Modelling of vibration assisted machining f.c.c single crystal

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Abstract

In this paper, a developed three-dimensional model combining finite-element and smoothed-particle hydrodynamics approaches is presented. It incorporates a crystal-plasticity theory for vibration-assisted machining into ABAQUS/Explicit software by using a user-defined subroutine VUMAT. The paper presents quantitative comparison of cutting-force variation for VAM and conventional machining with identical cutting parameters for anisotropic workpieces. The obtained simulation results demonstrated that the (101) crystal orientation with a cutting direction at 30° had the highest reduction in a cutting force for three levels of vibration amplitude (10, 20 and 30 μm) and three levels of frequency (15, 20 and 25 kHz).

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Keywords: Vibration-assisted machining; FE modelling; cutting force; single crystal; frequency; amplitude

1. Introduction

Vibration assisted machining (VAM), also known as ultrasonically assisted machining (UAM), is a relatively new machining technique [1-2], which is used increasingly for various industrial applications, evidenced by the introduction of ultrasonic machines by leading manufacturers, e.g. DMG. In VAM, vibration is imposed on the movement of a cutting tool in a primary cutting direction. This vibration is typically with high frequency and low amplitude. Due to imposed vibration, the cutting tool periodically loses contact with the workpiece transforming a continuous cutting process typical for conventional machining (CM) into an intermittent, vibro-impact one. Application of this technique has shown considerable improvement in surface roughness of machined workpieces and a significant reduction in the level of cutting forces [3].

From micromechanics it is well known that the crystallographic structure of metals play a significant effect in determining their deformation characteristics [4-5]. This ultimately influences machining forces in micro-machining processes. Still, in most previous studies, isotropic material parameters were assumed for the cutting-force analysis of the VAM process [6-7]. Since experimental studies demonstrate the importance of an underlying crystalline structure in machining, it becomes vital to account for this in numerical models of VAM. FE simulations were traditionally used to reduce the need for extensive experimental studies, which are expensive, and also help to extend the usability envelope of next-generation components to untried loading levels and environment conditions.

The mechanism of material’s deformation in single-crystal machining is rather complex and requires the development of special subroutines in a finite-element model framework [8]. An elasto-viscoplastic crystal plasticity-based constitutive law was used to describe the anisotropic behaviour of the crystal. The constitutive relationship is based on the Schmid’s law and incorporates the effect of crystal orientation and activated slip systems. The magnitude of the slipping rate \( \dot{\gamma} \) on the slip system \( \alpha \) is represented as

\[
\dot{\gamma}(\alpha) = \dot{\gamma}_0 \left( \frac{\tau}{\tau_0} \right)^n,
\]

where \( \dot{\gamma}_0 \), \( \tau_0 \), and \( n \) are the reference strain rate, strength of the slip system and resolved shear stress, respectively, on the slip system \( \alpha \). \( n \) is the macroscopic rate sensitivity of the material. The strain-hardening behaviour or evolution of slip resistance for all slips systems is calculated from
The crystal plasticity theory was implemented numerically within the VUMAT subroutine. For each incremental time step, in a f.c.c. crystalline structure, used here as an example of the workpiece material, the number of active slip systems and amount of slip is defined uniquely for 12 slip systems. The active slip system consists of \(\{111\}\) slip planes and \(<110>\) slip directions. Plastic work during the deformation process was determined using a rate-insensitive plasticity approach as f.c.c. crystals are inherently rate- and temperature-insensitive. Criteria for activation of a slip system approach as f.c.c. crystals are inherently rate- and temperature-insensitive. Criteria for activation of a slip system were defined based on the Schmid’s law. Material properties were updated for subsequent deformation increments to account for hardening. Finally, shear strain was identified for given cutting parameters (rake angle, cutting velocity, depth of cut, uncut chip thickness and coefficient of friction) and crystal orientation with regard to the tool movement (workpiece zone axis, cutting plane orientation and cutting direction).

The cutting force is one of the critical governing parameters defining efficiency of the machining process. In this paper, the influence of crystal orientations was studied with a combined three-dimensional FE and smoothed particle hydrodynamics (SPH) model for VAM and CM processes. The crystal-plasticity formulation was implemented in a commercial FE software ABAQUS/Explicit employing a user-defined subroutine VUMAT.

