Ultrasonically Assisted Turning: Finite Element Model

N. Ahmed ¹, M. Abid ¹, A.V. Mitrofanov ² and V.V. Silberschmidt ²

¹ Faculty of Mechanical Engineering, GIKI, Topi, NWFP, Pakistan
² Wolfson School of Mechanical and Manufacturing, Loughborough University, UK

ABSTRACT Ultrasonically assisted turning (UAT) is an advanced machining technique, where high frequency vibration (frequency \( f \approx 20 \text{ kHz} \), amplitude \( a \approx 20 \mu m \)) is superimposed on the movement of a cutting tool. Compared to conventional turning (CT), this technique allows significant improvements in processing intractable materials, such as high-strength aerospace alloys, composites and ceramics. Superimposed ultrasonic vibration yields a noticeable decrease in cutting forces, as well as a superior surface finish.

The current paper presents a 3D model of UAT that allows studying various 3D effects in turning, such as oblique chip formation, as well as to analyze the influence of tool geometry on process parameters, e.g. cutting forces and stresses generated in the workpiece material. The FE model (based on the general FE code MSC.MARC) is used for transient, coupled thermomechanical simulations of elasto-plastic materials under conditions of both UAT and CT. It is used to study the effect of cutting parameters and friction on UAT and CT. Also the effect of changing ultrasonic amplitude and frequency is studied. Numerical results are validated by experimental tests performed on UAT prototype.

INTRODUCTION

Turning is a type of metal cutting where a single-point tool is used to remove unwanted material to produce a desired product, and is generally performed on a lathe machine. Modern turning techniques have been improved considerably to achieve easy machining of difficult-to-cut materials and better surface finish. Methods such as high speed turning have been in use now for considerable time. But still machining of high-strength aerospace alloys, composites and ceramics causes high tool temperatures and fast wear of cutting edges, lacks dimensional accuracy and requires a considerable amount of coolant and thus requires the development of new cutting techniques.

Ultrasonically assisted turning (UAT) has proved to bring significant benefits in machining of hard-to-cut alloys. It is an advanced cutting technique, where high-frequency vibration (frequency \( f \approx 20 \text{ kHz} \), amplitude \( a \approx 15 \text{ mm} \)) is superimposed on the movement of the cutting tool. Compared to conventional turning (CT), this technique allows significant improvements in processing intractable materials. A multifold decrease in cutting forces, as well as an improvement in surface finish can be achieved with the use of UAT [1].
Despite all its advantages, this technique has not yet been widely introduced in the industry. Problems such as instability of the cutting process that resulted in poor surface finish prevented the full implementation of this process. The development of an autoresonant control system [2] added stability to the system by making the vibrations regular, thus opening the way to the industrial introduction of UAT [2].

The prototype of the UAT system has been designed at Loughborough University, UK, and a program of experimental tests has been implemented confirming advantages of UAT in comparison to CT. The dynamics of UAT as a non-linear vibro-impact process was studied in [3], and the amplitude response of the cutting tool under loading was analysed for this cutting technique.

However, thermomechanics of the tool-workpiece interaction, which is of special importance for the regime with multiple microimpacts in the process zone, and other specific features of the cutting process in UAT have not been fully understood. The finite element method (FEM) is a main computational tool for simulation of the process zone and of the tool-workpiece interaction in metal cutting. A detailed review of FE models of cutting can be found in the monographs [4, 5]. In order to understand the mechanics of tool-chip interaction in UAT, and to analyse stresses and strains distributions in the cutting region, heat transfer in the workpiece material and in the cutting tool and also of the cutting forces, a 2D finite-element model was developed. An initially purely mechanical finite-element model was further improved, resulting in a transient, fully thermomechanically coupled one for both UAT and CT. Some computational results obtained with this model were discussed in [6].

The current paper discusses the 3D FE model of UAT that was developed as extension to the 2D model. This model allows studying various 3D effects in turning, such as oblique chip formation, as well as the influence of the tool geometry on process parameters, e.g. cutting forces and stresses generated in the workpiece material.

Up to now, 3D FE models were used to simulate conventional cutting processes. The majority of the suggested schemes employ the method of chip separation along a predefined line, separating finite elements in the initial discretization of the area, hence reducing the flexibility of the analysis. Only a few schemes use other techniques, such as elements deletion based upon penetration [7], adaptive remeshing of the workpiece elements [8], and combination of both the manual deletion and remeshing [9]. Adaptive remeshing that is employed in the current paper maps calculated fields of parameters onto the new mesh to eliminate distortion in the element shapes, which could otherwise cause analysis termination. The method has an advantage of a relatively easy adjustment in the cutting direction and angles, as well as other cutting parameters, such as the feed rate, without a necessity to reformulate the boundary-value problem as in the case of separation along a predefined line.

