Dynamic forces and energy dissipation in vibration diamond cutting of copper

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Introduction

In this paper we introduce a method for studying the interaction between tool and workpiece in elliptical vibration cutting at ultrasonic frequencies. The method is based on recording process force signals from a piezoelectric transducer synchronously with the tool displacement. The workpiece-sensor-system is modeled as a harmonic oscillator with known mass, resonance frequency and damping. An interpretation of the recorded data is suggested by means of an harmonic analysis.

Experimental set-up

The kinematics of elliptical vibration cutting and the set-up used in the machining experiments is shown in figure 1. An ultrasonic resonator operating at 20 kHz is mounted vertically with the tool fixed at the lower end of the sonotrode. Although the primary excitation is in the vertical direction (x-axis), a horizontal movement of the tool is superimposed due to periodic bending of the resonator resulting in an elliptical tool path [1]. The ratio of the major to the minor axis of the ellipse approximately is a/b ≈ 20.

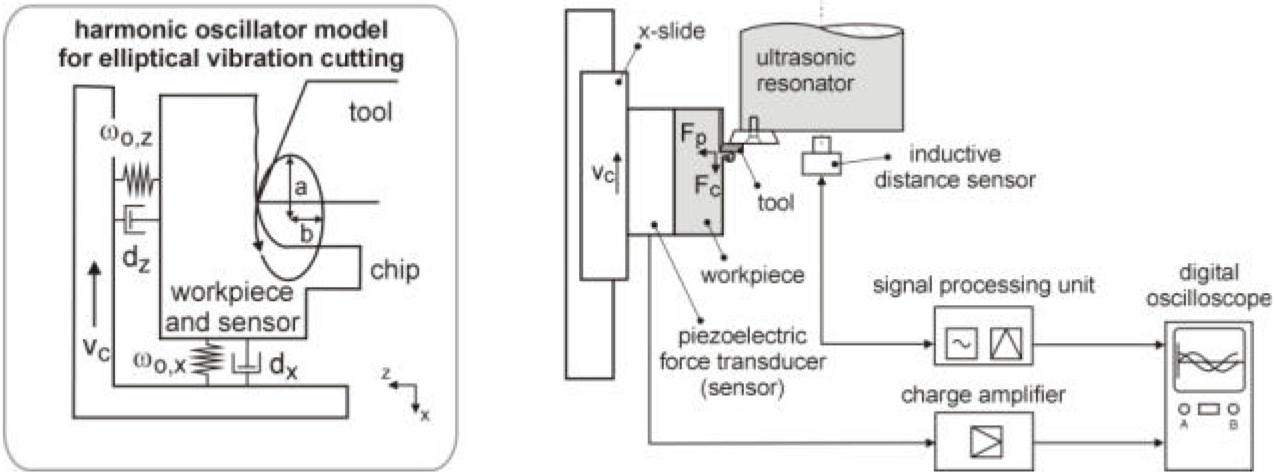


Fig. 1: Harmonic oscillator model for elliptical vibration cutting process and experimental set-up

An OFHC-copper specimen is fixed on a numerically controlled precision xyz-table. A continuous cutting speed v_c is obtained by moving the workpiece along the negative x-direction. The displacement of the tool is monitored by an inductive distance sensor (µ-epsilon), while the displacement of the workpiece-sensor-system is measured with a Kistler type 9251A piezoelectric force transducer in both cutting- and thrust-force direction. All three signals are recorded with a digital oscilloscope sampling at a rate of 3 MHz (Fluke View). The resolution of the measuring device is determined by the limiting frequency of the charge amplifiers (100kHz).

The resonance frequency and damping rate of the workpiece-sensor-system, consisting of workpiece, fixture, transducer and preloading plate have been determined experimentally by recording transients after impulse exciation. The following values were obtained:

$\omega_{0,x}$ = 1.3 kHz and $d_x = 0.05$ in the cutting force direction

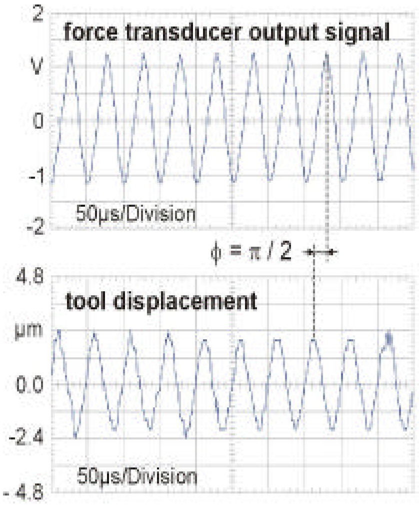
$\omega_{0,z}$ = 1.27 kHz and $d_z = 0.06$ in the thrust-force direction

In a vibration cutting process, the system can be regarded as a pendulum which is excited at a frequency far beyond its own resonance frequency. In this case, the exciting force is phase shifted by π with respect to the pendulums' reaction. Moreover, the exciting force at a given circular frequency is transformed into an vibration amplitude according to the amplitude resonance function [2]. Therefore, the output signals of the transducer do not directly convert into a force, but have to be corrected accordingly. The figures below show the uncorrected output signals as received on the digital oscilloscope in volts.

Experimental results

If the workpiece is fed in at a very low speed v_c, cutting- and thrust force are sinusoidal and in phase. This is also the case, if the motion of the workpiece is stopped altogether ($v_c = 0$). The frequency of the sinusoidal force signals is equal to the excitation frequency (20 kHz).