2. Modelling procedure

In simulations, a 3D deformable single-crystal body was selected as a workpiece while a cutting tool was assumed to be rigid. Instead of applying the same general solver to all domains of a problem, solvers optimized for particular regions of material’s behaviour were used. This approach allows for the use of finite elements in the low-distortion regions of the modelled workpiece while SPH particles were used in the high-distortion regions of the process zone. Although the SPH approach can be applied to severe distortions, it is generally not as good as standard finite elements for assessment of a structural response.

The length of the workpiece in numerical simulations was 250 \(\mu\)m, the height was 100 \(\mu\)m and the thickness was 10 \(\mu\)m. The workpiece was divided into two equal regions, one representing the SPH domain (250 \(\mu\)m \(\times\) 50 \(\mu\)m \(\times\) 10 \(\mu\)m) and the remaining part a continuum FE domain (Figure 1). The cutting tool had a zero rake angle and a cutting-edge radius of 2 \(\mu\)m. A clearance angle of the tool was equal to 5°. The depth of cut was fixed at 5 \(\mu\)m in nearly all of the simulations in this paper. The bottom and left-hand-side nodes of the workpiece were fixed with regard to displacements and rotations. A ‘tie contact’ condition was specified for the interface nodes between the SPH and FE domains. A general node-based contact condition was used for the tool-workpiece interface. The slave surface (SPH domain), which is mechanically less stiff than the master surface (tool), was defined for contacting parts. A Coulomb friction law with a constant coefficient of friction \(\mu = 0.12\) [10] was used. The same crystal-plasticity formulation was used in both FE and SPH domains.

The continuum domain was meshed with eight-node brick elements with reduced integration (C3D8R), while the PC3D element type was used for the SPH area. A mesh-sensitivity study was performed and, based on this, an optimized model was developed consisting of 14491 brick elements with 21517 nodes. The element size of 1.25 \(\mu\)m in the continuum FE and SPH domains was sufficient to characterize the machining process. Additionally, a distribution of von-Mises stress across the SPH-FE interface was carefully analysed. As expected, small stress fluctuations around the transition between two domains were observed; however, this was deemed to be too small to warrant further mesh refinement.

In the current study, the tool movement was along four specific directions, 0°, 30°, 60° and 90°, on three chosen crystal orientations, (100), (101) and (111). The crystal-plasticity constitutive model proposed in [10] was used to describe deformation of the machined material; properties of single-crystals aluminium were used. The rigid tool oscillated harmonically in the cutting direction to simulate VAM. The vibration motion of the tool in the X (cutting) direction can be written in the following form:

\[ y^0 = \sum h_{0k} p_k^0, \]  

where summation ranges over all active slip systems and \(h_{0k}\) corresponds to the slip-hardening modulus. The hardening model by Peirce [9] was used to represent the hardening behaviour of each slip system by the following equations:

\[ h_{0k} = h_{0k} \left( \frac{\sigma_n}{\sigma_0} \right)^{n}, \quad \sigma_0 = \gamma \sigma_n \left( \epsilon \sigma = \sigma \right). \]

\[ y = \sum_{k} \int_{0}^{t} \sigma_{0k} \, dt. \]  

\[ g^0 = \sum h_{0k} p_k^0. \]  

\[ \gamma = \sum h_{0k} \sigma_{0k} \, dt. \]  

\[ \mu = 0.12 \]  

\[ \tau_{0k} = \text{equiv. to the initial value of current strength of the slip system}. \]  

\[ \gamma \]  

\[ \text{corresponds to cumulative shear-strain on all slip systems and is described by} \]

\[ \mu = \text{friction} \]

\[ \text{corresponds to the slip-hardening modulus}. \]  

\[ h_{0k} \]  

\[ \text{is the break-through stress, where large plastic} \]

\[ \text{strains on} \]

\[ \text{all slip systems} \]  

\[ \text{and amount of slip is defined uniquely for 12 slip systems}. \]  