A FEA analysis of heat generation in machining of isotropic materials was conducted in [10] in order to study the effects of the convective heat transfer. A different approach, using an orthogonal FE model coupled with an analytical 3D model of cutting, was developed in [11] to predict a chip flow angle and three-dimensional forces in the tool. Another 3D model was introduced in [8] that took into account dynamic effects, thermo-mechanical coupling, constitutive damage law and contact with friction in order to study the cutting forces and plastic deformation.
With 3D modelling of CT being used for the study of tool forces and chip flow for the last two decades, this paper presents the first three-dimensional FE model of UAT. It has been recently developed and the computational results, emerging from this 3D formulation, are discussed.

MODEL DESCRIPTION

General features

A detailed description of the our previously developed 2D numerical model can be found in [6, 12]. The current FE model utilizes the MSC MARC/MENTAT FE code [13] and is based on the updated langrangian analysis procedure that provides a transient analysis for an elasto-plastic material and accounts for the frictional contact interaction between the cutter and workpiece as well as material separation in front of the cutting edge.

The relative movement of the workpiece and cutting tool in CT is simulated by the translation of the tool with the constant velocity. Harmonic oscillation with vibration amplitude of 15 μm (peak-to-valley) is then superimposed on this movement in the tangential direction (i.e. along X-axis in Fig.1) in order to model ultrasonic vibration of the tool. The vibration speed is several times greater than the chosen translational speed of the tool leading to the periodic separation of the tool from the newly formed chip, thus transforming the process of cutting into one with a multiple-impact interaction between the tool and chip. Various stages of such vibration cycle are described in detail in [14].

![Diagram of relative movement in 3D simulations of UAT](image)

Figure 1: A scheme of the relative movement of the workpiece and cutting tool in 3D simulations of UAT

The developed FE model is fully thermomechanically coupled in order to properly reflect interconnection between thermal and mechanical processes in the cutting zone: excessive plastic deformation and friction at the tool–chip interface lead to high temperatures generated in cutting region. This results in generation of thermal stresses and volumetric expansion as well as affects material properties of the workpiece, such as thermal conductivity and specific heat. More details on thermomechanical processes in UAT in comparison to CT can be found in [12].
The mechanical behaviour of the workpiece material (aged Inconel 718) at high strains, strain rates and elevated temperatures can be adequately described by the Johnson-Cook material model [15], accounting for the strain-rate sensitivity, that is employed in simulations (Fig. 2):

$$\sigma_y = (A + B \varepsilon_p^n)\{1 + C \ln[(d\varepsilon_p/dt)/(d\varepsilon_o/dt)]\} (1-T^*m) \quad (1)$$

where \(A = 1241\) MPa, \(B = 622\) MPa, \(C = 0.0134\), \(n = 0.6522\), \(T^* = (T-T_{room})/(T_{melt}-T_{room})\), and \(d\varepsilon_p/dt\) are plastic strain and a strain rate, \(T_{room}\) and \(T_{melt}\) are the room and melting temperatures, respectively. A term \(T^*m\) is assumed to be negligible since thermal softening of Inconel 718 is insignificant (less than 5%) within the temperature range that is modelled in FE simulations and justified by infrared thermography experiments. This material model, utilised by various researchers (see, e.g. [16, 17]), has been modified to prevent unrealistically high stress values at high strains, so that maximum stress values are now limited to ultimate tensile strength of Inconel 718 at corresponding strain rates (that can reach 105 1/s for standard cases).

Figure 2: Effect of strain rate on plastic behaviour of Inconel 718.

**FE MODEL**

A 3D model for orthogonal turning process, i.e. the one where the tool edge is normal to both cutting and feed direction, is considered. The dimensions of the part of the workpiece modelled in simulations are 2.5 mm in length by 0.5 mm in height by 0.4 mm in depth with the uncut chip thickness \(t_1\) being 0.1 mm (Fig. 3). The material’s properties adopted for the workpiece are those of Inconel 718. The cutting tool is simulated as a rigid body and the material properties defined are those of tungsten-carbide. The current model possesses a number of advantages compared to the 2D model. Various 3D effects in turning, such as non-orthogonal / oblique chip formation, as well as the influence of the tool geometry on process parameters (cutting forces and stresses generated in the workpiece material) could be studied. The 3D model also permits to investigate the effect of various vibration directions of the cutting tip in UAT on the cutting process, and eventually should serve as an optimisation tool for the UAT technology. Various combinations of vibration directions can also be studied numerically, whereas their experimental implementation can be extremely laborious, as it may require new types of ultrasonic transducers and mounting systems to be designed. Furthermore, the three-dimensional FE formulation helps to perform a direct comparison of
numerical results and experimental tests for oblique cutting, thus not requiring any changes to a standard cutting setup. This is important since the FE results, e.g. cutting forces, based on the 2D model can be directly compared only to orthogonal turning tests. Such turning tests can be very difficult to implement for intractable materials, as they require special setup arrangements or specific workpiece shapes, e.g. thin tubes. In addition, the 3D model does not need as many assumptions as the 2D model, for example, the workpiece thickness is introduced here explicitly as compared to its artificial introduction in 2D. The 3D model also accounts for chip expansion in the lateral dimension (along Z-axis in Fig. 1) that was impossible in the 2D model and led to generation of excessive stresses in the cutting region. Finally, the real geometry of the cutting tool can be studied with the 3D model, thus allowing the analysis of the influence of the tool sharpness and wear on the cutting process.

