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主論文の要旨

論文題目 Micro/Nano Machining of Steel and Tungsten Carbide Utilizing Elliptical Vibration Cutting Technology（楕円振動切削による鋼と超硬合金のマイクロ・ナノ加工）
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論文内容の要旨

Structured surfaces with sophisticated micro/nano geometry can provide advanced, useful and fascinating functions. To promote widespread use of the structured surfaces, manufacturing technology of the structured surfaces for a variety of materials, especially for ultra-precision dies and molds made of hardened steel and tungsten carbide, is essential. Elliptical vibration cutting (EVC) technology has been expected to be one of the solutions to fabricate the micro/nano structures on hardened steel and tungsten carbide in the molding industry. Hence, feasibility of practical micro/nano structure machining of hardened steel and tungsten carbide is studied by applying EVC in the thesis. This study mainly consists of two topics for the develop of practical technology for difficult to cut materials. The first one is conducted to attain ductile machining of tungsten carbide and to extend the tool life by applying EVC technology. Through a series of grooving and planing investigations, empirical models to predict the cutting performance are proposed. In the second topic, the amplitude control sculpturing method in EVC is studied through theoretical analyses and experimental investigations on hardened steel. Restrictions in machinable part geometry are clarified, and a new compensation method is proposed to improve machining accuracy. The contributions and new findings of the thesis are summarized as follows:

In Chapter 1, the background of the thesis is described. Subsequently, the motivation and objectives are introduced.
Chapter 2 clarified a criterion to achieve ductile machining of tungsten carbide by applying EVC. The mechanism of ductile machining of tungsten carbide by applying EVC was clarified firstly. In the EVC process, the tool cuts the surface that is finished in the previous vibration cycle. Thus, the actual uncut chip, i.e., instantaneous uncut chip thickness, becomes extremely thin. Based on this process, the actual cutting thickness becomes smaller than the critical value for ductile machining. In what follows, the influence of vibration

and cutting conditions on the surface quality was investigated in an empirical manner. And then, the influence of material properties of workpiece on the machined surface quality was also investigated. Experimental results indicated that the machinability of tungsten carbide depends on its grain size and binder phase. In order to attain better surface quality, smaller grain size and presence of the binder phase are advantageous to prevent fracture generation. In addition, the ductile mode machining can be realized when the maximum instantaneous uncut chip thickness (MIUCT) while cutting the finished surface is less than or equal to 4 nm. Based on these fundamental results, ultra-precision textured grooves and a dimple pattern were fabricated successfully on tungsten carbide in ductile mode by applying the amplitude control sculpturing method in EVC.

In Chapter 3, the comprehensive study on tool life and surface integrity in elliptical vibration cutting of tungsten carbide were carried out for practical applications. It was clarified that finer grain size and presence of the binder material are advantageous to prevent fracture generation on the finished surface. However, these conditions are inversely disadvantageous to realize longer tool life. The tool wear progresses faster due to higher hardness and toughness of finer grain materials. The binder materials also accelerate the tool wear development due to their thermo-chemical affinity to diamond. Moreover, due to the specific cutting process with elliptical vibration, the tool damage progress has a strong relation with the cumulative cutting distance. Furthermore, the diamond tool with a crystal orientation of R(110)F(100) is significantly advantageous to decrease the cutting force due to the reduction of flank wear. Based on the clarified nature and obtained results, prediction models of the tool wear, cutting force, and surface roughness were developed. By utilizing the proposed models, appropriate conditions can be selected to make a good balance in the surface quality and the tool life.

Chapter 4 investigated the amplitude control sculpturing method for the micro/nano machining. According to the vibration/cutting conditions and the tool geometry, restrictions in machinable part geometry were clarified and formulated by considering the kinematic model of EVC. For concave structure machining, the curvature radius of the vibration locus needs to be smaller than or equal to that of the target profile at the tangential position on the target shape. At the same time, the clearance angle of cutting tool needs to be larger than the critical entrance angle in the EVC process, while avoidance of the rake face contact to the target structure is important especially in uphill machining. The tool radius also restricts the sharpness of a concave part geometry in the nominal pick feed direction. The curvature radius of the concave part geometry always needs to be larger than the tool radius. Moreover, due to the existence of a finite amplitude in the nominal cutting direction, the proposed amplitude control machining method imposes a machining error between the amplitude command and the envelope of the tool trajectory especially at portions with steep slopes and sharp corners. In order to cancel out this machining error, the amplitude command in the depth of cut direction was compensated. In the proposed compensation method, the vibration locus is controlled to be tangential to the target profile in each vibration cycle. For analytical and experimental verification, a target profile with sine sweep geometry was assumed, where the structure height is 1 μ m and the wave length is changed from 31.62 μ m to 6.75 μ m. Without the command compensation, the maximum machining error increases up to 0.235 μ m in simulation. As a comparison, the envelope of the tool trajectory is accurately identical with the ideal target profile by applying the proposed command compensation method. The machining error is completely cancelled out to be zero in the simulation step.

Chapter 5 clarified the feasibility of highly-accurate micro/nano structure fabrication through experimental investigations. It was confirmed that nano step structures can be fabricated with a machining accuracy of about ± 1 nm in the depth of cut direction. Subsequently, the target sine sweep structure introduced in Chapter 4 was machined. Without the command compensation, the overcut caused serious machining accuracy deterioration, where a maximum machining error of 242.5 nm (peak-to-valley) was generated. The error value is almost identical with analytical one predicted in Chapter 4. On the other hand, it was confirmed that the proposed command compensation method improves the machining accuracy significantly and the maximum machining error was significantly decreased from 242.5 nm to 22.4 nm (peak-to-valley). The restriction in the clearance angle of the tool was also evaluated by demonstrating the comparison of the theoretical analyses and the experimental results. The contact between the flank face and the target shape resulted in significant tool damage and deterioration of the machining accuracy, where a maximum machining error of about 378.2 nm (peak-to-valley) was generated in the machining of the same sine sweep structure. Next, a variety of geometry were machined, where accurate nano sculpturing with a structure height of 20 nm and wave length of 1 μ m was attained by applying the amplitude control commands with sinusoidal, zigzag, and ramp waves. A sophisticated 3D micro/nano structure, i.e., a sinusoidal grid surface, was also machined on a hardened steel workpiece. Without the command compensation, there was a maximum machining error of 114.1 nm (peak-to-valley) between the target profile and the measured profile in the depth of cut direction. Meanwhile, the maximum machining error was decreased significantly into 22.6 nm (peak-to-valley) with the command compensation. The experimental results verified the feasibility of efficient and accurate micro/nano machining by the proposed sculpturing method with the proposed command compensation.

Chapter 6 summaries the brief conclusions obtained in each chapter with brief summary of the achieved results.