主　論　文　の　要　約

論文題目　Research on High-Performance High-Precision Elliptical Vibration Cutting
（楕円振動切削加工の高性能化・高精度化に関する研究）

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論　文　内　容　の　要　約

Manufacturing of dies and molds is an essential area in the industry because it affects the feasibility and economics of producing a tremendous number of assembly products. Especially, dies and molds for information equipment and devices, such as front/back light panels for LCD, holographic optical elements, and optical wave-guides, require ultraprecision machining technologies for their superior dimensional and surface qualities. Mechanical micromachining, i.e. cutting, grinding, and polishing can be adopted to ultraprecision machining of dies and molds with good surface quality. However, ultraprecision grinding and polishing are not suitable because of their incompatibility to machine sophisticated free form surfaces as well as their large manufacturing cost and lead time. Meanwhile, ultraprecision diamond cutting is superior to produce ultraprecision and sophisticated structures because of its high geometrical accuracy, good surface quality and high machining efficiency. More specifically, ultraprecision diamond cutting is utilized practically in the machining of soft metals such as copper and aluminium alloy. On the other hand, difficult-to-cut materials such as hardened steel and tungsten carbide are used for ultraprecision dies and molds which are the main concern of this research. However, conventional ultraprecision diamond cutting of ferrous material could not be applied in die steel machining because of the excessive tool wear. This results from the high chemical activity between the carbon of the tool and iron of the workpiece.

Elliptical vibration cutting method was proposed by Shamoto et al. and it was demonstrated that the mirror-quality surface finishing of hardened steel was obtained by applying an ultrasonic elliptical vibration to the diamond tool. As a result, it was clarified that the ultrasonic elliptical vibration cutting method significantly improves diamond tool life and does not require the practically difficult adjustment between the vibration and cutting directions which is different from the conventional ultrasonic vibration cutting method. After that, follow up studies and developments have been carried out to demonstrate its performances, to expand its applications, and to clarify its mechanics.

The elliptical vibration cutting technology has been successfully utilized in the industry for mirror surface finishing of hardened dies and molds steel without the polishing process but with a diamond tool. Even though the ultrasonic elliptical vibration cutting technology has been successfully commercialized and applied in industry practically, it is still limited mainly in the optical and electric field which demand a precision of nano-level, so called ultraprecision machining. However, the author considers that there are much larger industrial fields such as automobile and aerospace, where the ultrasonic elliptical vibration cutting technology can be applied. There are dies and molds for precision parts, such as lens of LED headlight and landing gear beam, which require a precision surface and shape accuracy of micro-level, hereinafter called high-precision machining. To realize this level of machining, however, research on high-performances of ultrasonic elliptical vibration cutting technology is indispensable. There are several methods to make the ultrasonic elliptical vibration cutting to be a more efficient and/or effective technology.

・Decreasing the manufacturing cost
・Increasing the material removal rate
・Various applicable materials
・Integrated and/or automated processes

To realize the high-performance and high-precision ultrasonic elliptical vibration in the several perspectives mentioned earlier, the author carried out researches as follows:

1. Development of a high-power ultrasonic elliptical vibration cutting device
2. Clarification and suppression of chatter in elliptical vibration cutting
3. High-precision cutting of Titanium alloy Ti-6Al-4V
4. Process monitoring of elliptical vibration cutting

The author, as a researcher of Graduate Program for Real-World Data Circulation Leaders, Program for Leading Graduate Schools of Nagoya University, also tried to study how Real-World Data Circulation (RWDC) can contribute to the elliptical cutting process. RWDC is a new academic field established by Graduate Program for Real-World Data Circulation Leaders, Program for Leading Graduate Schools of Nagoya University. RWDC encompasses the acquisition, analysis and implementation of the real-world data. Moreover, it emphasizes interactive integration of these three procedures to explore unknown mechanisms and create new values from the real-world. Digital data is acquired mainly through the observation and/or measurement of various phenomena in the real-world. Those data should be analyzed with a practical and comprehensive manner to figure out and predict the mechanism of the real-world phenomena. Moreover, those results should be implemented in the real-world to solve the real-world problem or to improve the existing phenomena. A new approach with a perspective of RWDC will assist for understanding the real-world problem clearly which is intricately connected all over the society and for creating a new value which overcomes the stagnant general society circles such as humanities, economics, and manufacturing industries. The author's main concern is how RWDC will be activated for improving the circumstance of the manufacturing industry, especially related to the elliptical vibration cutting process.

