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Journal of Materials Processing Technology 162–163 (2005) 649–654
Journal of Materials Processing Technology
www.elsevier.com/locate/jmatprotec

Effect of lubrication and cutting parameters on ultrasonically assisted turning of Inconel 718

A.V. Mitrofanov, N. Ahmed*, V.I. Babitsky, V.V. Silberschmidt

Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University,
Loughborough, Leicestershire LE11 3TU, UK

Abstract

The paper further develops the finite element (FE) model of ultrasonically assisted turning (UAT) discussed in Mitrofanov et al. [A.V. Mitrofanov, V.I. Babitsky, V.V. Silberschmidt, Finite element analysis of ultrasonically assisted turning of Inconel 718, J. Mater. Process. Technol., in press]. The advanced FE model (based on the general FE code MSC.MARC) allows transient, coupled thermomechanical simulations of both UAT and conventional turning of elasto-plastic materials. This model is used to study the effect of cutting parameters (such as the cutting speed, depth of cut and feed rate) and influence of lubrication on various features of two turning techniques, including cutting forces and chip shapes. The recently obtained results on three-dimensional FE modelling of UAT are also presented. This 3D model allows a study of chip formation in oblique turning.

Keywords: Turning; Ultrasonic vibration; Finite element analysis; Inconel 718

1. Introduction

Ultrasonically assisted turning (UAT) is an advanced machining technique, where high-frequency vibration (frequency $f \approx 20$ kHz, amplitude $a \approx 15$ mm) is superimposed on the movement of the 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 for Inconel 718 (a nickel-base alloy widely used in aerospace industry) a multi-fold decrease in cutting forces, as well as an improvement in surface finish by up to 50% compared to CT [2]. The prototype of the UAT system has been designed at Loughborough University, UK, and a number of experimental tests have been performed confirming advantages of UAT in comparison to CT [3].

This dynamics analysis has been used in Ref. [4] to study and to analyse UAT as a nonlinear vibro-impact process and the amplitude response of the cutting tool under load for this cutting technique. However, thermomechanics of the tool–workpiece interaction, which is especially important for the regime with multiple microimpacts in the process zone, and other specific features of the cutting process in UAT has not been fully understood, and the first finite element (FE) model of the UAT has been proposed only recently [5]. That initial, purely mechanical finite element model was further developed into a transient, fully thermomechanically coupled one for both UAT and CT. Some computational results obtained with the latter model were discussed in Ref. [1]. The current paper offers further results obtained with this improved model with regard to the influence of lubrication and cutting parameters on the turning process, as well as with its 3D version.

Finite element modelling is a main computational tool for simulation of the process zone and of tool–workpiece interaction in metal cutting. A detailed review of such FE models can be found in the monographs [6,7], with a short overview being given in our previous paper [1].

Since this present paper presents a transition from the two-dimensional to a three-dimensional one that is applied to ultrasonically assisted turning, a brief review of 3D FE models for conventional cutting processes is given below. The majority of the suggested schemes employ the method of

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* Corresponding author.
E-mail address: n.ahmed2@lboro.ac.uk (N. Ahmed).

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doi:10.1016/j.jmatprotec.2005.02.170

chip separation along a predefined line, separating finite elements in the initial discretisation of the area, hence reducing the flexibility of the analysis. Only a few schemes use other techniques, such as elements deletion based upon penetration [8], adaptive remeshing of the workpiece elements [9] and combination of both the manual deletion and remeshing [10]. Adaptive remeshing that is employed in the current paper maps calculated fields of parameters onto the new mesh to eliminate distorted in the shape of elements, which could otherwise cause termination of simulations. The method has an advantage of a relatively easy adjustment in the cutting direction and angles, as well as other cutting parameters, such as feed rate, without a necessity to reformulate the boundary value problem as in the case of separation along a predefined.

