INTRODUCTION

In "vibration-assisted machining" (VAM) a cutting tool moves at high frequency in a small-amplitude (10's of µm) path. This motion can be linear ("1-D VAM") or elliptical ("2-D VAM"). The oscillating tool motion is superimposed on the main upfeed motion of the workpiece. When the vibration parameters are properly selected relative to the upfeed motion, the tool will separate from the uncut work material for a portion of each cycle. Several notable benefits result from this interrupted cutting characteristic. Tool forces (thrust and cutting forces) are smaller than in conventional cutting. Tool life is extended—most dramatically when VAM is used with diamond tools on ferrous metals, which generally cannot be precision-machined by conventional means. Surface finish and form accuracy are improved.

VAM MOTION

In 1-D vibration-assisted machining the tool is driven harmonically in a linear path parallel to the workpiece upfeed motion. For VAM frequency \( f \), vibration amplitude \( A \), and upfeed velocity \( V \), the position \( X(t) \) and velocity \( X'(t) \) of the tool relative to the workpiece are

\[
X(t) = A \cos(2\pi ft) + Vt
\]

\[
X'(t) = -2\pi ft A \sin(2\pi ft) + V
\]

From Eq. (2), when \( 2\pi ftA < V \) the tool will separate from the uncut work material for a portion of each cycle. This is depicted in Figure 1. At \( t=0 \) the tool initially contacts the workpiece. At \( t=t_1 \) it has finished cutting and is about to move backwards relative to the work. Between \( t_1 \) and \( t_2 \) the tool is separated from the work and not cutting. At \( t=t_2 \) the tool is again in contact with the uncut work material and is about to cut. Figure 2 shows 2-D vibration-assisted machining. The tool moves at frequency \( f \) in an ellipse with horizontal amplitude \( A \) and vertical amplitude \( B \). The horizontal position and velocity relative to the work are again given by Eq. (1) and Eq. (2). The vertical position \( Z(t) \) and vertical velocity \( Z'(t) \) are

\[
Z(t) = B \sin(2\pi ft)
\]

\[
Z'(t) = 2\pi ft B \cos(2\pi ft)
\]

Again, when \( 2\pi ftA < V \) the tool will separate from the uncut work material for a portion of each cycle.

The operating point of a VAM system can be characterized by three terms. The "upfeed index" \( F_{UP} \) (Eq. 5) is the distance traveled by the tool relative to the work in one cycle. The "horizontal speed ratio" \( HSR \) (Eq. 6) relates the peak cutting speed of the tool to the upfeed velocity.

\[
F_{UP} = \frac{V}{f}
\]

\[
HSR = \frac{V}{2\pi ftA}
\]

Small values of \( F_{UP} \) and \( HSR \) lead to low theoretical surface roughness. The third
characterizing term, “duty cycle”, is the proportion of each cycle the tool is cutting.

**VAM SYSTEMS**

A typical 1-D VAM system uses a piezoelectric or magnetorestrictive actuator to create a reciprocating harmonic motion at ultrasonic frequency but small amplitude. This motion is amplified by a shaped-acoustical waveguide booster and horn. A cutting tool is attached to the end of the horn, aligned so that the rake face is normal to the direction of vibration. 1-D VAM systems operate at discrete frequencies of 20-40 kHz, achievable by commercial ultrasonic generators. Amplitude is typically 10 to 25 µm.

“Resonant” 2-D VAM systems create elliptical tool motion by causing the tool support structure to vibrate at its resonant frequency in two directions. Figure 3 is a resonant 2-D VAM system developed by Moriwaki and Shamato [1]. Piezoelectric actuators are attached to the side faces of the beam structure, and are activated in opposed pairs to induce bending in two directions at right angles to one another. The beam is supported at its nodal points. Bending vibration of the beam ends at the 3rd resonant frequency amplifies the motion induced by the piezo strips. The diamond tool is mounted on the end of the beam. The combination of the two bending vibrations makes the tool move in an elliptical path. This system operates at discrete frequencies above 20 kHz.

“Non-resonant” 2-D VAM systems use a mechanical linkage to convert the expansion and contraction of piezoelectric actuators into an elliptical tool path. Figure 4 shows a system developed at North Carolina State University [2]. Sinusoidal voltages, with a phase difference between them, are supplied to the two parallel actuators. The toolholder acts as the linkage. This system operates at up to 4 kHz with ellipse dimensions as large as 36 µm x 6 µm. The ellipse size, aspect ratio and orientation can be varied by changing the phase shift between the stacks and/or the voltage signal amplitude. The frequency can also be varied. This design requires a cooling system because of large actuation and hysteresis history.

**VAM BENEFITS**

**Cutting Dynamics and Reduced Tool Forces**

VAM's interrupted cutting results in a small chip being formed during each machining cycle, at lower tool force. The high vibration frequency means that many cycles take place in a specified time interval. Therefore in VAM many small chips are made, instead of a large continuous chip as in conventional cutting. Also, the tool moves with lower average force for a much larger cumulative distance in repetitive passes, compared to conventional machining in the same amount of time. For the same volumetric material removal, the work performed by VAM is therefore consistent with that of conventional machining.

1-D and 2-D VAM have different cutting dynamics. Figure 5 compares instantaneous 1-D VAM thrust and cutting forces to those of conventional machining. These results are from an experimental system operating at up to 6 Hz [3] (instantaneous force measurements are difficult to obtain at ultrasonic frequencies because of the high sampling rate required). The peak VAM forces are the same as the steady-state forces. Interrupted cutting is the cause of smaller average forces seen in 1-D VAM. A rough estimate of the average force can be found by multiplying the steady state

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2 Another concern for ultrasonic VAM systems: when the operating frequency is much larger than the measurement system's natural frequency forces transmitted to the sensor are highly attenuated. Unless corrections are made based on the vibration response of the specific measurement setup, the force measurements will be inaccurate.
force by the duty cycle. The shape of the instantaneous 1-D VAM profiles reflects material loading transitions from elastic to plastic regimes, and changing strain rates.

