penetrates into a workpiece when the cutting tool actuated by the piezoelectric actuators is brought into contact with a workpiece. The elliptical path of the cutting tool was generated with two orthogonally assembled

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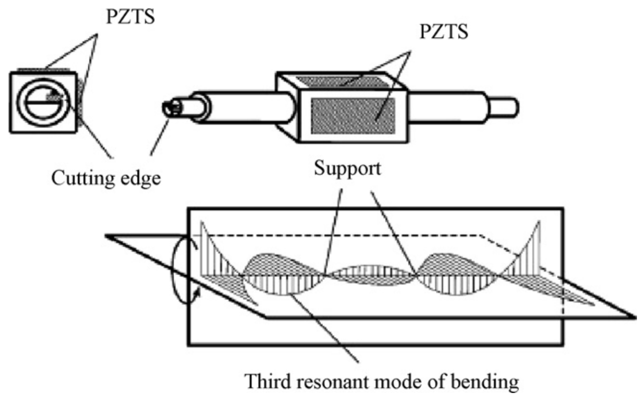

Fig. 1. Elliptical cutting tool path created by superposition of two spatially orthogonal bending modes (by Shamoto and Moriwaki [6,7]).

piezoelectric actuators. The experimental results indicated a significant decrease in the cutting force using the EVC compared with the conventional machining. Shamoto and co-workers [6] continued their research into increasing the excitation frequency to 20 kHz and creating an elliptical cutting tool path by attaching two pairs of piezoelectric actuators to a rectangular metal block in the orthogonal directions as in Fig. 1. In this method, the vibration amplitude of the cutting tool could be greatly amplified by selecting the excitation frequency as one of the resonance frequencies of the system, and the elliptical cutting tool path was created as superposition of two orthogonal bending modes excited by two pairs of piezoelectric actuators oriented 90° to each other. The generation of the elliptical cutting tool path by superimposing two orthogonal modes seems simple in principle, but it is practically challenging to have the elliptical cutting tool path coplanar with the plane containing the cutting and chip-flow direction. Furthermore, there are drawbacks in the design such as zero bandwidth, i.e. fixed excitation frequecny, difficulty in synchronizing two resonant frequencies of the spatially orthogonal bendig modes, compliance of the support, and lack of methodologies to design the optimum shape of horns [7].

Cerniway [8] proposed a device creating an elliptical tool path using two parallel stacked piezoelectric actuators with bandwidth of 4.5 kHz and investigated creating a precision surface on the diamond turning machine. The audible actuation frequency creates unpleasant noises, and the low bandwidth limits the feedrate of the workpiece, resulting in prolonged machining time.

Among many potential applications of the ultrasonic elliptical vibration cutting (UEVC), the UEVC is ideal for patterning micro V-grooves that have been widely used for optical devices, because fabricating micro V-grooves free of burrs with conventional techniques, such as etching and lithography is known to be costly and time-consuming, but cutting in conjunction with ultrasonic vibration has demonstrated its effectiveness in fabricating a surface with high surface finish. Capabilities for fabricating an array of micro V-grooves on a surface are essential to manufacturing optical devices, such as a Fresnel lens and a liquid crystal display (LCD). Accordingly, an in-depth grasp of machining characteristics of micro V-groove using the UEVC would play a critical role in establishing low-cost and reliable micro V-groove fabrication technology.

Lee et al. [9] studied the characteristics of micro V-grooves produced on a planar lightwave circuit and glass by the UEVC. It is notable that feasibility of applying the UEVC to micro V-grooving has been studied, but the elliptical tool paths are generated with superposition of two orthogonal resonant modes, which puts constraints on its industrial implementation as discussed in review of Shamoto's studies.

In this study, a UEVC system, which is based on Cerniway's design but modified to increase the operating frequency to 65 kHz and to facilitate fabrication, is presented, and its kinematical analysis is performed to investigate the formation of the elliptical cutting tool path. In addition, micro V-groove machining characteristics of the UEVC, such as the primary and thrust cutting force, surface finish, and the formation of chips and burrs are experimentally investigated.

2. Generation and analysis of the elliptical vibration of the cutting tool

2.1. Principle of the elliptical vibration cutting (EVC)

In Fig. 2(a–d), the principle of the EVC is illustrated. In the EVC, the elliptically rotating speed of the cutting tool is set to be greater than the cutting speed, which allows the cutting tool to make contacts with a workpiece and to lose contacts in succession along a proceeding elliptical path in the process of cutting as shown in Fig. 2(a). Cutting is initiated bringing the cutting tool into contact with the workpiece as in Fig. 2(b), and then, the cutting tool cuts into the workpiece in a way similar to the conventional cutting process as in Fig. 2(c). What differentiates the EVC from the conventional cutting is the process illustrated in Fig. 2(d) where the cutting tool moves up along the upward elliptical path and lifts off the workpiece. This upward elliptical motion contributes to the reduction of the cutting force, because the frictional force between the rake face of the tool and the chip is reversed in contrast to the conventional cutting process, assisting in discharging of chips. The cutting tool completely looses a contact with the workpiece at lift-off and moves to a position to repeat the cutting cycle as in Fig. 2(a).

2.2. Ultrasonic elliptical vibration cutting system (UEVCS)

Fig. 3 shows the picture of the piezoelectric actuator for the ultrasonic elliptical vibration cutting system (UEVCS) which consists of two parallel stacked piezoelectric actuators, a single crystal diamond cutting tool, and supporting metal structures. The stacked piezoelectric actuators which enable low voltage operation are sandwiched between the assembling structures and preloaded with a bolt. When energized with sinusoidal voltages, the stacked piezoelectric actuators periodically expand and contract, and controlling a phase between the sinusoidal voltages applied to the actuators allows for translating or rotating the cutting tool along a prescribed elliptical path.