Elliptical Vibration Cutting of Steel with Diamond Tools
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Abstract
Diamond turning of steel alloys is impractical due to catastrophic tool wear caused by a combination of chemical and abrasive wear. In the literature, several modifications of the cutting process have been proposed, e.g. cutting in an inert gas atmosphere, cryogenic cutting and vibration assisted cutting, e.g. elliptical vibration cutting (EVC) [1-5]. In this work, the EVC method was investigated, because of best results due to wear reducing effect [3]. By carefully monitoring and adjusting the tool oscillation, tool wear could be reduced by a factor of 10 and surface roughness could be improved.

Introduction
Several discussions regarding the wear mechanisms of diamond tools have been presented in the literature [1-5]. The observed wear has been divided into mechanical-abrasive wear (abrasion, micro-cracking) and chemical-reactive wear (diffusion, oxidation, catalytic graphitization and carbide-formation) or a combination of both. Correlation between tool wear and workpiece hardness or the melting point of the workpiece material do not seem to help predicting the wear behaviour. An interesting correlation was published by Evans [3] who compared the diamond machinability of the elements with the electron configuration of the atoms. He presumes that unpaired d-electrons are responsible for breaking up the carbon bonds in the diamond lattice and therefore should be responsible for chemically activated wear.

Experimental setup
The experiments were carried out on a precision lathe Hembrug Super-Mikrotum CNC. The diamond tools used in the face turning experiments had a tool nose radius of 3 mm, rake angle of 0° and a clearance angle of 5°. The radius of the unused cutting edge was less than 40 nm. Mineral oil was used as lubricant. The outer diameter of the workpiece was 60 mm and the inner diameter 15 mm. The workpiece material was Ck45N (0.45 % C) carbon steel. Surface roughness of the turned samples, cutting edge radius and wear characteristics were determined with a Perthen roughness-profiler, a scanning electron microscope (SEM), a Phase Shift Technology MicroXAM white-light interferometer (WLI) and a Nanoscope III atomic force microscope (AFM).

In Figure 1 the experimental set-up is shown. A 40 kHz, 700W ultrasonic generator (BRANSON) and an air-cooled piezoelectric converter was used to stimulate the tool. A ‘booster’ enlarges the amplitude up to 6 µm and was coupled to a non amplifying resonator (length 5·λ/2). The diamond tool was fixed 'off axis' to the face side of the transducer. Due to the displacement of the tool mass the tool vibrates elliptically. Using a counterweight, the elliptical motion could be controlled within a certain range.
Figure 1: Experimental set-up for EVC (elliptical vibration cutting) of steel with monocrystalline diamond tools

In order to understand chip-forming, surface-structure and the process-stability it is necessary to record the full motion of the diamond tool. Therefore, two eddy-current sensors were used to record the main oscillating direction parallel to the resonator (y) and normal to the face turned surface (z) (Figure 1). A MICRO-EPSILON Series 500 displacement measuring system and a LE-CROY Series 9310A digital oscilloscope were used to record the tool motion. The accuracy of the system was better than 0.2 µm. In-situ measurement is possible due to the insensitiveness to oil-contamination. The recorded signal was analyzed with a personal computer. The amplitudes in y and z direction, the phase lag between the two axes and the tool path were documented.

If $b/a \approx 0$, the effective contact time only depends on vibration frequency, vibration amplitude and cutting speed, since in this case the depth of cut is unimportant. Figure 2 shows the theoretical effective contact times for different amplitudes and cutting speeds for a fixed vibration frequency of 40kHz. If tool and workpiece are in permanent contact, the effective contact time reaches 100%.

Figure 2: Calculated effective contact time in EVC
Results

Surface generation

The roughness of EVC surfaces depends on several factors, e.g. cutting parameters, shape of the cutting edge shape, tool motion and the plastic and elastic properties of the workpiece material. In Figure 3 the machined surfaces of aluminum and steel are compared which were machined under identical conditions. The aluminum surface exhibits regular chatter marks across the whole measured area. Apparently, grain boundaries have no influence on the formation of chatter marks.

On the other hand, two effects are observed when cutting carbon steel:

1) Height variation from one feed mark to the next, caused by an increasing cutting edge radius due to progressive tool wear.

2) Height variation from one chatter mark to the next, caused by irregularly oriented ferrite and pearlite grains with different elastic and plastic properties. Metallographic investigations including SEM of taper sections did reveal a plastically deformed surface layer in the range of the PV-roughness.

![Figure 3: Comparison of EVC machined surfaces of aluminum and steel](image)

Tool wear and effective contact time

The effective contact time has a large influence on diamond tool wear, since the rate of chemical reactions and the temperature in the cutting zone both depend on the effective contact time. Figure 4 shows the measured cutting distance as a function of the effective contact time. A cutting distance of 20 m could be achieved with an effective contact time of 22%. The end of the useful tool life was defined as the cutting distance with a roughness of the machined surface of RMS > 40 nm.

![Figure 4: Relation between cutting length and time of contact](image)
No wear reduction was detected for effective contact times >54 %. Probably, elastic response of the workpiece material and of the resonator lead to a longer effective contact time than calculated.

**Optimized cutting conditions**

In further experiments the ratio of $b/a$ was varied between 0 and 0.1. Tool wear and surface roughness were investigated as a function of the cutting distance. It was found that tool wear decreases significantly with increasing ratio $b/a$. Strong abrasive wear (chipping) is observed, if $b/a$ is close to 0. If $b/a$ approaches 0.1, wear characteristics change into chemical rounding of the cutting edge (Figure 5b). Using optimized conditions the cutting edge radius was only 105 nm after a cutting distance of 1500 m (Figure 5a).

![Figure 5: EVC cutting of Ck45N steel with diamond tools:](image)

- a) Dependence of cutting edge radius and roughness of machined surface on cutting distance
- b) AFM-image of a tool edge after a cutting distance of 1500 m with optimized conditions

**Conclusions**

Several cutting experiments of aluminum and carbon steel using elliptical vibration cutting (EVC) were performed in order to determine diamond tool wear when cutting steel. A strong correlation between diamond tool wear, effective contact time between tool and workpiece and tool motion could was found. Using optimized cutting conditions, the cutting distance on steel could be increases up to 1500 m while the roughness of the machined surface was still acceptable.

**References**


