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Elliptical vibration cutting of hardened die steel with coated carbide tools

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ABSTRACT

Elliptical vibration cutting of hardened die steel with coated carbide tools is examined in this research in order to achieve low-cost high-precision machining. Diamond coated tools are applied because of superior hardness of their polycrystalline diamond coating and its low manufacturing cost. TiN coated tools are also tested, since they are widely used for conventional machining of steels. Machinability of hardened die steel by the elliptical vibration cutting with coated carbide tools is discussed in three aspects in this study, i.e. transferability of cutting edge profile to cut surface, cutting force, and tool life. The transferability is evaluated quantitatively by calculating correlation coefficients of measured roughness profiles. It is clarified that the diamond coated tools have high transferability which leads to diffraction of light on the surface machined at micro-scale pick feed. Total cutting forces including ploughing components are measured at various feed rates, and then shearing components and ploughing components are separated utilizing linear regression. The measured results indicate, for example, that the all forces become considerably smaller only when elliptical vibration is applied to the TiN coated tool without cutting fluid. It is also found that this considerable reduction of forces interestingly corresponds to higher friction coefficient, which is identified from the ploughing components. Tool life tests are carried out by various machining methods, i.e. elliptical vibration/ordinary wet/dry cutting with diamond/TiN coated tools. The result shows, for example, that the flank wear is smallest in the wet elliptical vibration cutting with the diamond coated tool.

1. Introduction

Development of high precision and cost effective machining method for hardened die steel has been demanded especially in die and mold manufacturing. Hardened die steel is generally finished after hardening to prevent geometrical change and surface oxidation due to the heat treatment. However, the hardness and the brittleness of the hardened steel make it difficult to achieve high quality surface by using conventional machining methods. Single crystalline diamond tools are suitable for ultraprecision machining since they have superior mechanical properties such as high hardness and nano-order sharpness of cutting edges. On the other hand, the use of the single crystalline diamond tools is restricted to nonferrous materials such as oxygen-free copper, electroless nickel or plastics, and they cannot be used for ferrous materials because of rapid tool wear [1]. Song et al. reported that the diamond tool wear is highly dependent on the tool–workpiece contact time, and that the wear can be greatly reduced when the contact time is less than 0.3 ms [2]. Elliptical vibration cutting, which is one of the intermittent cutting processes, has succeeded in suppressing the wear of the single crystalline diamond tools when machining ferrous materials, and it realized ultraprecision machining of hardened die steels [3–6]. However, the cost of the single crystalline diamond tools is higher than ordinary cutting tools made of sintered carbide or high speed steel. To overcome this problem, alternative low cost cutting tools have been examined. For example, Rahman et al. achieved sub-micron surface roughness of hardened steel by applying the elliptical vibration cutting with PCD (Poly-crystalline diamond) tools [7]. The elliptical vibration cutting with PCD tools is tested on other hard-to-machine materials such as sintered carbide as well [8]. Although the manufacturing cost can be reduced by using the PCD tools compared with the single crystalline diamond tools, the PCD tools are still more expensive than the ordinary cutting tools.

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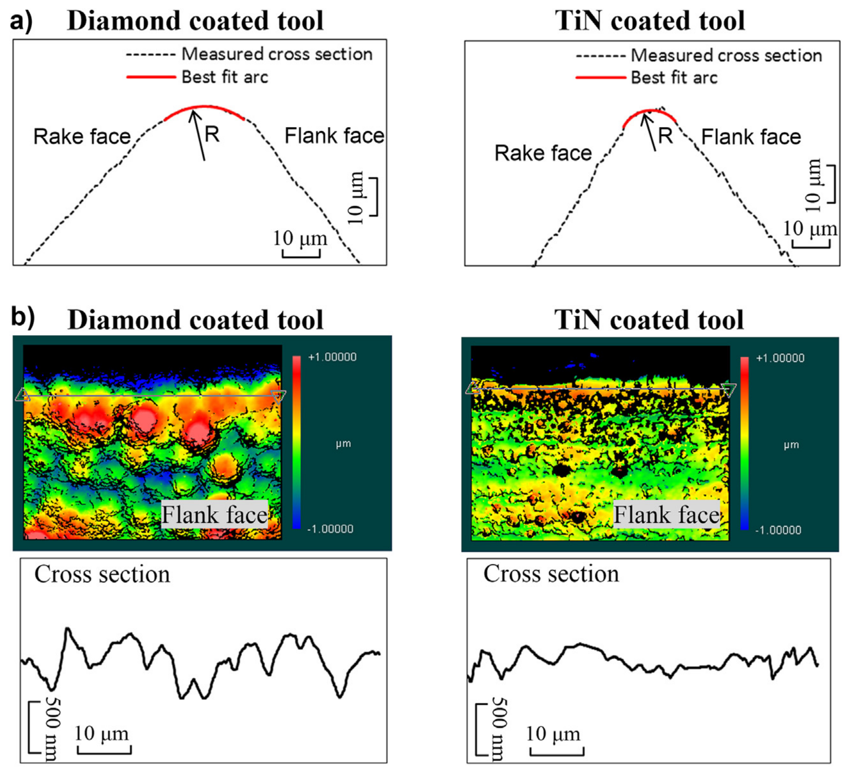

