INTRODUCTION

Studies [1] have shown the benefits of applying micrometer-scale elliptical vibration (EVAM) motion to a tool during diamond turning (DT). In this process, the tool comes out of contact with the workpiece over part of each cycle. Reported benefits include a decrease in machining forces, tool temperatures and wear of the diamond tool. The particular causes for decrease in force and wear using EVAM depend, to some extent, on the general lack of understanding of tool wear mechanics of a normal DT operation. The research discussed here will provide insight into EVAM cutting mechanics and create the necessary foundation for future industrial implementation.

A baseline understanding of tool wear for standard (non-vibration) DT is necessary before proceeding with EVAM wear studies. Correlation of diamond tool wear with standard models allows different workpiece materials or chemical processes to be evaluated. Paul and Evans [2] studied the chemical aspects of diamond tool wear. They theorized that the volumetric wear rate would follow the Arrhenius equation:

$$\frac{dV}{dt} = A \exp \left( \frac{E_a}{RT} \right)$$

(1)

where $V$ is the worn volume, $R$ is the gas constant (8.3144 J/mol), and $T$ is process temperature (K). $A$ and $E_a$, the pre-exponential constant and activation energy, are empirical constants specific to the interacting materials. The wear rate dependence on temperature is the same function for catalytic reactions or diffusive reactions [2], though individual process contributions are not considered here.

To determine the empirical constants, tool wear and tool temperatures must be determined. To measure the tool wear, a process called Electron Beam Induced Deposition (EBID) has been developed and a tool cutting model is used to estimate the tool temperature.

EBID [3] is performed in a scanning electron microscope (SEM) by creating a hydrocarbon line on the diamond tool perpendicular to the cutting edge. This line provides the contrast needed to measure the edge and create a 2D worn profile. If orthogonal cutting is conducted with a straight-edged tool, the worn volume can be estimated as the 2D worn area multiplied by the workpiece width. Because EBID process requires costly time on the SEM, a technique using a scanning white light interferometer (SWLI) was developed that allows rapid wear land measurements in addition to the more precise EBID measurements [4].

The second input needed is the local tool temperature. Since this is nearly impossible to measure, a finite element (FE) cutting model was used to estimate the tool/workpiece temperatures. AdvantEdge, developed by ThirdWave Systems, provides the forces and temperatures necessary to complete the Arrhenius model for tool wear.

An elliptical tool vibration routine was recently added to AdvantEdge. An EVAM simulation provides tool temperatures which are then supplied to the Arrhenius wear model developed from conventional machining experiments. A conventional cutting simulation with the same parameters depth of cut and surface speed allows direct comparison of forces, temperatures and other factors that may contribute to tool wear.

CONVENTIONAL MACHINING ON ST1215

Experimental Setup

To create the orthogonal cutting conditions, fins were machined into a 4” diameter round of St1215. The fins were 1.2 mm wide and the straight-edged diamond tool (supplied by Chardon Tool) was 2.1 mm wide. This creates a localized section of wear on the tool, shown in Figure 1.
One steel fin was machined at 1 µm depth of cut at 1.06 m/s on an ASG 2500 DT machine with a continuous stream of Mobilmet Omicron cutting fluid and compressed air to remove the chips. After machining a certain distance (typically 20 m), the tool was removed and cleaned. A 5% nitric acid solution was used to remove any pickup incurred while machining. The worn edge of the tool was examined via SWLI or a combination of SWLI and EBID [3,4]. This process was repeated for successive machining distances, and volumetric wear loss as a function of time was acquired. This process was then repeated for machining speeds of 2.12 m/s and 4.24 m/s for a total of three volumetric wear rates.

**Conventional Machining FE Simulations**

Three two-dimensional machining simulations were created in AdvantEdge that mimicked the conventional machining experiments [4]. AdvantEdge supplies a library of tool and workpiece materials. St1215 was not available, so AISI-1118 steel was used in the simulation. Density, hardness, and thermal conductivities of 1215 and 1118 steel differ less than 10% [5]. Contour temperature plots from simulation results showed the maximum tool temperature occurred at the tool tip, and steady state values were extracted from the simulation results.

**Arrhenius Wear Model Results**

Wear rates determined from conventional machining experiments were combined with maximum tool temperatures from FE simulations to create an Arrhenius plot shown in Figure 2. Three points are shown; one for each machining speed. Though the three points did not show a linear trend, a range of Arrhenius empirical constants are suggested and given in Table 1.

**Arrhenius plot of measured diamond tool wear rate and peak tool temperatures from FE simulations.**

**TABLE 1. Arrhenius constants from Figure 3.**

<table>
<thead>
<tr>
<th>Line in Figure</th>
<th>Activation Energy, $E_a$</th>
<th>Pre-exponential Constant, $A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_{hi}$</td>
<td>83.5 kJ/mol</td>
<td>$4.08 \times 10^{12}$ µm³/s</td>
</tr>
<tr>
<td>$y_{mid}$</td>
<td>42.5 kJ/mol</td>
<td>$4.5 \times 10^7$ µm³/s</td>
</tr>
<tr>
<td>$y_{lo}$</td>
<td>22.1 kJ/mol</td>
<td>$2.52 \times 10^8$ µm³/s</td>
</tr>
</tbody>
</table>

Review of several papers [2] indicated activation energy estimates from 80-300 kJ/mol for catalytic metal-on-metal reactions or graphitic carbon diffusion into various metals. The lower $E_a$ determined in Figure 2 and Table 1 is likely a result of constant tool contact with new, untouched workpiece material during the cutting process.

