NUMERICAL SIMULATIONS OF VIBRATION ASSISTED MACHINING

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ABSTRACT

A two-dimensional (2-D) finite element model (FEM) has been developed to perform numerical simulations of vibration assisted machining (VAM). The model is based on an updated Lagrangian formulation, with adaptive remeshing. The model is capable of simulating the amplitude and frequency independently of the tool in the cutting (x) and thrust (y) force directions over a wide range of values. The resultant vibrations include linear, circular, and elliptical paths. Results of the finite element analysis include: chip formation, work piece deformation, cutting and thrust forces, pressures, temperatures, stress, strain, and strain rate. Materials modeled include: aluminum, steel and silicon carbide. These materials represent a comprehensive array of material properties and demonstrate the general utility of the modeling method. Other variables in the model include: cutting edge radius, rake angle, clearance angle, feed, cutting speed, depth of cut, length of cut, work piece dimensions, friction coefficient, and ambient conditions. The simulation results allow for a detailed study of the materials behavior in response to the VAM process variables. The work reported in this paper includes nano to micro meter feeds and depth of cut. VAM results are compared to base line simulations without vibrating conditions. The results reported are for diamond cutting tool material, i.e. single point diamond turning (SPDT) operation. The VAM results show a significant reduction in cutting (F_c) and thrust (F_t) forces as the degree of vibration (amplitude) and frequency are increased. Other parameters determined directly from the simulation results of interest include: Force ration (F_c/F_t), maximum temperatures and maximum pressures in the work piece. The results and analyses for the VAM process demonstrate the model's general utility over a wide range of process conditions (work piece materials), machining parameters (speeds, feeds and depth of cut) and VAM variables (amplitude and frequency of vibration). Comparisons to experimental results are included. Future work will attempt to reduce the scale of the vibration, to nanometers, and provide enhancements to the tool wear model to directly incorporate the effect of VAM to improve the machining process. This latter work will concentrate on further reductions in tool forces and temperatures, and research on the beneficial results of cutting fluids to the machining process in general the VAM process in particular. It is expected that improved tool designs will directly result from this work.

INTRODUCTION

Vibration assisted machining (VAM) has proved beneficial at machining metals and ceramics, with special applications being applied to steels and SiC [1-3]. This paper presents complementary work on numerical simulations of the VAM process using a commercial FEM software package AdvantEdge, from Third Wave Systems Inc. One of the authors (Patten) worked with TWS on the development and implementation of the VAM module, which is now incorporated into their commercial software product. The software has been tested and evaluated for a limited set up materials and process conditions. The work reported on in this paper concerns diamond turning of steels, as practiced by Overcash [2]. Of particular interest is the evaluation of the forces (cutting and thrust) and resultant temperatures. It is often assumed that the primary benefit of the VAM process to do reduce tool wear, when cutting (particularly diamond machining) difficult to machine materials (such as steels and ceramics). Reduced tool wear is assumed to result from decreased machining forces and/or decreased temperatures during machining. Tool wear is not explicated considered in this paper, nor is the application of a cutting fluid or coolant addressed. These conditions will be explored further in future work.

EXPERIMENTS-SIMULATIONS

A 2-D Lagrangian Finite Element Model (FEM), utilizing adaptive remeshing is utilized [5] for the simulations. Process parameters of interest include, which are explicated simulated include: feed, speed, amplitude and frequency of vibration. The work reported in this paper is for machining steel with single crystal diamond tooling. The work piece material is a 12L14 Steel [2] and the diamond tool used is a zero degree rake angle of varying cutting edge radius (0.002 to 0.001 mm). A constant frequency of vibration of 10,000 Hz is utilized in all of the results reported on herein [2], however the simulation model is capable of a wide range of vibration frequencies. The feed, or uncut chip thickness, used for these simulations is 20 micrometers (µm, or 0.020 mm) and the amplitude of vibration ranges include: 0, 2, 4 and 8 micrometers (0, 0.002, 0.004, and 0.008 mm respectively). Three different cutting speeds are reported on in this paper, these are: 1 m/s, 0.5 m/s and 0.25 m/s. The simulated conditions are summarized in Table 1. Only circular vibrations are considered in this paper, i.e. the x and y vibrations are identical (amplitude and frequency); however the software can simulate linear and elliptical vibrations as well. For reference, at the intermediate cutting speed, 0.5 m/s, the tool and work piece partially separate (lose contact) at the highest vibration amplitude (8 µm, in accordance with [1]).

