Vibration-assisted Surface Texturing

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Outline

- Introduction and Motivation
- Types of Vibration-assisted Cutting and Texturing
- 1D Methods
- Resonant Mode Surface Texturing
- Non-resonant Mode Surface Texturing
- Conclusion
Motivation – Imagine Surfaces:

that never get icy...

1998, 2005 and 2007 ice storm in NE of US, each cost about $4-6B

that inhibit fouling ...

Billions of $ in loss of productivity in agriculture and $56M fuel cost for US destroyers only

that increase heat exchange rates by 10X ...

95% electricity in the US is generated by steam engines; a slight efficiency increase can make a huge impact.

that never “wear”...

1/3 of energy consumption in mechanical systems is to overcome friction and replace worn materials.
Applications of Micro Textured Surfaces


How to Fabricate Micro Textured Surfaces?

- Lithography
- Focused Ion Beams
- Electron beam machining
- Electrical discharge machining
- Laser machining
- Elliptical vibration texturing
Surface Texturing Domain

Application areas of large-area textured surfaces on hard materials

<table>
<thead>
<tr>
<th>Surface Area [m²]</th>
<th>Surface Feature Size [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.010 m²</td>
<td>~ 1 μm</td>
</tr>
<tr>
<td>&gt;100 m²</td>
<td>&gt;100 μm</td>
</tr>
</tbody>
</table>

Peta Technologies
Tera Technologies
Giga Technologies

Future Directions
Required Texturing Technologies
Conventional Texturing Technologies

X-Technology:  
X = Surface features / m²
### Processing Times by Different Texturing Methods

![Image: 100 µm diameter dimple array with 100 µm pitch in both directions](image)

<table>
<thead>
<tr>
<th>Processes</th>
<th>Time (per m²)</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibro/ultrasonic - machining</td>
<td>1 hour</td>
<td>Working at 28 kHz</td>
</tr>
<tr>
<td>Laser ablation</td>
<td>115 days</td>
<td>Each dimple takes 0.1s</td>
</tr>
<tr>
<td>Micro-rolling</td>
<td>50s</td>
<td>Rolling speed: 20mm/s</td>
</tr>
<tr>
<td>Micro-milling</td>
<td>1.5 years</td>
<td>Each dimple takes 0.5s</td>
</tr>
</tbody>
</table>
Vibration-assisted Machining - 1D and 2D Motions

- **1D VAM**: tool is driven in a linear path, which is superimposed on the upfeed motion of the workpiece:
  \[ x(t) = A \sin(\omega t) + Vt \]
  \[ x'(t) = \omega A \cos(\omega t) + V \]

- **2D VAM**: a vertical harmonic motion is added to the horizontal motion of 1D VAM. The tool moves in a tiny circle or ellipse, which is superimposed on the upfeed motion:
  \[ x'(t) = \omega A \cos(\omega t) + V \]
  \[ z'(t) = -\omega B \cos(\omega t) \]

1D Motions

Surface Texturing Method

Texture Designs
1D Motions

![Graph showing Coefficient of Friction vs Rotational Speed (RPM)]

- Texture #17
- Non-Textured
- Texture #14

Prof. Wang
Resonant vs. Non-resonant Mode

Resonant Mode

Non-resonant Mode

Generation of Simple Sinusoidal Micro-structures

Generation of Controlled Complex Topography

Vibration-assisted Texturing Methods

- In the cutting direction, the tool’s position relative to the workpiece is given by:
  \[ x_1(t) = A \cos(\omega t + \phi) + V_c t \]

- Then the velocity can be derived:
  \[ x'_1(t) = -A \omega \sin(\omega t + \phi) + V_c \]

- EVC: \( \lambda \leq 1 \)
- EVT: \( \lambda > 1 \)
- MFVT: Multi-frequency / Arbitrary trajectories
Resonant Mode Motion Generators

Measured tool vibration trajectories at the resonant frequency

Influences of the principal overlapping ratio and the minor overlapping ratio

Example 1: Wettability Control

P. Guo et al., "Experimental Studies of Wettability Control on Cylindrical Surfaces by Elliptical Vibration Texturing," 2014, to be submitted
Example 2: Structural Coloration

Process Principle

Cutting velocity

Spacing distance: \[ d = \frac{2\pi v}{\omega} \]

Vibration angular frequency

Orientation: Perpendicular to the cutting direction

\[ f = \frac{\omega}{2\pi} \approx 30 \text{ kHz}, \quad v \approx 10 \sim 30 \text{ mm/s} \]

Visible spectrum

Ping Guo
The Chinese University of Hong Kong
Example 2: Structural Coloration

Color Spectrum on brass surface marked by ten segments: each segment has been textured with different spacing distances (from 400 nm to 760 nm).