\[ \text{The active slip system consists of} \{111\} \text{slip planes and} \]  

\[ \langle110\rangle \text{slip directions}. \]  

\[ \text{Plastic work during the deformation process was determined using a rate-insensitive plasticity approach as f.c.} \]

\[ \text{crystals are inherently rate- and temperature-insensitive.} \]  

\[ \text{Criteria for activation of a slip system were defined based on the Schmid’s law}. \]  

\[ \text{Material properties were updated for subsequent deformation increments to account for hardening}. \]  

\[ \text{Finally, shear strain was identified for given cutting parameters (rake angle, cutting velocity, depth of cut, uncut chip thickness and coefficient of friction) and crystal orientation with regard to the tool movement (workpiece zone axis, cutting plane orientation and cutting direction).} \]  

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\[ x = vt + a \sin(\omega t), \]  

where \( a \) and \( \omega \) are the vibration amplitude and angular frequency, respectively; \( v \) is the constant nominal tool speed. The phase angle was fixed at zero for all simulations in this research. The cutting-tool vibration was implemented as a displacement boundary condition in the model. Typical variations of tool’s displacement and velocity in VAM and CM are shown in Figure 2. The frequency and amplitude of vibration in VAM were chosen as 20 kHz and 20 µm, respectively. The nominal machining velocity was 1 m/s for both CM and VAM (Figure 2). Based on the presented tool motion for VAM, the tool came in intermittent contact during the machining process, in contrast, in CM, the cutting tool was in permanent contact with the workpiece material.

![Figure 2](image)

**Figure 2.** Cutting tool’s displacement (in the X axis of Figure 1) and velocity in CM model ((a) and (b)) and VAM model ((c) and (d)).

Implementation of the harmonic velocity in contact with the SPH domain is not as straightforward as in the FE-based numerical models. Abrupt changes of the cutting-tool velocity in contact to the particles in the SPH domain during short time periods lead to numerical instabilities. To circumvent this problem, the model was divided into 50 sequential analysis steps. In contrast, thanks to continuous contact between the tool and workpiece in CM, the entire machining process can be modeled in a single step.

Currently, there is no experimental data in the literature on VAM for a single-crystal workpiece that can be used to verify the developed model; hence, the data for CM was used for this purpose. Figure 3 presents specific cutting energy (forces) resulted from our simulations of CM and the experimental study [11] for machining of single-crystal aluminium. A convenient way to represent the crystallographic orientations is to specify the angle of rotation of each plane normal from a specific direction. The rotation in Figure 3 provides the counter-clockwise rotation of each plane normal about the [001] direction from the [100] direction. The experimental data was for three crystallographic orientations, namely, (100), (110) and (120) at three cutting directions [100], [110], and [120], respectively. The tests were conducted at cutting speed of 5 mm/s with 5 µm chip thickness for each cutting orientation of the workpiece. The acceptable correlation was observed between the results of the developed model and experiments in [11].

![Figure 3](image)

**Figure 3.** Specific cutting-energy magnitudes for developed FE/SPH model and experimental study [11]

3. Comparison of cutting forces for CM and VAM

All FE/SPH simulations were performed for VAM and CM processes with identical cutting parameters; the idea was to use results for the latter as a reference for the former. The intermittent character of the chip-cutting tool contact is the main reason for differences in the cutting force for two machining techniques. Figure 4 demonstrates cutting-force signatures for VAM and CM as an example. Here, simulations were performed for (100) crystal orientation and 0° cutting direction; the magnitudes of frequency and amplitude of tool vibration in VAM was 20 kHz and 20 µm, respectively. Apparently, in CM the force on the cutting tool remained practically unchanged after an initial engagement process, whilst in VAM it changed during each cycle. The quantitative analysis of the average levels of the cutting forces for one full cycle of vibration demonstrated its significant reduction compared to that in CM.

