Dynamic Modelling of the Cusp Error Reduction Phenomenon in High Speed Micro/meso-scale Milling Processes with Ultrasonic Vibration Assistance

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Abstract

A simulation methodology is proposed to understand and illustrate the surface quality improvement phenomena in precision micro/meso scale milling processes with ultrasonic vibration-assistance as well as the influence of the motion parameters on the topography of the generated surfaces. In the simulation of the machined surface generation process, the trochoidal cutting edge motion is dynamically tracked considering the feed per tooth, cutter runout, deflection, and ultrasonic vibration assistance. The feed per tooth influences the interval between consecutive cutting edge positions on the machined surface, which results in cusps. In addition to this, the cusp geometry is altered by cutter deflection and runout. The machined surface topography can be simulated from the continuous cutting edge motions with and without ultrasonic vibration-assistance. The ultrasonic vibration motion enables an overlap between successive cutting trajectories leading to their intrusion into the previously generated cusp. This leads to an array of possible surface topographies and better surface roughness.

1 Introduction

There are only a very few references in the technical literature dealing with the investigation of the effects of vibration assisted milling that highlight the advantages of vibration-assistance in intermittent milling processes. Chern et al. [1] have demonstrated that in vibration-assisted micro-slot milling at 3,000 rpm, surface roughness and dimensional accuracy can be markedly improved. Moriwaki et al. [2] have, in turn, developed an elliptical vibration milling system which aligns the tool spindle slightly off the rotating axis of the servo motor at speeds less than 1,500 rpm. So far, the published studies have investigated only low spindle speeds up to

3,000 rpm and machining conditions that are not representative of micro/meso-scale milling processes that are generally performed at very high speeds and conditions in which ploughing effects dominate shearing. Under these conditions it is anticipated that vibration-assistance will require ultrasonic vibration frequencies. Contrary to previous approaches, the current paper investigates the one-directional ultrasonic vibration-assisted milling process performed at ultrasonic frequencies at high spindle speeds, e.g., at 40 kHz with amplitudes of a few microns and over 10 krpm, respectively. Dynamic modeling is also discussed to demonstrate the possibility of using ultrasonic tool motions superimposed on the nominal tool trajectories as a plausible method for the deliberate control of the dominant features of the micro-milled surfaces.

2 Modeling and experimental tests of cusp error reduction

The successive actual cutter center positions are computed based on the Runge-Kutta method by considering the cutter's dynamic deflections, static runout and vibration assistance as:

$$x_a = x_n + x_\rho + x_d + x_{uv},\ y_a = y_n + y_\rho + y_d \tag{1}$$

where (x_a, y_a), (x_n, y_n), (x_ρ, y_ρ), and (x_d, y_d) are the actual cutter center position, nominal position, runout, and deflection values, respectively. In addition, the ultrasonic vibration motion is defined as $x_{uv} = v_a \sin(2\pi f \cdot dt \cdot \theta)$, where v_a, f, dt, and θ are the vibration amplitude, the ultrasonic frequency, incremental simulation time per the rotation angle unit, and cutter rotation angle, respectively. Regenerative chips, generated by inner and outer modulation effects, were also considered in the simulations [3]. When the edge cuts through surface, the machined surface profiles, i.e., the cusp height and shape can be constructed by connecting the simulated edge positions around the surface area as reported in [4].

For model verification a high speed milling setup capable of in-feed and cross-feed directional vibration-assistance was designed as shown in Fig. 1. To perform simulations, firstly, the dynamic response of the micro mill should be determined. Since direct experimental modal testing is not feasible for obtaining the micro flute section's frequency response due to its fragile structure, harmonic FEM analysis of the micro mill was performed to evaluate its frequency response function as shown in Fig. 2. The simulated natural frequency and stiffness are 6,292 Hz and 1,314,840 N/m for a damping ratio of 0.02, respectively.