In Chapter 1, the background of the ultra-precision diamond cutting of dies and molds made of difficult-to-cut materials and the introduction of ultrasonic elliptical vibration cutting technology are described. Then, a brief overview of the elliptical vibration cutting researches are presented from its proposal to recent developments. Motivation and scope of the thesis is also described based on the disadvantages of this technology which are revealed from the past researches and the industrial demand especially in the field of automobile and aerospace. In order to realize high-performance and high-precision machining of difficult-to-cut materials with ultrasonic elliptical vibration, several objectives of the thesis are set and briefly introduced. Moreover, the new academic field called Real-World Data Circulation (RWDC) is introduced in terms of the necessity of RWDC to comprehend and lead the Industry 4.0 and improving the cutting process. In Chapter 2, the high-power elliptical vibration cutting device was developed and its machinability was verified experimentally. Increased size of PZT actuators were adopted to load more electrical charge for its high-power. At the same time, it adopted the half wavelength mode of axial vibration and 3rd mode of bending vibration for its practical size. Consequently, the developed compact-sized device could generate a stable elliptical vibration with an amplitude of about 10 $\mu m_{p\text{-}p}$ at about 16.9 kHz. With this developed device, the mirror surface finishing of hardened steel with a SCD tool was examined. The performance of the high-power elliptical vibration cutting device was evaluated in terms of cutting forces, finished surface quality, and tool wear. As a result, it was verified that mirror quality surfaces with roughness of 0.013 μm Ra or less could be obtained even at a large depth of cut of 0.4 mm. Considering the conventional elliptical vibration cutting devices were utilized at a small depth of cut of 0.02 mm, this was a remarkable increase in the material removal rate. It was also found that there was no significant tool wear for finishing the surface at least up to a cutting distance of 100 m and the surface roughness was kept to less than 0.007 μm Ra at a depth of cut of 0.3 mm. Chapter 3 mainly clarified the mechanism of frictional chatter in the elliptical vibration cutting, i.e. it was self-excited by the fluctuation of the ploughing force acting on the tool flank at the beginning of cutting in the elliptical vibration cycles. The mechanism led to unique features in chatter mechanics such as occurrence with sharp tools, low amplitude, decreased cutting forces and surface waviness at the beat frequency. Based on the generation mechanism, the lead angle of the vibration tool was tuned, and it was clarified that the chatter could be suppressed successfully with a slight lead. As a result, the elliptical vibration cutting at large widths of cut was realized while clear mirror surfaces were obtained efficiently. In Chapter 4, the ultrasonic elliptical vibration cutting of titanium alloy Ti-6Al-4V was examined. The forced vibration due to the chip segmentation was the most critical problem that limits the material removal rate and deteriorates the cut surface quality. Through a series of cutting experiments, it was found that the periodicity of chip segmentation was linearly increased when the average uncut chip thickness was increased. Moreover, the magnitude of the forced vibration due to the chip segmentation was increased quadratically as the average uncut chip thickness increased. As a result, a simple strategy was proposed to suppress the forced vibration without sacrificing the material removal rate by increasing the cutting width and decreasing the average uncut chip thickness. It was because of the averaging effect, i.e. the force fluctuation with random phases resulting from the randomly occurred chip segmentation tended to cancel each other, so that the decreased dynamic cutting force and better cut surface could be obtained. As a result, the principal component and the thrust component were about 655 MPa and 50 MPa respectively, which are 40% and 12.5% of those of ordinary cutting, and the surface roughness along the cutting direction was 0.15 μm Ra when the cross-sectional area of the uncut chip was 0.3 mm^2. In Chapter 5, a new monitoring method of the elliptical vibration cutting process was proposed and experimentally verified. By utilizing the internal data of the controller of the ultrasonic elliptical vibration cutting device, it was possible to detect the cutting process elements such as machining load and tool wear. Here, the internal data was the changes of power consumption for each PZT actuator and excitation frequency for the elliptical vibration. According to the vibration model of the elliptical vibration cutting process, the frictional force affected the change of power consumption for the PZT actuator, and the normal force affected the change of excitation frequency which was identical to the natural frequency of the vibration. For example, as the tool wear increased during the cutting process, the change of power consumption for the bending vibration and the change of excitation frequency were increased and the change of power consumption for the axial vibration was decreased. The experimental results verified the validity of the proposed process monitoring model. In Chapter 6, the applied Real-World Data Circulation, i.e. data acquisition, analysis, and implementation, in this thesis were described. Moreover, the RWDC in the cutting process was proposed based on Cyber-Physical Systems. To capture a clear image of the RWDC in the cutting process, several related researches were explained. Conclusions of the thesis will follow in Chapter 7.

Based on the researches in the thesis, the low-cost and high-efficiency mirror surface finishing of hardened steel, high-efficiency and high-precision machining of titanium alloy with low cutting forces, and a new function of the elliptical vibration cutting process monitoring can be achieved. Hence, this study is significantly advantageous to expand the applicable industrial fields because of its verified high performance and high precision.