An FEA analysis of heat generation in machining of isotropic materials was conducted in Ref. [11] in order to study the effects of the convective heat transfer. Another approach, using an orthogonal FE model coupled with an analytical 3D model of cutting, was developed in Ref. [12] to predict a chip flow angle and three-dimensional forces in the tool. Another 3D model was developed in Ref. [9] that took into account dynamic effects, thermomechanical 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 in conventional turning in last two decades, this paper presents the first three-dimensional FE model of UAT. It has been recently developed and some computational results, emerging from this 3D formulation, are discussed.

2. Model

2.1. FE approach

The detailed description of the suggested numerical model for a 2D formulation is given in Refs. [1,13]. Its main features of the computational scheme are described below. Both the two-dimensional and three-dimensional thermomechanically coupled FE models are based on the MSC.Marc general FE code [14].

In the plain–strain 2D model, an orthogonal turning process, i.e. the cutting process where the tool edge is normal to both cutting and feed directions, is considered. Fig. 1 shows a scheme of relative movements of the workpiece and cutting tool in orthogonal 3D simulations of UAT: the feed direction is vertical, thus the uncut chip thickness t_1 corresponds to the feed rate ($t_1 = 0.1$ mm was used in simulations). The dimensions of a part of the workpiece used in 2D simulations are 2.5 mm in length by 0.5 mm in height. The depth of cut (or cutting edge engagement length) $d = 0.4$ mm. The cutting is simulated from the moment of initial engagement between the tool and the workpiece till the steady state, characterised by the saturation level temperatures and non-changing deformation patterns.

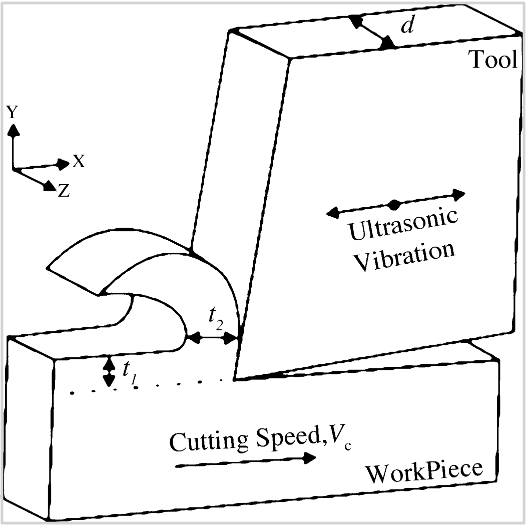

Fig. 1. A scheme of relative movements of the workpiece and cutting tool in 3D simulations of UAT. The magnitudes of cutting parameters are given in the text.

The relative movement of the workpiece and cutting tool in CT is simulated by the translation of the tool with the constant velocity. Harmonic ultrasonic vibration with a vibration amplitude of 15 μm (peak-to-valley) is then superimposed on this tool movement in the tangential direction (i.e. along *X*-axis in Fig. 1) in order to model UAT. 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 Ref. [3].

The current FE model is fully thermomechanically coupled in order to properly reflect the 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, and that not only result in thermal expansion/stresses but also affect material properties of the workpiece, such as thermal conductivity and specific heat. The detailed description of the thermomechanical processes in UAT in comparison to CT can be found in Ref. [13].

The mechanical behaviour of 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 for the aged Inconel 718 (Fig. 2):

$$\sigma_{\mathrm{Y}} = (A + B\varepsilon_{\mathrm{p}}^{n})\left(1 + C\ln\left(\frac{\dot{\varepsilon}_{\mathrm{p}}}{\dot{\varepsilon}_{0}}\right)\right)(1 - T^{*m}), \qquad (1)$$

where $A = 1241$, $B = 622$, $C = 0.0134$, $n = 0.6522$, $T^{*} = (T - T_{\mathrm{room}})/(T_{\mathrm{melt}} - T_{\mathrm{room}})$, ε_{p} and $\dot{\varepsilon}_{\mathrm{p}}$ are plastic strain and a strain rate, respectively, T_{room} and T_{melt} are the room and melting temperatures, respectively. A term T^{*m} is assumed to be negligible since within the temperature range, modelled