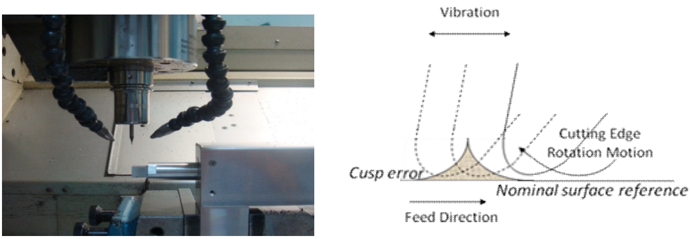


Figure 1. Designed ultrasonic vibration-assisted milling system on Roeders HSM

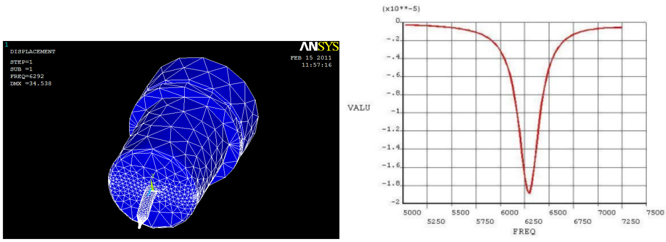
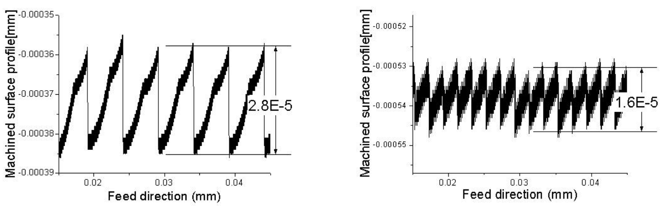
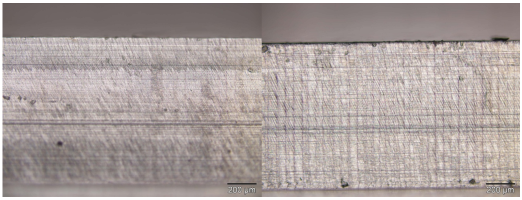


Figure 2. Harmonic analysis of a micro mill using Ansys ® (TiAlN coated carbide tool with a 0.8 mm flute diameter, 4 mm shank diameter and a 25 mm overhang)

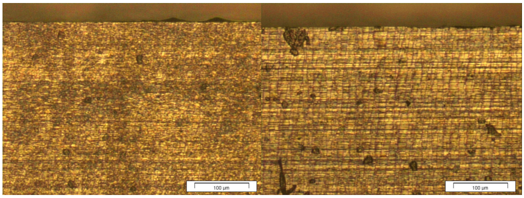
Simulation results performed with v_a and f at 2.7 µm and 39.7 kHz respectively, as measured using a laser vibrometer on the setup in Fig. 1, are shown in Fig. 3. The simulated cusp height is predicted as 2.8E-05 mm without ultrasonic vibration-assistance for 12,000 rpm, 12 mm/min, width of cut 0.1 mm, depth of cut 1 mm, runout offset 1 µm, angle 70º and Al6061-T6. With ultrasonic vibration assistance it can be seen that the cusp error is reduced to 1.6E-05 mm. Typical machined surfaces from a set of more than 40 cutting experiments are shown in Fig. 4. As it can be seen, the experimental tests validate the anticipated reduction in cusp heights on the milled surface in the presence of ultrasonic vibration motions.



(a) Without ultrasonic vibration assistance (b) with ultrasonic vibration assistance
Figure 3. Comparison of simulated cross-sectional surface profiles



(a) $R_a = 0.1677$ µm (*) $R_a = 0.2956$ µm



(b) Ra = 0.1212 µm(*) Ra = 0.1462 µm

Figure 4. Experimental results: (a) 18,000 RPM, 3mm/min, 0.1 mm width, 1 mm depth (b) 28,000 RPM, 16 mm/min 0.1 mm width, 1 mm depth, Al6061-T6 *(*): With feed directional vibration assistance*

3 Conclusion

The addition of ultrasonic vibrations to the trochoidal motion of the cutting edges affects machined surface topography. Surface generation under these conditions has been simulated considering the dynamic response of the micro mill in high speed milling. Surface topography is improved by reducing cusp errors through adjustments of the cutting configuration based on the developed simulation methodology.

References:

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