Fig. 1. Cross sections and surface roughness of coated carbide tools. (a) Cross sections of coated carbide tools (*R*: radius of circular arc fitted to cross section curve of cutting edge by least-squares method); (b) surface roughness of the flank face measured along the cutting edge.

Two kinds of coated carbide tools, i.e. diamond coated tool and TiN (titanium nitride) coated tool, are applied to the elliptical vibration cutting of hardened die steel to achieve its low-cost high-precision machining in this research. The diamond coated tool has thin diamond layer which is coated on carbide tool by CVD (Chemical Vapor Deposition) process. It has superior mechanical properties such as high hardness and low coefficient of friction [9–11]. Moreover, the manufacturing cost of the diamond coated carbide tool is lower than other diamond tools [12]. The TiN coated tool is widely used in dies and molds industry, and the characteristics of the TiN coated tool is thought to be different from the diamond coated tool (for example, the cutting edge of the TiN coated tool is generally sharper than that of the diamond coated tool). In order to clarify performance of the coated carbide tools, various experiments are conducted and machinability of hardened die steel by the elliptical vibration cutting with the coated carbide tools is discussed as follows. Transferability of cutting edge profiles to workpiece surfaces is evaluated quantitatively by utilizing correlation coefficients of roughness profiles. Moreover, mechanics of elliptical vibration cutting of the hardened die steel with the coated tools are discussed based on analysis of measured cutting forces and observation of finished surfaces and chips. Influence of elliptical vibration and cutting fluid on the tool wear is also examined by conducting various tool life tests. At last, cutting performances and characteristics of these coated carbide tools are discussed based on analysis of the experimental results.

2. Methods for experiments and evaluations

2.1. Workpices and cutting tools

A typical hardened die steel of Stavax (AISI 420 modified) with hardness of 54 HRC is used for workpieces. The size of the workpiece is 60 × 40 mm, and it is fixed on the dynamometer (Kistler, 9256 °C) to measure cutting forces. Two kinds of coated carbide tools, diamond coated tools and TiN (titanium nitride) coated tools, are tested in this study. The nose radii of the both coated tools is 0.4 mm, and their base materials are sintered carbide. Coated carbide tools have cutting edge roundness according mainly to thickness of coatings. Fig. 1(a) shows cross sections perpendicular to the cutting edges measured with an optical surface profiler (Zygo, NewView7300). The cutting edge roundness is evaluated by calculating the best fit circular arc. The measurements and their evaluations are conducted 9 times for each kind of coated tools, and the mean edge radii of the diamond coated tools and the TiN coated tools are identified to be 16.3 μm and 5.8 μm respectively. Accuracy of the cutting edge profile is also an important factor because its roughness is transferred to the finished surface of the workpiece. However, it is difficult to measure the cutting edge profile engaged to the workpiece. Instead of measuring the cutting edge profile, surface roughness of the flank face along the cutting edge is measured as shown in Fig. 1(b). The roughness Rt of the diamond coated tool and the TiN coated tool are identified to be about 750 nm and 500 nm, respectively.

2.2. Fundamental planing experiments

The elliptical vibration cutting process can be illustrated schematically in Fig. 2. The elliptical vibration is applied so that the process becomes intermittent. The chip is pulled up during cutting while the tool moves down without cutting. The pulling force reduces or reverses the tool-chip friction force and decreases chip thickness, cutting force or energy [3]. The intermittent process and the reduced energy result in practically long tool life [2]. Experimental setup for fundamental planing experiments is shown in Fig. 3. Elliptical vibration cutting device (Taga Electric, EL-50Σ) is equipped on an ultraprecision machine tool (Nagase Integrex, N2C-53US4N4). The cutting tools are vibrated at a frequency of about