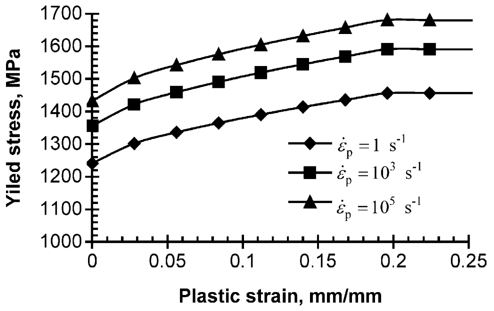

Fig. 2. Effect of strain rate on plastic behaviour of Inconel 718.

in FE simulations and justified by infrared thermography experiments, thermal softening of Inconel 718 is insignificant (less then 5%). This model, utilised by many researchers (see, e.g. [16,17]) as well as in our previous paper [1], has been modified to prevent unrealistically high stress values at high strains, so that maximum stress values are limited to ultimate tensile strength of Inconel 718 at corresponding strain rates (reaching 10^5 1/s in FE simulations).

2.2. 3D formulation

The 3D model is introduced as an extension of the 2D model and possesses a number of advantages compared to the latter. The additional dimension corresponds to the thickness of the workpiece material layer being cut, i.e. the depth of cut or the engagement length of the cutting edge. This model allows studying various 3D effects in turning, such as non-orthogonal/oblique chip formation, as well as the influence of the tool geometry on process parameters, such as cutting forces and stresses generated in the workpiece material. The 3D model also permits to investigate the effect of various vibration directions of the cutting instrument in UAT on the cutting process, and eventually should serve as an optimisation tool for the UAT technology. Various combinations of vibration direction can also be studied numerically, whereas experimental implementation of them can be extremely laborious, as it may require designing of new types of ultrasonic transducers and mounting systems. Furthermore, the three-dimensional FE formulation helps to perform a direct comparison of results of numerical simulations 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, such as thin tubes. In addition, the 3D model does not need as many assumptions as the 2D model, for example, the workpiece thickness is introduced explicitly in the 3D formulation as compared to artificial introduction in 2D. The 3D model also accounts for chip expansion in the lateral dimension (along *Z*-axis in Fig. 2) 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.

2.3. Friction models

The paper is mainly focused on the influence of lubrication on the cutting process. The presence/absence of the lubricant is simulated within the finite element framework by changing friction conditions at the tool–chip interface. As generally observed experimentally, adding lubricants causes the chip to become thinner and more curled. The extent of influence of lubricants on the cutting process also depends on the cutting speed, feed rate and rake angle.

In CT, the cutting tool is in permanent contact with the chip, and it is generally agreed that no lubricant can penetrate the contact area where normal stresses at the chip–tool interface are high [7]. However, lubricants can infiltrate along the non-contact channels due to surface roughness of the rake face of the tool. The length of these channels generally varies from half to full chip thickness. When the lubricant reacts with the chip in the region of these channels, the resistance to chip flow is reduced, and that increases the shear plane angle. Consequently, the chip becomes thinner and unpeels from the tool surface. Hence, the lubricant does not have to penetrate the whole contact distance at the rake face to reduce the contact area, its influence at the edge of the contact length is enough.

The nature of lubrication processes in UAT has not been studied yet. Nevertheless, the intermittent character of the contact at the rake face of the tool in this case should allow gaseous or liquid lubricants to penetrate deep inside the contact area. It is believed that this should further increase the shear angle in cutting, and decrease the chip thickness.

In many papers, the frictional contact at the tool–chip interface in conventional turning is taken into consideration, and various friction models are employed for this purpose. They include the Coulomb friction model, with friction stress being proportional to normal pressure at the interface ($\tau = \mu\sigma_n$) [16,18,19]; the shear friction model ($\tau = mk$, where k is shear yield strength) [20]; the modified shear friction model (described below) [21] and the stress-based polynomial model [22].

