TUNABLE, ULTRASONIC, VIBRATION ASSISTED DIAMOND TURNING

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ABSTRACT

An ultrasonic, vibration assisted diamond turning (UVADT) device has been constructed that allows for variation of vibration frequency and vibration amplitude via a direct drive actuator [1]. This device has been used to identify the relationships between the tool vibration variables and the process parameters. Frequencies as high as forty kilohertz and amplitudes up to seven micrometers have been achieved at the tool tip during cutting. This paper discusses the tool design, the experimental results, and the model used to describe the mechanism by which vibration assisted turning reduces tool wear.

FINAL DESIGN / ACTIVE TOOLING

Prototype vibration assisted machining (VAM) devices have been described in [1] and [2]. The tool used in this work represents an integrated tool that couples the actuators directly into the tool shank, creating a UVADT device that can now be integrated with a standard tool holder mechanism on conventional precision machine tools, shown in Figure 1. The new tool also has the distinct advantage of being adaptable to conventional or hard turning operations. The tool uses multiple PZTs actuated sequentially to achieve the desired frequency.[1] Additionally, this new integrated cutting tool / actuator system is now embeddable in other systems. For example, the compact tool has been coupled with a long-range fast-tool servo (FTS). The merged technology can now realize precision free-form components produced in hard materials directly on a diamond turning machine. This technology opens a new domain of precision single point tooling, whereby, the tool becomes active during the machining process.

MODEL DEVELOPMENT

The UVADT device was used to determine that tool wear and workpiece carbon content is reduced by the VAM process. The advantage is 40% less tool wear over nearly three times the length of cut for UVADT as compared with conventional diamond turning of 12L14 steel [2]. Based upon the experimental results, a model has been developed specifically for VAM which examines the effects of dynamic heat generation from the cutting process founded on the calculated instantaneous cutting velocity. The model shows that the dynamics of the heat generation for VAM can result in a significant reduction in the average temperature during cutting. This reduction directly effects the diffusion of carbon from the diamond tool into the steel work material, subsequently reducing wear. Based on this direct link between temperature and tool wear, time dependent temperature curves have been generated.

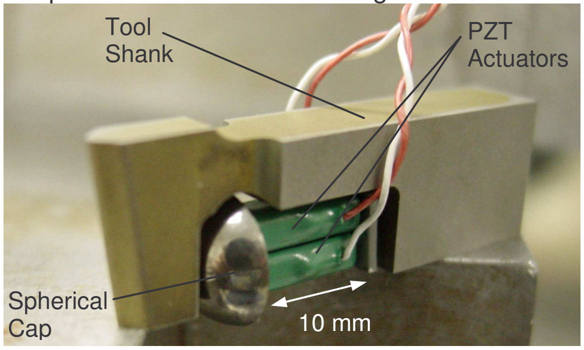

Figure 1. Integrated cutting tool with actuator system.

Tool Model

The experimentally measured tool displacement serves as the basis for the constructed model of VAM using the developed pulse activated cutting tool. The observed waveform for the cutting tool actuated at 40 kHz and 3.5 micrometers is included in Figure 2. The rise and decay times were obtained from a sample of measurements at various frequency and amplitude combinations.

Considering these effects the model approximates the tool displacement with ramp functions combined with a periodicity function. The resulting model output verifies the waveform at 40 kHz and 3.5 micrometers, shown in Figure

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[1] Patent Applied for, Tunable Vibratory Actuator, serial number 10/409,746.

3. The derivatives of the displacement functions reveal the resulting periodic tool velocity. The model approximates the tool velocity as positive and constant over the extension period, negative and constant over the retraction period and zero between the pulsing intervals, as shown in Figure 4.