![Figure 4](image)

**Figure 4.** Cutting-force variations for VAM and CM

In VAM, in each cycle of vibration the evolution of a cutting force could be divided into two main stages. During the first stage, the tool penetrates into the workpiece; the force increased with penetration and attained levels somewhat higher than those in CM. The varying magnitude of speed in VAM at each increment resulted in a non-unique set of slip systems active and, hence, fluctuations in the maximum cutting force observed. The attainment of the maximum penetration depth is characterized by the highest level of
generated stresses in the process zone and marks the end of the first stage. Figure 5 shows the distribution of shear strain over two active slip systems. These two slip systems were the most active ones, whereas the contributions of other systems were comparatively small. It is to be noted that the Schmid factors for these two slip systems were both equal to -0.4082 initially. The crystal began to deform plastically by slip on these active systems. The stress required to cause slip on the slip system is the yield stress of the single crystal.

When a major slip plane is coincident with the cutting direction, the material’s glide does not significantly contribute to material removal; chips are formed by fracture along the direction of maximum shear stress. Plastic flow becomes possible when the specimen is rotated so that the slip plane makes an acute angle with the cutting direction. These differences in the material motion lead to significant variations in the nature of plastic deformation ahead of the tool and consequent variation in the magnitude of the forces, force ratio, specific energy, and subsurface deformation.

Figure 5. Distribution of shear strain for two main slip systems

The second stage is unloading: the velocity direction of the tool changes and it moves backwards. During this stage, the full separation of the cutting edge from the chip happens, resulting in a vanishing level of the cutting force. The force magnitude starts to decline at the unloading stage until it vanishes when the tool separates from the workpiece as the process repeats with the next cycle of vibration. Since in CM the cutting tool was in permanent contact with the workpiece and has a constant speed, a non-fluctuating force was experienced by the cutting tool.

The specific cutting energy is defined as the energy required for removing a unit area of material. It is calculated by dividing the measured cutting force by the chip area, which is computed from the product of uncut chip thickness and the width of the cut. For VAM, this force is the average force over one full cycle of vibration. The averaged values of cutting force in one completed cycle and the extent of its reduction in VAM for the chosen orientation of cutting direction and three basic crystal orientations for the f.c.c. structure were calculated and are presented in Table 1.

Table 1. Cutting forces (in µN) for three basic orientations of f.c.c. and four cutting directions (angles) depth of cut 5 µm, vibration amplitude 20 µm, frequency 20 kHz over one full cycle of vibration

<table>
<thead>
<tr>
<th>Angle</th>
<th>(100) Reduction</th>
<th>(101) Reduction</th>
<th>(111) Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>14 5.2 62%</td>
<td>16 9.0 40%</td>
<td>10 5.2 41%</td>
</tr>
<tr>
<td>30°</td>
<td>14 6.1 51%</td>
<td>14 3.3 76%</td>
<td>12 5.1 55%</td>
</tr>
<tr>
<td>60°</td>
<td>15 6.2 55%</td>
<td>13 4.5 65%</td>
<td>8 5.3 41%</td>
</tr>
<tr>
<td>90°</td>
<td>13 5.1 60%</td>
<td>11 5.6 49%</td>
<td>13 6.0 55%</td>
</tr>
</tbody>
</table>

In order to get a good understanding of the effect of different machining parameters on single-crystal cutting, a series of simulations was conducted. It is well known that selection of appropriate levels of amplitude and frequency of vibration is critical for VAM [6]. The effect of these two parameters on cutting forces is investigated in more detail in the next section in comparison with CM.

4. Parametric study of VAM

In order to evaluate the effect of process parameters such as frequency and amplitude on machining of aluminium single crystals, three levels of frequency - 15 kHz, 20 kHz and 25 kHz - and three levels of amplitude - 10 µm, 20 µm and 30 µm - were analysed for the chosen orientations and directions. The selected levels of frequency and amplitude were common for analysis of VAM [6].

4.1. Effect of vibration amplitude

In the previous study, performed for polycrystalline materials with effective macroscopic properties, it was reported that the cutting force declined with an increase in the vibration amplitude for the same frequency [6]. Our simulations of single-crystal machining for the (100) crystal orientation generally confirmed this trend (see Figure 6). For comparison, the cutting force in CM with the same machining parameters is also presented for each orientation.