**EVAM SIMULATIONS**

An EVAM simulation was created in AdvantEdge utilizing the elliptical toolpath routine. Figure 3 shows the simulated workpiece and tool size, and the FE simulation mesh. For comparison, a conventional machining simulation was also created with the vibration turned off.
Table 2 gives the cutting conditions assumed in the AdvantEdge EVAM simulation. Depth of cut in the EVAM simulation is defined as distance from workpiece surface to the lowest point of the toolpath.

**TABLE 2. Cutting parameters for EVAM FE simulations**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of Cut</td>
<td>40 µm</td>
</tr>
<tr>
<td>Ellipse Minor Axis</td>
<td>20 µm</td>
</tr>
<tr>
<td>Ellipse Major Axis</td>
<td>110 µm</td>
</tr>
<tr>
<td>EVAM Frequency</td>
<td>10 kHz</td>
</tr>
<tr>
<td>Workpiece Velocity</td>
<td>0.2 m/s</td>
</tr>
</tbody>
</table>

**Forces, Temperature, and Chip Formation**

Maximum tool temperatures and forces were extracted from the EVAM and conventional machining simulations, shown in Figure 4.

Peak tool temperatures from the EVAM simulation were higher than steady state temperatures from the conventional machining simulation. This is due to the higher peak tool tip velocity during EVAM. The horizontal speed ratio (HSR) is an important EVAM parameter [1] created by dividing the forward velocity of the ellipse center by the peak ellipse velocity. Larger values of HSR produce higher EVAM velocities that lead to higher tool temperature. Another observation is the negative $F_y$ force seen at timepoint C in Figure 6. This is due to higher speed of the tool vs. the chip that 'lifts' the chip from the workpiece. This change in direction of the tool force has been proposed as a key factor for the reduced tool forces in EVAM [6].

**FIGURE 4. Maximum tool temperature and tool forces extracted from the Si1118 EVAM simulation.**

The heat generated in the primary shear zone is shown in Figure 7. Initially, the EVAM tool creates a smaller chip with localized heating. As the tool contacts the main chip, the shear zone extends behind the main chip. Friction is then reversed as the tool pushes and lifts the chip.

**FIGURE 5. Expanded view of data composing 7th peak in Figure 4.**

**FIGURE 6. Heat generation rate contour plot of tool and chip from the EVAM simulation. Screenshots correlate to time points in Figure 5.**
To fully understand the benefits of EVAM, multiple simulations varying ellipse shape, HSR, material and heat transfer parameters must be compared. Increasing peak tool temperature shown in Figure 4 (top) is a result of the workpiece heating up toward a steady state value each time the tool comes in contact. This shows that the relative heat transfer rates of the diamond and workpiece are important factors when considering EVAM tool temperatures.

**Arrhenius Wear Model Applied to EVAM**

Applying Eq. 1 to the temperature during an EVAM cycle gives the wear rate \( \frac{dV}{dt} \) as a function of time in Figure 7. During the EVAM cycle, however, the tool is only in contact a fraction of the total EVAM period (about 25%). The average wear rate is determined by finding the total wear volume during contact, then averaging over the total EVAM cycle period.

\[
\left( \frac{dV}{dt} \right)_{\text{Avg}} = \frac{1}{T_{\text{Total}}} \left( \int_{T_{\text{Contact}}} \frac{dV}{dt} \, dt \right)
\]

During conventional machining, the tool is always in contact and \( T_{\text{Total}} \) is equivalent to \( T_{\text{Contact}} \) in Eq. 2.

**FIGURE 7.** Maximum tool temperature for one EVAM cycle (Figure 5) is applied to the Arrhenius wear model (Equation 1) to give the \( \frac{dV}{dt} \) curve. Average wear rate for the EVAM tool is determined by integrating the \( \frac{dV}{dt} \) curve according to Equation 2.

Figure 7 shows that although the peak temperature during the EVAM cycle is higher than the steady state temperature in conventional machining, the average wear rate is nearly 50% less. This is because the calculated wear rate only applies while the tool is in contact but the average wear rate depends on the total time. However, as HSR decreases, EVAM temperatures increase due to higher velocities. This suggests that an HSR exists where the EVAM wear rate equals that of conventional machining and demonstrates that HSR is an important parameter in determining tool wear in addition to its relationship with surface finish.

**CONCLUSIONS**

1.) A chemical wear model was developed based on the Arrhenius equation. Wear measurements made during conventional DT of St1215 were coupled with tool temperatures obtained from FE simulations to construct an Arrhenius plot. The proposed activation energy is in the range of 22-83 kJ/mol.

2.) An EVAM cutting simulation was compared with a conventional cutting simulation with the same machining parameters minus tool vibration. Peak EVAM tool temperatures were higher than steady state conventional machining temperatures due higher peak velocities. But despite higher temperatures, application of the Arrhenius wear model gives an average wear rate of the EVAM tool 50% less than conventional machining. Reduced contact time is the major contributor to the lower EVAM wear rate.

**ACKNOWLEDGEMENTS**

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**REFERENCES**