**FIGURE 5.** Tool force comparison between 1-D VAM and conventional cutting. Steel tool, copper work. $f=6$ Hz Redrawn from [3].

Figure 6 shows instantaneous thrust and cutting force measurements for 2-D VAM at 1 kHz [2]. Only the portion of the overall cycle when the tool is cutting in the material is shown. Thrust and cutting forces are seen to be always smaller than the forces for conventional machining. The peak VAM thrust force is 38% of the conventional thrust force and the peak VAM cutting force is 54% of the conventional cutting force. Integrating the instantaneous forces over one cycle gives an average VAM cutting force 8%, and an average VAM thrust force 5%, of the respective values for conventional machining. In 2-D VAM, the tool force reduction is due to making chips that are thinner than the overall depth of cut in conventional cutting. These thin chips occur because of the consecutive overlapping elliptical tool paths. See Figure 2.

**FIGURE 6.** Tool force comparison between 2-D VAM and conventional machining. Diamond tool, copper work. $f = 1000$ Hz [2].

Limited published work exists on quantitative prediction of VAM tool forces. Babitsky [4] and various collaborators carried out theoretical, finite element, and experimental studies of 1-D VAM. They modeled individual tool/work contact cycles as viscoelastic interactions. Cerniway [5] developed a tool force model that evaluated the varying chip thickness due to the consecutive overlapping elliptical tool paths, as well as variation in tool contact area and rake angle resulting from the 2-D motion through the work. Model predictions agreed well with experimental results at frequencies up to 4 kHz.

**Extended Tool Life**

Increase in surface roughness with cumulative machining distance can be used as an indication of tool wear. Figure 7 shows surface roughness vs. cutting distance for a diamond tool machining hardened steel, for 1-D and 2-D VAM. 2-D VAM is seen to extend tool life in steel to almost 2000 m cutting distance (compared to < 100 m for conventional diamond-machining). Thermochemical mechanisms are mainly responsible for diamond tool wear in ferrous metals. VAM’s interrupted cutting extends tool life by reducing the duration of tool-work contact, limiting the time for these mechanisms to operate. VAM may also reduce tool temperature, limiting the driving potential for the relevant reactions. Tool life in ferrous metals for 2-D VAM is superior because in 1-D VAM the tool cutting edge can chip from accidental contact with the workpiece during the non-cutting portion of the machining cycle.

**FIGURE 7.** Tool wear (indicated by surface roughness) as a function of cutting distance for 1-D and 2-D VAM. Diamond tool, hardened steel work. Redrawn from [1].

VAM extends tool life for other combinations of tool and work materials. 1-D VAM improved the life of carbide tools by a factor of 20, when machining glass ceramics [6]. Another experiment used 1-D VAM and carbide tools to machine stainless steel. After 500 m, conventional machining caused a 350 µm wear land in the tool, compared to 100 µm for VAM.
In these examples abrasive-mechanical wear mechanisms dominate. VAM appears to reduce wear because smaller instantaneous and average tool forces lead to reduced local stress in vulnerable parts of the tool.

**Surface Finish and Form Error**

Surface finish in VAM is frequently superior to conventional machining for the same combination of tool and workpiece materials. The cyclic nature of VAM allows the tool to traverse the cut area from the preceding cycle and remove material peaks left over from the last pass. Small $F_{up}$ and $HSR$ give low theoretical surface roughness by maximizing the overlap between successive cycles. The smaller forces in 2-D VAM, and the smaller average forces in 1-D VAM, lead to improved form accuracy and surface finish by decreasing relative vibration between tool and work. The reduced tool forces also inhibit chatter.

**APPLICATIONS**

2-D VAM appears to be well-suited to traditional precision machining applications, where a feature must be made to precise form and nanometer-scale surface roughness. Figure 8 shows microstructures machined in hard plated copper by the non-resonant 2-D VAM system of Figure 5 using diamond tools. The Angstrom symbol is 200 µm x 200 µm overall with the smallest feature (vertical bar of the topknot symbol) only 15 µm wide. Surface roughness is ~20 nm RMS. The trihedron array has structures 80 µm tall on a 112 µm pitch, and also includes interstitial trihedrons 10 µm tall. These parts show burr-free edges in an SEM at 2000x magnification. Figure 9 shows micromolds in hardened die steel made using the resonant 2-D VAM system in Figure 3. This system has also machined steel optical parts including flat mirrors up to 91 mm x 121 mm.

1-D VAM systems have been used in applications requiring significant material removal (e.g. depths of cut .01 to 1 mm). Here the objective often is to achieve a desired finish in hard-to-work materials with economical tool life. Babitsky et al [9] aimed to machine Inconel and titanium while extending carbide tool life with 1-D VAM. As another example, thin aluminum camera drawtubes (0.8 to 1.2 mm wall) were finished using a 1-D VAM system installed on a conventional lathe [10]. A finish of 600 nm PV was achieved which exceeded the part specification.

**CONCLUSIONS**

The interrupted cutting characteristic of vibration-assisted machining leads to significant reduction in tool forces, extended tool life, and improved surface finish. The cutting dynamics differ between 1-D and 2-D VAM. Example applications are presented for both 1-D and 2-D VAM.

**REFERENCES**