A change in the vibration amplitude in VAM affected the cutting process through two opposing mechanisms. With increasing amplitude, the maximum value of the cutting force in VAM became somewhat higher compared to that in CM for nearly all of the cases. This growth can be attributed to the increased deformation rate and maximum shear strains resulting in strain-rate hardening of the workpiece material. Although this increase in the maximum cutting force differed, the maximum of it reached only 4% in (100) orientation compared to the respective magnitude for CM. On the other hand, the increased amplitude is related to a larger separation between the tool and workpiece and, subsequently, a shorter period of their contact in each complete cycle. As a result, a larger reduction in the average cutting force in VAM was observed compared to the case of interminable tool contact in CM over the entire cutting time.

A separate study was conducted to analyse the effect of vibration amplitude on the cutting forces for two other studied orientations of the workpiece - (101) and (111); the respective
results are given in Figs. 7 and 8.

4.2. Effect of vibration frequency

Obviously, for VAM with a constant vibration amplitude, the number of instants of contact between the tool and the workpiece in any given period is always higher at a higher frequency. To investigate the effect of the latter on the cutting process, three levels of frequencies - 15, 20 and 25 kHz - were selected for another case study. It is important to mention that though the three cases had different frequencies, they were all modelled for the same time domain. The same machining parameters were used in all the simulations conducted for (100), (101) and (111) crystallographic orientation presented in Figs. 9, 10 and 11, respectively.

Machining in the (101) orientation resulted in a higher force reduction compared to two other orientations for each level of amplitude. This crystal orientation also caused a large cutting-force variation compared to two others crystal planes [12]. The number of active slip systems in this orientation seems to be higher than that for two other planes thanks to the symmetric orientation of the f.c.c. structure. The maximum force reduction happened in the (101) crystal orientation at 30° cutting direction for three selected amplitudes.

Still, though in the case of this combination of crystal orientation and cutting direction more energy can be saved with VAM process, large levels in force reduction were not recorded for VAM. A possible source of this behaviour is activation of different slip systems near to each other due to the changing cutting speed. When a set of slip systems is active, an increased state of stress makes it energetically more preferable for slip to occur in a different system. This could lead to low values of average cutting force in the (101) crystal orientation and 30° direction rather than for other sets of cutting directions.

5. Conclusions

A detailed numerical analysis of VAM of single-crystal material has not been considered and implemented before. The three-dimensional FE/SPH model described in this paper was a powerful and flexible tool for dynamic analysis of a response of single-crystal materials to various machining techniques. In this work, the developed model was employed to study the level of cutting-force reduction for cutting in different orientations and with various parameters of cutting-tool vibration.

Generally, it was observed that increasing the vibration amplitude and frequency resulted in the growth of force reduction compared to that in CM with the same machining parameters. This reduction was observed for different crystalline orientations and cutting directions. Basically, the average cutting force decreased with an increase in the
amplitude for all the orientation sets. A decrease of approximately 33% in the average force was recorded for an increase in the amplitude from 10 μm to 20 μm, and an additional low-magnitude decrease - some 10% - was observed when the amplitude was increased further to 30 μm.

An average reduction of 8.5% in the cutting forces compared to CM was noted for 15 kHz. A further increase in the frequency to 20 kHz and 25 kHz resulted in an average reduction of 26% and 40%, respectively, compared to CM. Simulations for three basic crystal orientations - (100), (101) and (111) - demonstrated the highest cutting-force reduction for (101) plane. In this plane, the 30° cutting direction was always characterised by the maximum extent of reduction in the cutting force and can be a suitable choice for application of VAM. Importantly, the developed and validated numerical model of CM and VAM can diminish costly experimental efforts in analysis of single crystals. Additionally, the described approach can also serve as a viable and numerically robust way to study other large-deformation problems.

Figure 9. Variation of cutting force with constant vibration amplitude of 10 μm for different frequencies for (100) crystal orientation for various cutting directions: (a) 0°, (b) 30°, (c) 60° and (d) 90°

Figure 10. Variation of cutting force with constant vibration amplitude of 10 μm for different frequencies for (101) crystal orientation for various cutting directions: (a) 0°, (b) 30°, (c) 60° and (d) 90°

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