Investigation of the effect of tooling axial ultrasonic vibration assistance on meso-scale milled surfaces

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Abstract

This paper explains the effects of ultrasonic vibration assistance applied in the axial direction of the tool on milled surface quality. A test-bed is set up with an ultrasonic vibration generation system which excites the workpiece with a frequency of around 39 kHz and amplitude of 1.6 µm. The experimental results demonstrate that meso-scale milled surface roughness can be improved from 20 % to 65 % with axial ultrasonic vibration assistance in high speed milling processes. In particular, chatter marks have been effectively suppressed through axial ultrasonic vibration assistance. The experiments as well as simulations have validated that the tool's axial ultrasonic vibrations change the cutting velocity in a way that reduces forced or chatter vibrations resulting in surface quality improvements.

1 Introduction

In high speed intermittent machining, the cutting speed is much higher than the ultrasonic vibration speed. The cutting mechanisms with axial ultrasonic vibration assistance at higher cutting speeds have not yet been explored [1, 2]. In this paper, as shown in Figure 1, ultrasonic vibration assistance with around 390 mm/sec is applied at cutting speeds from 470 to 1100 mm/sec. Ultrasonic vibrations induce changes in the resultant cutting velocity which result in surface quality changes.

2 The cutting velocity change with tooling axial ultrasonic vibrations

With ultrasonic vibration assistance in the tool's axial direction, the resultant cutting velocity vector varies which results in the change of surface quality. By varying the resultant cutting velocity ($\vec{\rho}$) in the way of reducing the effective rake angle, the shearing process can be improved. In Figure 2, the cutting velocity vector in the presence of ultrasonic vibrations ($\vec{u}$) is calculated as:

$$\vec{\rho} = v\vec{i} + u\vec{j} \ , \ \beta = \tan^{-1}(u/v) \quad (1)$$

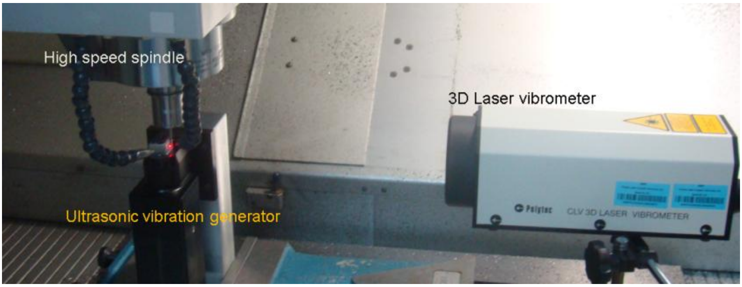


Figure 1: The high speed milling system with ultrasonic vibration generator

The effective rake angle (α_e) is calculated using the normal vectors ($\vec{n}_r$, $\vec{n}_\beta$) on the planes (π_r , π_β) as:

$$\alpha_e = \cos^{-1}(\cos\sigma \cdot \cos\alpha \cdot \cos(\beta+\sigma) + \sin\sigma \cdot \cos\alpha \cdot \sin(\beta+\sigma)) \quad (2)$$

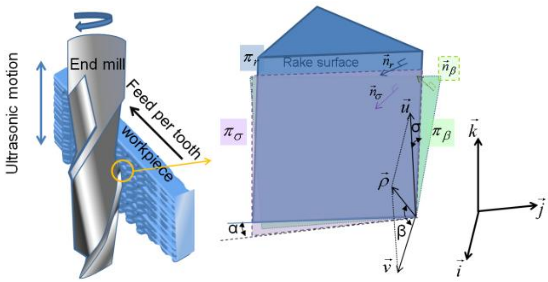
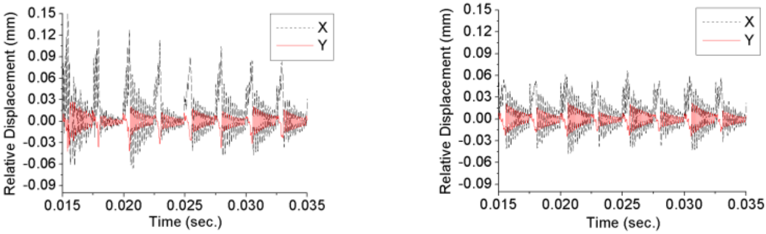


Figure 2: The effect of cutting velocity change with ultrasonic motion (where α = given rake angle, σ = helix angle, β = angle between the spindle velocity vector and the resultant cutting velocity vector with ultrasonic vibrations, π = reference plane, $\vec{n}$ = normal vector to the reference plane , $\vec{u}$ = ultrasonic vibration vector, $\vec{v}$ = spindle velocity vector, $\vec{\rho}$ = resultant cutting velocity vector with ultrasonic vibrations)

The variation of the effective rake angle is incorporated into the frequency and time-domain simulation [3]. For example, the simulation results in Fig. 3 show that the displacement of the tool center in the presence of axial ultrasonic vibration assistance becomes smaller than without the assistance.