High contact stresses are generated at the tool–chip interface leading to significant friction forces. The classical Coulomb model is unable to adequately reflect friction processes under these conditions resulting in unrealistically high friction force. Hence, the shear friction model [14] was chosen for simulations, here the friction force depends on the fraction of the equivalent stress of the material and not the normal force as in the Coulomb model. Thus, friction stress is introduced in the following form:

$$\sigma_{\mathrm{fr}} \leq -\mu \frac{\bar{\sigma}}{\sqrt{3}} \frac{2}{\pi} \operatorname{sgn}(v_{\mathrm{r}}) \arctan\left(\frac{v_{\mathrm{r}}}{v_{\mathrm{cr}}}\right), \qquad (2)$$

where $\bar{\sigma}$ is the equivalent stress, v_{r} is a relative sliding velocity, v_{cr} is a critical sliding velocity below which sticking is simulated, μ is a friction coefficient.

3. Results of simulations and discussion

All variants of numerical (finite element) simulations below are performed for two cutting techniques (CT and UAT) for identical parameters so that results for CT could serve as a reference for ultrasonically assisted turning. Two contact conditions are studied at the tool–chip interface (a) a frictionless contact and (b) a contact with 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) corresponds to dry cutting conditions, with additional heat being generated due to friction between the tool surface and separated workpiece material.

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 in 2D simulations 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), i.e., 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.

An equivalent plastic strain ($\bar{\varepsilon}^{\mathrm{p}}$) is compared for CT and UAT simulations since it represents an important feature of the deformation process. A significant difference of $\bar{\varepsilon}^{\mathrm{p}}$ is observed in the cutting region in UAT compared to CT for all friction and thermal conditions (15–20% rise in case of UAT). A comparison between numerical simulations with and without friction shows somewhat higher magnitudes of equivalent plastic strains (by 5–7%) for the frictionless conditions. These results reflect higher degrees of deformation levels for the frictionless analyses for both CT and UAT leading to more curled chips, i.e. chips with a smaller radius of curvature. This phenomenon is observed both in frictionless numerical studies and well-lubricated turning tests for both CT and UAT.

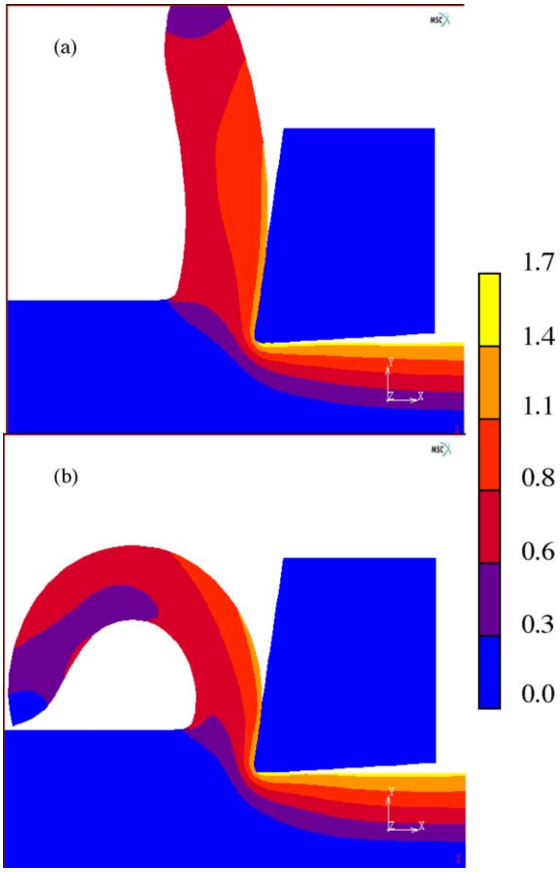

Fig. 3. Equivalent plastic strains in the cutting region in simulations of UAT with friction ($\mu = 0.5$) (a) and without it ($\mu = 0$) (b). Cutting parameters: $t_1 = 0.1$ mm, $V_{\mathrm{c}} = 310$ mm/s ($t = 3$ ms).