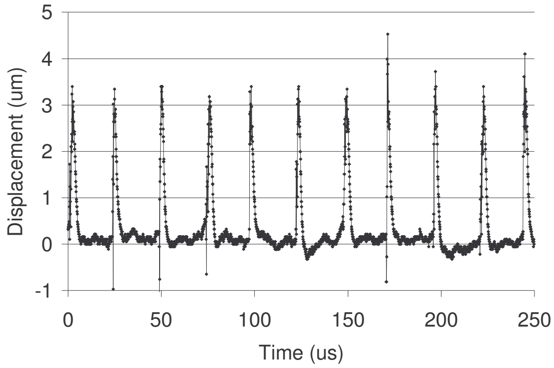

Figure 2.Measured tool displacement.

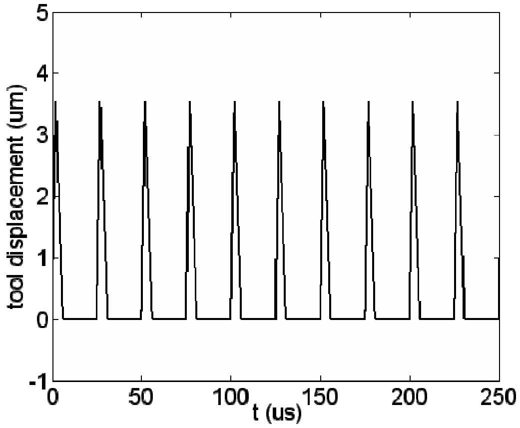

Figure 3. Model output of tool displacement.

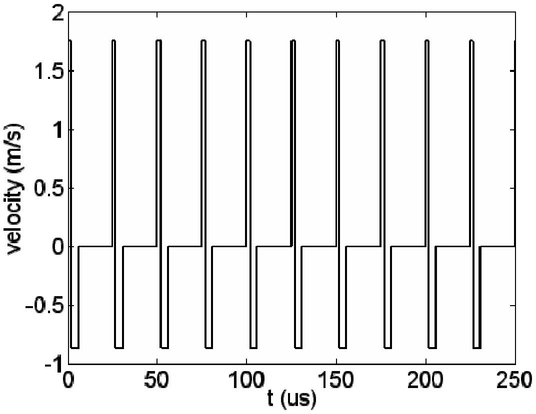

Figure 4. Model output of tool velocity.

Cutting Velocity Model

The cutting velocity for conventional turning operations is only a function of the speed of the work material approaching the cutting tool, considered to be a steady state value for constant velocity machining. The cutting velocity for vibration assisted turning has an additional term due to the tool velocity that is superimposed with the work velocity, creating a time varying cutting velocity. Therefore, the model of the tool motion was combined with the model describing the work motion to give the resulting cutting velocity, shown in Figure 5 for 40 kHz at 3.5 micrometers of tool motion and a workpiece velocity of 0.3 m/s.

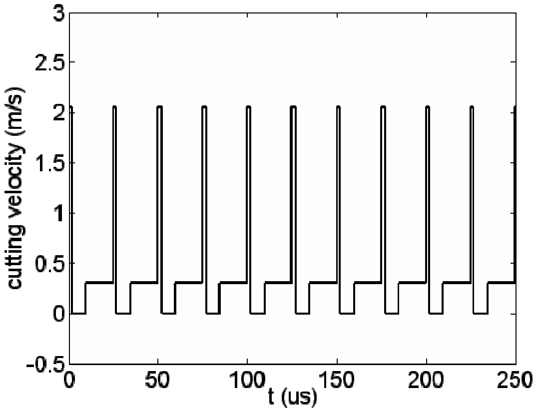

Figure 5. Model output of cutting velocity.

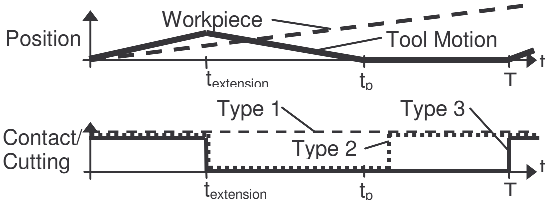

Figure 6. Displacement and contact profiles for VAM.