In the cutting force direction, the tool displacement runs ahead of the displacement of the workpiece-sensor-system by $\pi/2$ or – in other words – the tangential speed of the resonator is phase shifted by π with respect to the displacement of the workpiece-sensor-system (cf. fig. 2). This is due to the fact that the friction vector is always opposed to the velocity of the relative movement.



process parameters:
cutting speed: : v_c = 0.1 mm/s
vibration frequency : f = 20 kHz
vibration amplitudes : a = 2.5 µm
b ≈ 0.125 µm

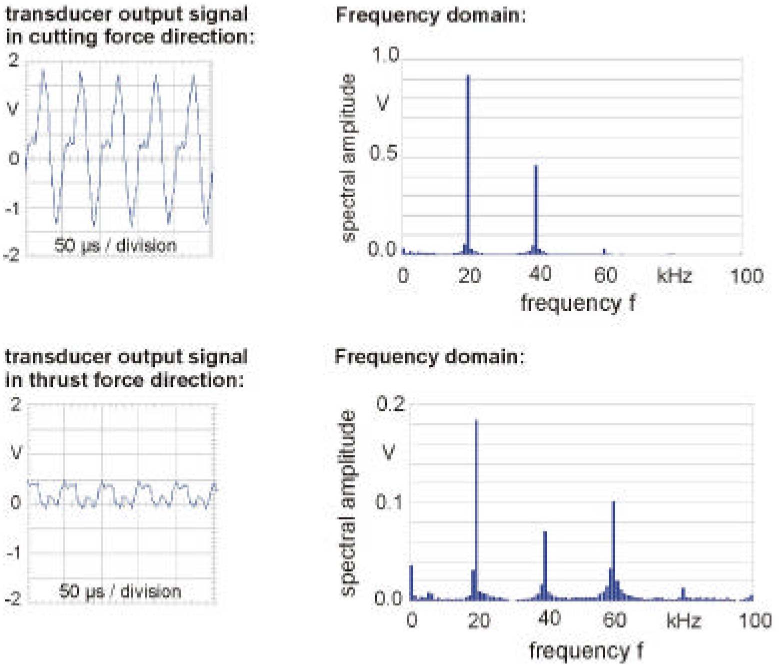
diamond tool:
nose radius : r_ε = 50 µm
rake angle : $\gamma = 0°$
clearance angle : $\alpha = 8°$

Fig. 2: Displacement of workpiece-sensor-system versus tool displacement

Analysis of the process forces in the frequency domain

Generally, one would expect the engagement of tool and chip to occur before the lower reversal point of the tool. The lower reversal of the tool conicides with the positive flank of the 20 kHz sinewave signal attributed to clearance face friction. With an increasing cutting speed v_c, a saddle point appears in the output signal of the force transducer in the cutting force direction. An analysis in the frequency domain reveals higher order harmonic waveforms in the transducer output signals (cf. figure 3). In the cutting direction, the displacement of the workpiece-sensor-system exhibits the second harmonic of the excitation frequency. The output signal in the thrust force direction also comprises a significant fraction of the third order harmonic.

Elastic loading occurs in both the cutting- and thrust force direction, because the elastic recovery of the force transducer is much slower than the resonator movement. Elastic loading results in a static off-set of both signals, if recorded in the DC-mode of the oscilloscope (cf. fig. 3, left).



process parameters:

cutting speed: : v_c = 10 mm/s
depth-of-cut : a_p = 20 µm
vibration frequency : f = 20 kHz
vibration amplitudes : a = 2.5 µm
b ≈ 0.125 µm

diamond tool:

nose radius : r_ε = 50 µm
rake angle : $\gamma = 0°$
clearance angle : $\alpha = 8°$

Fig. 3: Frequency spectra of transducer output signals

Discussion of results

The observations of the force-transducer output signals indicate that there is little cross-talk between the cutting- and thrust-force direction. Therefore, the workpiece-sensor-system is considered an harmonic oscillator with separate resonance and damping properties in each direction (cf. fig.1).

If the workpiece motion is stopped in vibration cutting, no chip formation is to be expected, but still a sinusoidal displacement of the workpiece-sensor-system is observed. The first harmonic in the force transducer output signal can be attributed to clearance face friction. Since the minor axis of the tool oscillation is very small with the ellipse being almost tangential to the workpiece, the clearance face is continuously in contact with the machined surface.

Higher harmonics appear, when the chip formation is initiated by increasing the cutting speed v_c. Thus, the harmonic workpiece vibrations with frequencies larger than the excitation frequency are caused by the chip formation process. In the cutting force direction, the chip is compressed once per tool oscillation. At low vibration frequencies in a quasistatic regime, the thrust force is known to change sign, when the chip is pulled off by rake face friction [3]. This may explain, why we see more complex harmonics in the workpiece displacement in the thrust force direction.

Based on the assumption that the harmonics with order >1 are related to chip formation, we can compare the energy stored in the higher order harmonic vibrations to that contained in the first order harmonic. This determines the minimum energy consumed in the chip formation process:

$$E_{chip} \sim \sum_{n=2}^{\infty} n^2 A_n{}^2 \omega_n{}^2 \qquad \text{(eq. 1)}$$

where A_n is the amplitude of the n^{th} harmonic and $n = 1$ is the fundamental vibration (20 kHz). The energy stored in the fundamental vibration of the workpiece-sensor-system contains fractions of both clearance face friction and chip formation. The overall energy transmitted from tool to workpiece is given by the sum of the energies contained in all harmonic vibrations.

From the practical point of view, a harmonic analysis of the workpiece-sensor vibrations allows to monitor the process in many ways: The beginning of the chip formation is indicated by higher order harmonics in the frequency spektra of the transducer output signals in both cutting- and thrust-force direction. Moreover, the energy consumed in the chip formation can be compared to the overall energy transmitted to the workpiece without explicit knowledge of the interaction forces.

References

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