The effect of the feed rate on the cutting-tool temperatures in CT and UAT is also studied with FE simulations. The feed rate, i.e. the distance covered by the tool in the feed direction at each revolution of the workpiece, corresponds to the uncut chip thickness t_1 in the FE model. In simulations t_1 is reduced from 0.1 to 0.05 mm ($\mu = 0.5$). Such a reduction leads to a decrease in the maximum temperature levels in the cutting region from 440 to 400 °C and from 410 to 375 °C for UAT and CT, respectively. A drop in the cutting-tool temperature is also observed: it diminishes from 155 to 125 °C and from 130 to 100 °C for UAT and CT ($t = 2.5$ ms), respectively. This temperature decrease with the reduction in the feed rate reproduces our experimental results and is naturally explained by the decrease in the amount of the material being removed per unit time.

The evolution of cutting-tip temperatures is also analysed for the frictionless case. Simulations demonstrate only a marginal increase in the tip temperatures with time for both UAT and CT. This shows that the temperature increase in the cutting tool is largely due to frictional interaction between the tool and chip. As in simulations with friction, the tip temperature in CT grows faster than that in UAT, in spite of the final temperature being higher for UAT (largely due to the effect of the additional factor linked to dissipation of the vibration energy).

The obvious decrease in the workpiece temperature is obtained in simulations of frictionless conditions, as heat generation due to friction is removed, with temperatures reaching approximately 380 and 350 °C compared to 440 and 410 °C for UAT and CT, respectively, in the analyses with friction. Still, temperature levels in UAT are higher than those in CT, demonstrating that this temperature difference cannot be attributed solely to frictional effects.

Our recent 3D simulations (Fig. 4) confirm the results obtained in the 2D analysis for the temperature distribution in the cutting region. Maximum temperature levels in the process zone and chip invariably higher in UAT simulations. The highest temperatures are registered along the contact area at the tool–chip interface in both UAT and CT models.

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 with the chip. Low-level fluctuations of the cutting force around zero level are explained by the remaining contact between the cutter and freshly formed workpiece surface, as well as by the numerical error of the FE simulations.

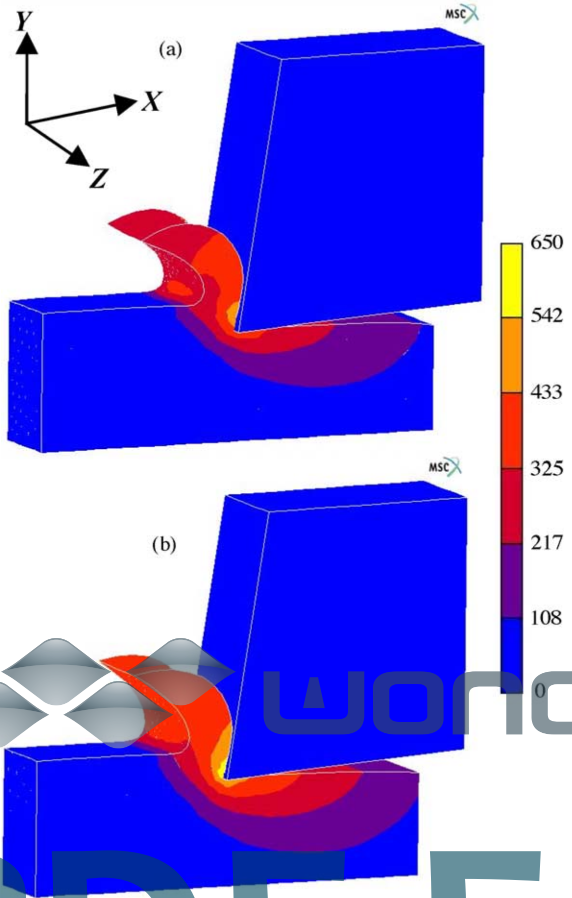

Fig. 4. Temperature distributions in the cutting regions in CT (a) and UAT (b) simulations ($\mu = 0$, $t_1 = 0.1$ mm, $d = 0.4$ mm, $V_c = 310$ mm/s, $t = 3$ ms).