TABLE 1. Simulated Process Variables

Amplitude (µm)	0	2	4	8
Speeds (m/s)	1.0 and 0.5	1.0 and 0.5	1.0 and 0.5	1, 0.5 and 0.25
Thermal on/off	On/off	On/off	On/off	On/off

RESULTS

The VAM simulation results are included for the effects of vibration amplitude and cutting speed on the resultant cutting forces and temperatures (tool and work piece).

Cutting Forces

The force values reflect the time varying periodic nature of the forced vibrations of the VAM process. These characteristic force signals are similar to the actual VAM processes as shown by Brehl and Dow [1]. The periodic nature of the time varying cutting force values are shown in figure 1, for the case of a 4 µm amplitude at a cutting speed of 1.0 m/s, these conditions are just below the threshold where the tool and work piece separate during the VAM machining process; i.e. there is no actual separation of the tool and work piece due to the VAM action.

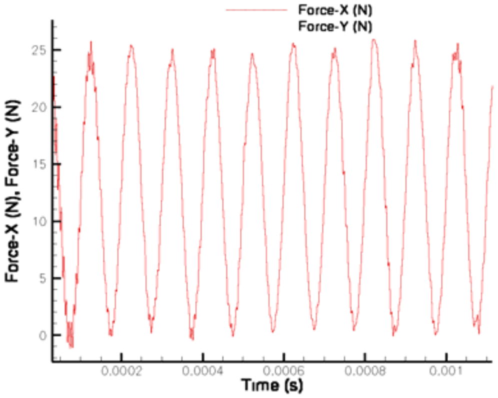

FIGURE 1. Cutting Forces (not filtered)

The average of the maximum or peak force values, at steady state, as a function of vibration amplitude are shown in figure 2. These values were determined by averaging the peak forces, as seen in the force plots (such as figure 1), to establish a force for comparison with thermal conditions not included, i.e. no thermal effect. The observed effects are due to the mechanical oscillations alone and do not include a thermal component, this is useful for separating out the influence of the mechanical induced vibrations from any resultant thermal effects due to the relative change in apparent cutting velocity (due to the vibration oscillations being superimposed on the cutting velocity).

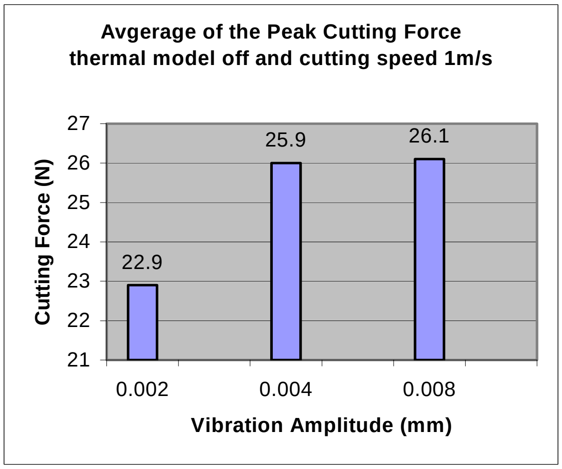

FIGURE 2. Cutting Forces (average of peak forces) as a function of vibration amplitude

The filtered force data results are presented in figure 3, where these values are representative of what a dynamometer would measure during an actual cutting test (the oscillations associated with the vibrations are filtered and smoothed). The reduction in cutting force with increasing vibration amplitude is expected, and is considered one of the primary benefits of the VAM process.