Mona Lisa
16 levels of color
40 x 40 um pixel

Ping Guo
The Chinese University of Hong Kong
Inclined Ultrasonic Elliptical Vibration Texturing (IUEVT)

Numerical comparison between CC and IUEVC methods regarding thrust force, tangential force, surface roughness and profile roughness. \( v_c = 5 \text{ mm/s}, a_p = 4 \mu\text{m}, f_r = 10 \mu\text{m}, R_n = 200 \mu\text{m} \)
Comparison of Conventional and UEVT Texturing

2D and 3D images of conventional and UEVT textures

Profiles and forces
Chip Adhesion and Morphology

Rake face adhesion: (a) non UEVT insert, (b) UEVT insert with a 400 µm pitch, (c) UEVT insert with a 200 µm pitch

Chip morphology: (a) non UEVT insert, (b) UEVT insert with a 400 µm pitch, (c) UEVT insert with a 200 µm pitch
Non-resonant Motion Generator

TARGET METRICS:

(a) Max displacement: 50 \( \mu \)m,
(b) Max cutting force: 100 N
(c) Stiffness: 10 N/\( \mu \)m
(a) one quarter of the CB mechanism,
(b) half of the ZFH mechanism

CB – Compound bridge
ZFH – Z-shaped flexure hinge
Non-resonant Motion Generator

- Compound bridge mechanism
- Preload bolt
- Z-shaped flexure hinge mechanism
- Insert
- Piezoelectric actuators
Modal Analysis

<table>
<thead>
<tr>
<th></th>
<th>1st mode</th>
<th>2nd mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>494.4</td>
<td>679.5</td>
</tr>
</tbody>
</table>
Vibration Trajectory Analysis

Frequency = 30 Hz, cycle = 30, Vp-p = 400 V
Texturing of Cylindrical Surfaces
Flow Chart of Surface Generation Simulation

1. Vibration of tool
2. Tool geometry in tool coordinate system
   - Addition
   - Vibration coordinate system
     - Rotation
     - Translational
     - Machining coordinate system
       - Rotation
       - Workpiece coordinate system
         - Transformation
         - Cylindrical form
         - Discretization of workpiece
1. Nominal chip thickness calculation
2. Materials spring back compensation
3. Update workpiece topography
## Experimental Conditions

### Table 1. Cutting parameters

<table>
<thead>
<tr>
<th>Spindle speed</th>
<th>Feed rate</th>
<th>Depth of cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 rpm</td>
<td>40 μm/rev</td>
<td>20 μm</td>
</tr>
</tbody>
</table>

### Table 2. Cutter parameters

<table>
<thead>
<tr>
<th>Nose radius</th>
<th>Rake angle</th>
<th>Clearance angle</th>
<th>Included angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 μm</td>
<td>10 deg</td>
<td>7 deg</td>
<td>55 deg</td>
</tr>
</tbody>
</table>

### Table 3. Vibration parameters

<table>
<thead>
<tr>
<th>NO.</th>
<th>Voltage</th>
<th>Phase</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>400 V</td>
<td>60 deg</td>
<td>30 Hz</td>
</tr>
<tr>
<td>2</td>
<td>10 Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>10 Hz+30 Hz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Experimental and Simulation Results

\( f = 10 \text{ Hz}, \ a_p = 20 \, \mu\text{m}, \ n = 23 \text{ RPM}, \ f_z = 50 \, \mu\text{m/rev} \) (1.41 mm x 1.06 mm)

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**Experimental result**

**Simulation result**
Experimental and Simulation Results

Experimental result
Simulation result

\( f = 30 \text{ Hz}, \ a_p = 20 \mu m, \ n = 23 \text{ RPM}, \ f_z = 50 \mu m/\text{rev} \) \( (1.41 \text{ mm} \times 1.06 \text{ mm}) \)
Experimental and Simulation Results

Experimental result

Simulation result

\( f=10 +30 \text{ Hz}, \ a_p=20 \ \mu\text{m}, \ n=23 \ \text{RPM}, \ f_z=50 \ \mu\text{m/rev} \) (1.41 mm \times 1.06 mm)
Example: Friction Reduction
Simulation and Experiment

(a) 3D measurement of micro-textures in 360°, (b) partial view, (c) theoretically generated surface (1.0 mm × 1.0 mm)
Texturing in Facing Operations
Generated Surface Textures
Constant Frequency

$f = 30 \text{ Hz}; n = 7 \text{ RPM}; f_z = 250 \text{ μm/rev}; a_p = 5 \text{ μm}$
Generated Surface Textures
Variable Frequency

\[ f = 30-1 \text{ Hz}; \, n = 7 \text{ RPM}; \, f_z = 250 \mu m/\text{rev}; \, a_p = 5 \mu m \]
Effect of Depth of Cut on Surface Texture

$f = 30-1 \text{ Hz}; n = 7 \text{ RPM}; f_z = 250 \mu m/\text{rev}$

- $a_p = 0 \mu m$
- $a_p = 5 \mu m$
- $a_p = 10 \mu m$
- $a_p = 20 \mu m$
Effect of Frequency on Surface Texture

f=30-1 Hz; n=7 RPM; f= 250 μm/rev; a_p=5 μm

f=45-1.5 Hz; n=7 RPM; f= 250 μm/rev; a_p=5 μm
Comparison between Resonant and Non-resonant Methods

- Resonant mode
  - Vibration frequency: 28 KHz
  - Single frequency
  - Vibration amplitude: tangential 8.79 μm
    normal 7.28 μm

- Non-resonant mode
  - Vibration frequency: 1-494 Hz
  - Multi-frequency
  - Vibration amplitude: tangential ±74.6 μm
    normal 90.7 μm
Conclusion

- Several methods for surface texturing have been presented along with the design of the corresponding devices.
- Methods for 1D and 2D resonant and non-resonant texturing were discussed.
- The developed surface generation model that predicts surface topography is in close agreement with the experimental results.
- Controlled uniform textures can be efficiently fabricated.
- Different topographies can be obtained by controlling the depth of cut, cutting speed, federate, amplitude and frequency of vibrations.
Thank You!

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