Through analysis of the cutting velocity, three distinct cases were identified, categorizing the pulse activated VAM process. Type 1 describes the non-separating type of vibration assisted cutting. Under these conditions, the tool remains in contact with the work surface during the entire vibration cycle due to the work velocity being greater than the tool velocity for retraction. Type 2 defines the separating type of vibration assisted cutting governed by workpiece motion where the workpiece initiates contact with the tool before the next vibration cycle is instigated. Type 3 identifies the separating type of vibration assisted cutting governed by tool motion, where, the motion of the tool dictates when cutting begins based on the ratio between tool velocity and workpiece velocity. These three categories are shown in the displacement and contact profiles as a function of time in Figure 6. As an example, Figure 5 depicts Type 2 cutting conditions.

Thermal Model

Based on the completed cutting velocity model, the cutting time is correlated to putting heat into the tool and the separation time to letting the heat be dissipated. This leads to defining the thermal time history. On this basis, a method was developed to estimate the temperature profiles for vibration assisted turning. The approach used in these simulations is adapted from interrupted metal cutting theory [3, 4]. Adapting this theory for multiple velocities is the foundation for the method developed for VAM using the pulse motion technique.

Figure 7 presents the adapted theory. At the onset of cutting, the cutting temperature increases as governed by the heating up curve at the work velocity, as shown by curve *a1*. Then, when tool motion initiates cutting, temperature is governed by the heating up curve at the tool velocity plus the work velocity, as shown be curve *a2*. Next the cutting temperature decreases as governed by the appropriate cooling down curve, as shown by curve *b*, during the separation period. After one complete cycle, the tool will usually not necessarily assume its original thermal condition, T_i; therefore, the subsequent temperature peaks will continuously increase until a limit value is reached.

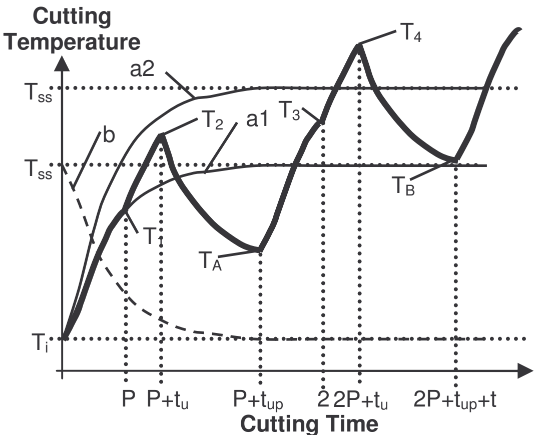

Figure 7. Model cartoon for temperatures in VAM.

Five steps were necessary to carry out the thermal model.

1. Conduct finite element modeling simulations of the cutting process under similar conditions as the experimental tests to obtain the temperature history throughout the cutting process for conventional, i.e. non-vibration assisted turning.
2. Extract the tool temperature profiles and steady state temperatures from the finite element model simulation results.
3. Adapt to vibration assisted machining by curve fitting functions to the extracted temperature data to obtain formulas that mathematically capture the profiles for the heating and cooling cycles including the thermal time constant effects.
4. Generate cutting velocity profiles founded on the combination of the work velocity with the tool displacement and tool velocity profiles.
5. Combine the curve fits of the finite element temperature data with the cutting velocity profiles to obtain estimates of the temperature profiles for vibration assisted machining.

Finite Element Results

The simulation conditions were fixed to values comparable to the experimental test conditions for conventional turning. The approach to the temperature simulation for the vibration assisted cases is to gather the temperature history for the heating and cooling cycles for conventional turning at various work velocities. Based on curve fits to the FEA data, equations were inserted into the temperature prediction program to generate the temperature histories for numerous VAM cases. The FEA simulations factor the cutting conditions into the simulations. The resulting family of curves generated by the FEA governed by constant velocity cutting adhered to the generally accepted power law function relating temperature to velocity.