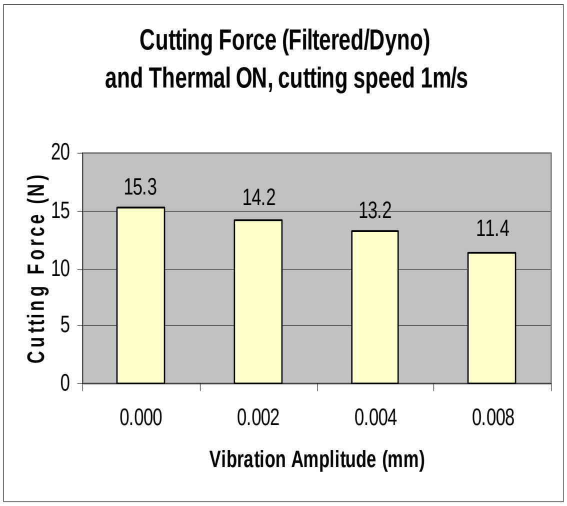

FIGURE 3. Cutting force for Various Vibration Amplitudes

Temperatures: Tool and Work piece

Two sets of simulations were conducted to evaluate the effect of the VAM process on the resultant temperatures associated with the machining operation. Initially, simulations were conducted without any thermal conditions or calculations being employed, i.e. thermal effects are ignored (as shown in figure 2). These simulations provide a base line to study the influence of the VAM process on the resultant forces, without a thermal component or influence. Next, the software's thermal model was implemented and the resultant temperature effects were determined (as shown in figure 3). However, the difference between the resultant forces, for the same simulated conditions (cutting speed and vibration amplitude) with thermal conditions on and off, were not significant (< 2% change), and are not specifically included in this paper. These results are also consistent with the small change in resultant temperatures (< 5 C) due to the affects of vibration amplitude. These latter results are also not included in this paper as they were determined to be insignificant.

Speed Effects:

The effect of the cutting speed relative to the resultant cutting forces and temperatures are shown in figures 4-6. Generally, in traditional machining processes, cutting forces are not sensitive to cutting speed. An exception to this general rule is when strain rate or thermal softening effects develop as a result of high speed machining. For the machining conditions reported in this paper, these effects are assumed to be negligible at the low cutting speeds evaluated. Figure 4 shows a reduction in cutting force with a decrease in cutting speed for the largest amplitude evaluated (8 µm). This result is consistent with the anticipated enhancement from the VAM process, i.e. as the cutting speed decreases, the relative influence and benefit of the vibrations increase.

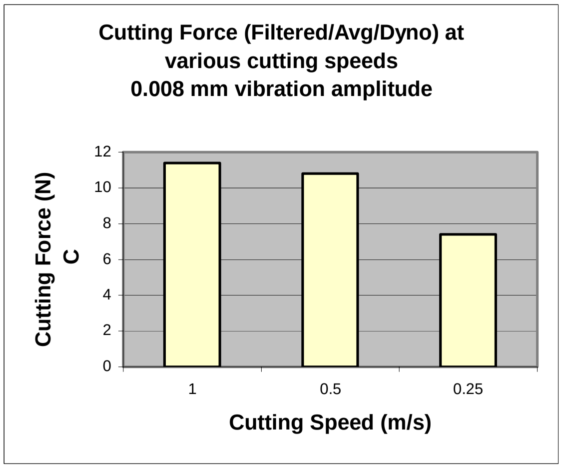

Figure 4. Cutting Force at various cutting speeds

Figures 5 and 6 show a reduction in peak (maximum) tool and work piece temperatures respectively as the cutting speed decreases, for the largest vibration amplitude evaluated (8 µm). A decrease in maximum or peak tool and work piece temperatures is expected as the cutting speed (velocity) decreases.