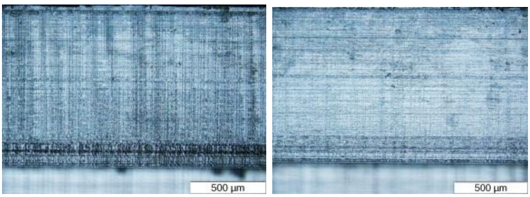


(a) without ultrasonic vibration (b) with ultrasonic vibration

Figure 3: Comparison of the simulated relative displacements of an end mill with and without ultrasonic vibration: 12,000 rpm, feed rate 38 mm/min, doc 1 mm, woc 0.1 mm for down milling with a 1.5 mm diameter end mill

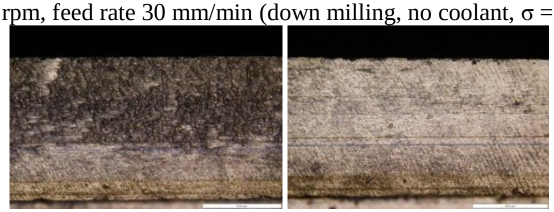
3 Improvement of the milled surface with ultrasonic vibration assistance

More than 80 cutting tests have been performed with Al 6061 workpieces and TiAlN coated carbide end mills with an overhang of 25 mm, flute diameter of 1.5 mm, and two different helix angles. For the tested conditions up to 14,000 RPM, the machined surface quality has been improved 20 to 60 %. However, if the spindle speed increases further at a fixed ultrasonic speed, the angle *(β)* decreases, which induces increased forced vibration magnitudes. Figure 4 shows examples of the milled surfaces where the forced and chatter marks were suppressed with ultrasonic vibration assistance. In addition, FFT graphs in Figure 5 indicate that that the peaks of the forced and chatter vibrations can be reduced with ultrasonic vibration.



R_a = 0.2110 μm R_a = 0.1524 μm(*)

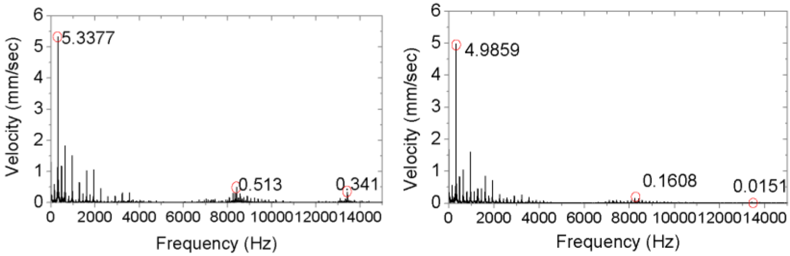
(a) 10,000 rpm, feed rate 30 mm/min (down milling, no coolant, σ = 0°, α = 10°)



R_a =0.9393 μm R_a = 0.3243 μm(*)

(b) 14,000 rpm, feed rate 33 mm/min (up milling, coolant use, σ = 30°, α = 10°)

Figure 4: Comparison of milled surfaces with(*) and without ultrasonic vibration assistance (axial doc 1 mm, radial doc 0.1 mm)



(a) without ultrasonic vibration (b) with ultrasonic vibration

Figure 5: FFT of the measurend velocities in the cross-feed direction 10,000 rpm, Feed rate 70 mm/min (down milling, no coolant, σ = 0°, α = 10°, axial doc 1 mm, radial doc 0.1 mm)

4 Conclusion

Ultrasonic vibrations have been applied parallel to the tool's axial direction to analyse the mechanisms leading to milled surface improvements. By considering cutting velocity changes in the presence of ultrasonic vibration assistance in dynamic simulations, it was shown that the cutter center's displacement is reduced with ultrasonic vibration assistance. Experimental results have demonstrated that surface roughness was improved from 20 % to 65 % for the given test conditions with axial direction vibration assistance. By selecting the ratio of the spindle velocity and ultrasonic vibration, based on the simulation approach, the surface quality was improved with the reduction of forced or chatter vibrations. More details will be discussed in future publications.

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