Temperature Results

With the theory developed mathematically, the temperature profiles were generated based on the vibration parameters and work velocity. Numerous cases were considered such that the effects of each parameter could be realized. The temperature profiles correspond to a 20 μm depth of cut for a diamond tool in AISI 12L14 work material since the temperature equations used are based on the curve fits to the finite element model at the specified cutting conditions. The following plots demonstrate the consequence of variations in the vibration amplitude and the work velocity. Figure 8 depicts the temperature rise for a tool motion of 40 kHz at 7 micrometers and a workpiece velocity of 0.2 m/s. This demonstrates Type 3 conditions where the tool motion dictates when cutting begins and ceases. The cutting velocity is provided as a reference to show how the temperature is reached through the process. Figure 9 shows the effect of increasing the work velocity to 0.6 m/s on the cutting temperature and the cutting velocity. Notice that the cutting state changes to Type 2 conditions and the mean cutting temperature rises approximately 15 degrees. Figure 10 demonstrates the effect of decreasing the vibration amplitude to 4 micrometers. This change reduces the separation between the tool and the work material thereby increasing the duration of the heat input and decreasing the duration of the heat dissipation, both acting to increase the cutting temperature. The result is a rise in the average temperature of approximately 7 degrees.

The results concur with experimental results that show increased tool wear as the tool motion changes from Type 3 to Type 2 to Type 1. Mapping temperature into diffusion equations resulted in trends showing this increase in tool wear; however, there were differences in the scaling between experiment and prediction.

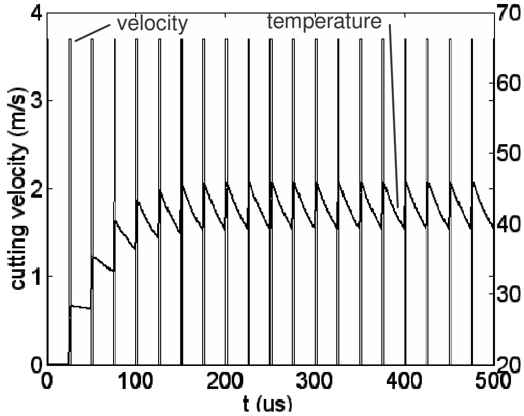

Figure 8. Cutting velocity and temperature at 40 kHz, 7 µm and 0.2 m/s

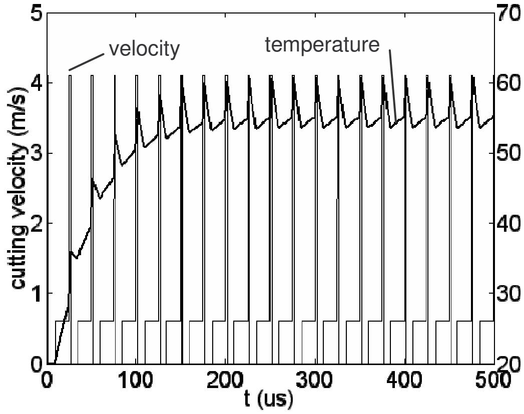

Figure 9. Cutting velocity and temperature at 40 kHz, 7 µm and 0.6 m/s

CONCLUSIONS

The simulations demonstrate that increases in the work velocity act to increase the temperature. From the same simulations, increases in the vibration amplitude and vibration frequency were found to be favorable for reducing temperature and hence diffusive wear, but must be addressed on a case by case basis for work velocity, vibration amplitude and vibration frequency for optimization.

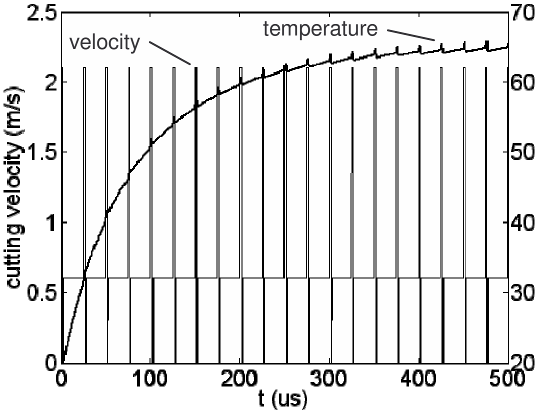

Figure 10. Cutting velocity and temperature at 40 kHz, 3 µm and 0.6 m/s

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