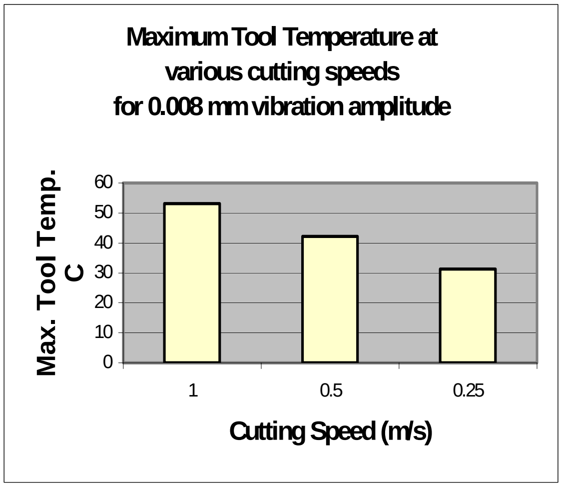

Figure 5. Peak Tool Temperatures at Various Cutting Speeds

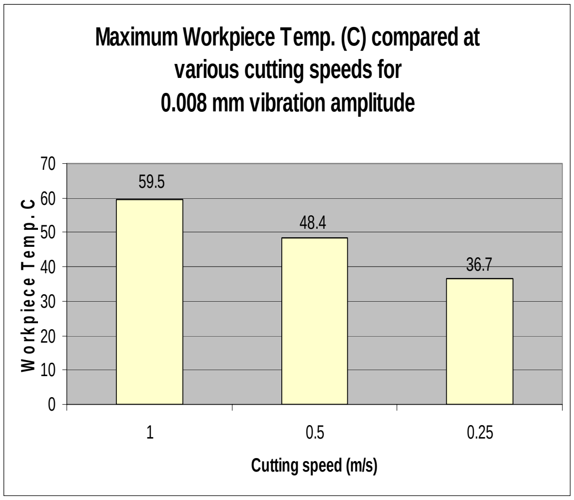

Figure 6. Peak Work piece Temperatures at Various Cutting Speeds

DISCUSSION

The peak force, associated with the peak in vibration amplitude, increased with an increase in the amplitude of vibration (as shown in figure 2). The filtered forces, cutting and thrust, (equivalent to a measured dynamometer force during an actual cutting experiment) decreased with an increase in the amplitude of vibration (cutting forces are shown in figure 3). These latter results are as expected, and is considered to be and consistent with one of the fundamental benefits of the VAM process, i.e. to reduce the resultant forces, which is expected to lead to reduced tool wear.

The variations in the tool and work piece temperature change, as a function of vibration amplitude, were minimal (about 5 C or less, showing a slight decreasing trend as the amplitude of the vibration increased) at the same cutting speed. Cutting speed had a much greater effect relative to the resultant temperatures produced, i.e. as the cutting speed is reduced, the temperatures are reduced significantly (20 to 40%, or 15 C to over 30 C), for the range of conditions simulated. This suggests that a cooling affect, for dry cutting conditions (the simulated conditions did not include a cutting fluid model), does not contribute significantly to the machining process, i.e. the change in vibration amplitude alone only had a small effect on the resultant temperatures. However, a cutting fluid or coolant may prove beneficial if the fluid can enter the chip-work piece-tool contact zone at higher vibration amplitudes. But, based upon the conditions evaluated in this research and presented in this paper, it does not appear that the potential contribution for additional cooling (and reduced temperatures) is significant.

No specific consideration was given as to the effects of strain rate on the material behavior and deformation. It is possible that the increase in “apparent” cutting velocity, due to the VAM action being superimposed on the process cutting velocity, that strain rate effects might be manifested as a result of the change in strain rate during the chip formation process.

CONCLUSIONS

The FEM is an excellent tool for studying the VAM process. The simulation results indicate that the cutting forces are directly and significantly affected by the vibration amplitude and the cutting speed (as shown in figures 3 and 4), while the resultant temperatures are mostly affected by the cutting speed (as shown in figures 5 and 6) and not significantly affected by the vibration amplitude. Also, there does not appear to be any significant thermal effects associated with the vibration amplitude alone that would contribute to a change in cutting force. All of the VAM process parameters are readily implemented in the commercially available machining simulation software package (AdvantEdge from TWS Inc.) used in this research project. While the focus of this paper is on SPDT of steel, ongoing work involves VAM of SiC and AlTic materials to evaluate the potential valuable effects associated with the VAM process on these hard and brittle (and nominally diamond turnable) materials. In addition to the work reported on in this paper (effects of vibration amplitude and thermal effects on the resultant forces), the software is capable of simulating the effects of cutting fluids (on friction and forces) and tool wear. Future work will be directed at evaluating these additional process parameters; in particular the influence on of a cutting fluid on tool and work piece temperatures as a function of vibration amplitude is of interest.

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