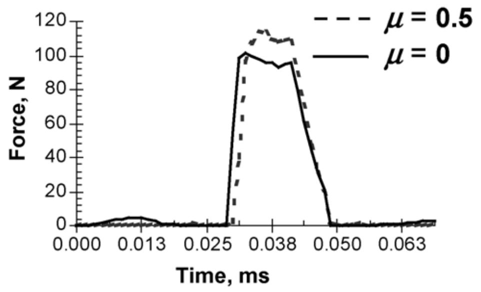

Fig. 5. Comparison of forces in the cutting tool for UAT with friction ($\mu = 0.5$) and without friction. For other parameters of the simulation, see Fig. 4.

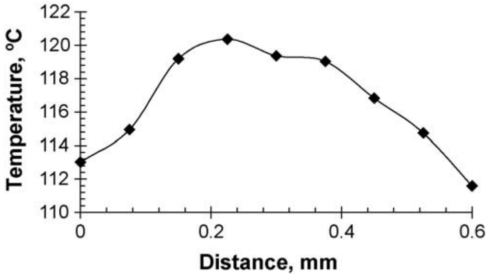

Fig. 6. Temperature distribution along the cutting edge of the tool (Z-axis in Fig. 1) in simulations of UAT. For parameters of the simulation, see Fig. 4.

The maximum magnitude of the cutting force in simulations with friction is by 20–25% higher than that in frictionless simulations.

The temperature distribution along the cutting edge was studied (see Fig. 6): this kind of analysis is possible only with 3D formulation, as in 2D simulations the cutting edge is reduced to a single point. The analysis showed that the maximum temperature is reached somewhere in the middle of the cutting edge, with insignificant drops towards the ends of the cutting length. This result can be attributed to the convective heat transfer from the surface of the tool into the environment. This kind of the distribution is observed throughout the simulation time, with the absolute values of the tool temperature growing with time due to the frictional heating and contact heat transfer from the chip and workpiece surfaces.

4. Conclusion

A 2D thermomechanically coupled FE model of ultrasonically assisted turning (UAT) is used to study the influence of lubrication and cutting parameters on the process of UAT. A 3D model is presented as an extension of this model and allows us to study three-dimensional chip formation and to predict distributions of stresses, strains, cutting forces and temperatures in the workpiece and cutting tool.

The effect of lubrication was studied by comparison of simulations with and without friction corresponding to dry and lubricated turning conditions, respectively. FEA showed that in the frictionless case (in comparison to simulations with friction):

- the radius of curvature of the chip is approximately 2.5 times smaller, i.e. chips are more curled, that is in good agreement with experimental results;
- the cutting force is by 20–25% lower due to the absence of the friction force at the tool–chip interface;
- the temperature in the cutting region is by some 60° lower due to elimination of frictional heating;
- the chip thickness ratio is insignificantly higher (chips are thinner by about 15%);
- the level of equivalent plastic strains is by 5–7% higher; larger plastic deformation levels lead to more curled chip, which was also observed experimentally;
- the drop in the process temperature was registered for numerical simulations of cutting with the reduced feed rate; this result is in good agreement with our experimental measurements and explained by a reduced material removal rate.

Acknowledgements

The authors would like to acknowledge the help of Dr. Alan Meadows and Mr. Peter Thomas in conducting experiments on the UAT prototype.

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