During the simulation, elements in the process zone can become highly distorted, and hence are no more appropriate for calculation. Automatic remeshing/rezoning is used in the workpiece and chip to replace those distorted elements with ones of better shape. Figure 4 shows the chip formed as a result of successful implementation of remeshing/reasoning.

![Figure 3: Finite-element mesh for the workpiece and cutting tool in the FE model](image1)

![Figure 4: Chip formation in FE simulations](image2)

In nearly all models developed for the simulation of metal cutting, an initial cut was introduced in the workpiece as the starting point for separation that leads to chip formation. The present FE model does not utilize such a cut (Figure 3). Hence, an adequate study of chip
formation from its very beginning to a fully formed chip is possible. This type of modelling also provides the benefit of using the same model of the workpiece for different shapes of the cutting tool thus forming a basis for optimisation studies for the tool shape.

Results of simulations and discussion

All variants of numerical (finite element) simulations below are performed for two cutting techniques (CT and UAT) with identical parameters so that results for CT could serve as a reference for UAT. Two contact conditions are considered at the tool–chip interface: (a) a frictionless contact, and (b) a contact with friction (coefficient of friction \( \mu = 0.5 \)). The former case corresponds to the well-lubricated cutting process, with heat generation occurring only due to plastic deformation processes. Case (b) models dry cutting conditions, with additional heat being generated due to friction between the tool surface and separated workpiece material.

Chip shape formation

Noticeable differences are observed between chip shapes obtained in FE simulations with and without friction for both CT and UAT. The radius of curvature of the chip under the frictionless contact condition at the tool–chip interface is approximately 2.5 smaller than that for the contact with friction of both CT and UAT (Fig. 3); that is supported by turning experiments with different lubricants, showing higher values of the radius of curvature for dry turning.

The chip thickness in simulations with friction is greater than that in simulations without friction. The chip thickness ratio \( r = t_1/t_2 \) (see Fig. 1), that is the ratio of thickness of the uncut chip to that of the deformed one, equals 0.6 and 0.7, respectively, for simulations with and without friction, for both CT and UAT. No significant differences between CT and UAT are found in the value of \( r \) for the same friction conditions. This numerical result is also in good agreement with experimental studies showing only insignificant variations in the chip thickness for both cutting schemes.

Cutting forces

A significant difference in forces acting on the cutting tool has been discovered for UAT and CT for similar cutting parameters. In CT simulations a practically non-changing force is acting on the cutting tool, while in UAT the forces start to increase with penetration and attain levels somewhat higher than the average force in CT at the maximum penetration depth. The force magnitude then starts to decline at the unloading stage until it vanishes when the cutter separates from the chip and starts to move away from it. The forces stay close to zero level until the cutter comes into contact with the chip again at the next cycle of ultrasonic vibration. The comparison of values from Fig. 6 shows that the averaged (over the vibration cycle) force in case of UAT is nearly 38% of the forces in case of CT. Low-level fluctuations of the cutting force at the withdrawal and approach stages of the cycles are explained by the remaining contact between the cutter and freshly formed workpiece surface, as well as by the numerical error involved in FE simulations.
**Effect of lubrication/friction**

The significant difference in forces acting on the cutting tool has been discovered between simulations of UAT with and without friction (Fig. 5). The maximum magnitudes of cutting forces are reached when the tool is in full contact with the chip, with these forces dropping to zero levels when the tool disengages from the chip. The maximum magnitude of the cutting force in simulations with friction is by 20-25% higher than that in frictionless simulations.

![Figure 5: Chip shape and distribution of equivalent plastic strains in the cutting region in simulations of UAT with friction ($\mu = 0.5$) (a) and without it ($\mu = 0$) (b). Cutting parameters: $t_1=0.1$ mm, $V_c = 310$ mm/s ($t = 3$ ms)](image)

Figure 5: Chip shape and distribution of equivalent plastic strains in the cutting region in simulations of UAT with friction ($\mu = 0.5$) (a) and without it ($\mu = 0$) (b). Cutting parameters: $t_1=0.1$ mm, $V_c = 310$ mm/s ($t = 3$ ms)

![Figure 6: Comparison of calculated forces in cutting tool for CT and UAT simulations ($\mu = 0.5$, $t_1=0.1$ mm, $d=0.4$ mm, $V_c = 335.2$ mm/s)](image)

Figure 6: Comparison of calculated forces in cutting tool for CT and UAT simulations ($\mu = 0.5$, $t_1=0.1$ mm, $d=0.4$ mm, $V_c = 335.2$ mm/s)
**Ultrasonic amplitude**

FE simulations were conducted to study the effect of vibration amplitude on the forces acting on the cutting tool in UAT. An increase in the peak force with an increase in the amplitude was observed (Figure 8). However, the average cutting force decreases with an increase in the amplitude. A decrease of approx. 28% in the average force was recorded for an increase in

![Graph showing comparison of forces with and without friction](image)

Figure 7: Comparison of calculated forces in the cutting tool for UAT with friction ($\mu = 0.5$) and without friction ($\mu = 0$) ($t_1=0.1$ mm, $d = 0.4$ mm, $V_c = 335.2$ mm/s)

![Graph showing effect of amplitude](image)

Figure 8 Effect of ultrasonic amplitude on forces in cutting tool ($t_1=0.1$ mm, $d = 0.4$ mm, $V_c = 335.2$ mm/s)
the amplitude from 7.5 µm to 15 µm, and a further approx. 33% decrease was observed when the amplitude was increased from 15 µm to 30 µm.

**Ultrasonic frequency**

A separate study was conducted to analyze the effect of ultrasonic frequency on the forces in the cutting tool (Figure). The results from these simulations show nearly the same peak force in the cutting tool in all three cases.

![Graph showing the effect of ultrasonic frequency on forces in cutting tool](Figure 9 Effect of ultrasonic frequency on forces in cutting tool (t₁=0.1 mm, d = 0.4 mm, V_c = 335.2 mm/s))

The average force demonstrated a drop by approx. 24% for frequency increase from 10 kHz to 20 kHz and a further drop by approx. 26% when frequency was increased from 20 kHz to 30 kHz. It is important to mention that as the three cases have different frequencies so they all have unique time duration of their single vibration cycle. For the purpose of comparison of these cases, with each of them having a unique frequency, a common time scale was selected. Average of forces was then calculated over this time scale (0.1 ms) and comparisons were made.
Effect of feed rate

The effect of the feed rate on the stresses and forces in the cutting tool was studied for UAT. Two different feed rates - 0.1 mm and 0.2 mm - were used at a constant cutting speed of 80 rev/min. Zones of high stress intensity were observed with a higher level of feed rate, while the maximum value of the stress rate was the same for both cases (Figure 10). Figure 11 shows the effect of feed rate on the forces in the cutting tool; increasing the feed rate from 0.1 mm to 0.2 mm gave a 45% increase in the force level in the cutting tool.

![Figure 10 Stresses in the cutting region for various feed rates: 0.1 mm (a) and 0.2 mm (b) (d = 0.4 mm, V_c = 335.2 mm/s)](image)

![Figure 11 Evolution of forces in cutting tool during a cycle of vibration for feed rates 0.1 mm and 0.2 mm (d = 0.4 mm, V_c = 335.2 mm/s)](image)

CONCLUSION

A 3D thermomechanically coupled FE approach was used to model UAT with CT forming a basis for comparative analysis. For the typical combination of vibration parameters (f = 20 kHz, a = 15 µm) the calculated cutting force in UAT was 40% of that in CT, whilst the experimental measurements showed that the force in UAT was 0.25 - 0.6 of that in CT for
various feed rates [18]. The comparison of feed rates indicated a 45% increase in the level of cutting forces in simulations of UAT for doubling the feed rate from 0.1 mm to 0.2 mm due to a higher material removal rate in the latter case. Experimental results showed a 60% increase in the cutting force in UAT when the feed rate doubles from 0.05 mm/rev to 0.1 mm/rev [18], hence we can conclude a fair agreement between experimental and numerical results. The comparison of simulations with and without friction, corresponding to dry and lubricated turning conditions, respectively, showed that in the latter case the cutting force was 10-15% lower and in a good agreement with experimental results [18] indicating 30% decrease in the cutting force when the lubricant was applied. Simulations also showed that temperature along the cutting edge reach higher values in the middle due to the convective heat dissipation. An increase in the vibration amplitude from 7.5 μm to 30 μm in FE simulations led to a 52% decrease in the average cutting force in UAT and could be explained by an increased part of a cycle of ultrasonic vibration without a contact between the tool and chip. An increase in the vibration frequency from 10 kHz to 30 kHz resulted in a 47% drop in the level of average cutting forces, which could be attributed to an increased number of micro-impacts between the tool insert and the workpiece. Hence, an increase in either vibration frequency or amplitude leads to a decrease in cutting forces in the UAT process that is beneficial to increasing the accuracy of the cutting process and improving material removal rates.

REFERENCES