

Comparative Analyses for Different Modeling Methods in High Speed Turning Operations for Hardened Steel

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The modeling of metal cutting process has been a challenging research topic due to the difficulty in accurate modeling of the contact and work material deformation with large plastic strain and friction, high temperature and strain rate, and their coupling effect. Among different modeling methods, finite element method (FEM) has proven to be a robust tool in predicting process parameters and optimizing cutting tool geometry. However successful implementation of a modeling method depends mainly on numerical formulation technique adopted for chip formation. The two formulation techniques namely the Lagrangian and the Eulerian have been used in the past by many researchers. Due to the various limitations of the two approaches, a new arbitrary Lagrangian Eulerian (ALE) method has been adopted for the orthogonal high speed turning operations for AISI H13 hardened steel. This approach does not need any chip separation criterion. For comparative analysis with other techniques, two Lagrangian models with element deletion and node splitting methods were also simulated and compared with experimental data. It has been found that ALE model results are in good agreement with the experimental ones as compared to the Lagrangian models.

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Keywords: high speed machining, process modelling, finite element methods, AISI H13 steel

0 INTRODUCTION

High speed machining (HSM) has emerged as a key technology in rapid tooling and manufacturing applications. Dies and moulds manufacturing represents a significant area of application for high speed cutting of cast iron, cast steel and alloy steel. Cost effective high speed cutting of these difficult to cut materials require advanced tooling like coated carbides, ceramics and poly crystalline cubic boron nitride (PCBN). High speed machining of hardened steel replaces slow EDM processes in many applications but the productivity is often limited due to frequent tool failures and undesirable surface characteristics of the workpiece. In order to optimize high speed machining processes, robust models are necessary that can correlate the process variables with the cutting parameters and tool geometry. Many investigators have attempted to develop analytical and numerical models to gain a better understanding of the processes which involve deformation with large strains, strain rates and temperatures. Through finite element simulation, one is able to obtain various quantities numerically calculated such as the

spatial distribution of stresses, strains, temperatures, but the main problem of those simulations is that we must introduce the physics of the process through very accurate constitutive and contact laws [1].

There had been mainly two formulation techniques for chip formation analysis, the Eulerian and the Lagrangian approach. In the Lagrangian approach, the mesh is attached to the material elements and deformed with the workpiece. In this approach, the analysis can be started from indentation to the incipient stage to steady state. However it needs an explicit chip separation criterion which is a big problem with the Lagrangian method. The Eulerian approach is more suitable for fluid flow problems involving a control volume [2]. In this method, the mesh consists of elements that are fixed in space and cover the control volume, and the material properties are calculated at fixed spatial locations as the material flows through the mesh. It does not need any chip separation criterion but is unable to simulate the initial chip formation and experiments are needed to find initial chip shape and geometry.

Due to these limitations a new method based on Arbitrary Eulerian-Lagrangian (ALE) approach has been used. Stresses and temperatures distributions are predicted using ABAQUS/Explicit for the orthogonal high speed turning operations when machining hardened steel (AISI-H13) using PCBN. Simulations are also run with the traditional Lagrangian models with element deletion and node debonds techniques and results are compared with the experimental data.

1 EXPERIMENTAL SETUP

Orthogonal turning experiments were conducted with the same cutting parameters on hardened AISI H-13 tool steel tubes (50 HRC) using triangular tool inserts having a honed edge preparation and nose radius of 1.2 mm. The properties and composition of the workpiece and tool materials are listed in Table 1. Three cutting speeds of 200, 250 and 300 m/min were used. A constant feed rate of 0.25 mm/rev and width of cut 2 mm were employed, for all cutting force measurement. Cutting and thrust forces were measured, using a Kistler model 9257B force dynamometer. The force signals from the dynamometer fed into Kistler model 5017B dual-mode charge amplifiers. The analog force signals from the charge amplifier were then passed through a data acquisition card. A PC-based data acquisition program (Dynaware) was used to acquire the sampled data and save for analysis.

2 FINITE ELEMENT MODELS

The ALE formulation used here for chip formation consists of two steps including initial chip formation followed by chip growth [3]. Since the Lagrangian approach is capable to simulate initial chip geometry without the need of any priori assumption about the chip shape, the chip formation is modeled as Lagrangian problem.

Here the workpiece is fixed and tool advances into the workpiece. In order to simulate chip formation with chamfered and honed tools, the workpiece has a slant edge or a concave at the top right corner. In the first step the workpiece has Lagrangian boundary regions i.e. the mesh at the boundary is constrained to move with the

material in the direction normal and tangential to the boundary surface.

Once the initial chip geometry is known, the Eulerian method is best to simulate chip flow around the tool tip. Therefore, second analysis step is based on Eulerian formulation. Now the tool is fixed and the deformed workpiece mesh serves as a control volume. The material flows into the control volume from the left boundary region and flows out from the right boundary at the cutting speed. The meshes at the left and right boundary are constrained in the cutting direction while the bottom is constrained in the vertical direction. The top boundary is unconstrained and forms the final chip shape as the cutting progress.

In the Lagrangian model with element deletion method, a chip separation criterion is adopted and the elements in front of the tool tip are deleted when the failure criterion is met. The Johnson Cook shear failure model is utilized which involves strain at failure, the pressure-deviatoric stress ratio, operating and melting temperatures [4].

In the node debond method [5], nodes on the inside of the chip surface and machined workpiece are tied together. These two sets of nodes are allowed to debond when a specified criterion is met. The separation criterion used is the effective plastic strain in the two elements adjacent to the tool tip region. The effective plastic strain $\bar{\epsilon}^p$ based on the Mises criterion is calculated for every node at each time step. When the value of the effective plastic strain at a nodal point reaches a prescribed critical value $\bar{\epsilon}_o^p$, that is:

$$\bar{\epsilon}^p \geq \bar{\epsilon}_o^p. \quad (1)$$

3 MATERIAL MODELING

Plastic deformation in the primary shear zone is such that elastic deformation can be neglected and the workpiece modelled as a nearly incompressible, elastic-plastic material. The workpiece material was represented by the Johnson-Cook plasticity model. The Johnson-Cook formulation involves the yield stress σ at nonzero strain rate, strain hardening index n , equivalent plastic strain ϵ , equivalent plastic strain rate, the melting temperature of the workpiece T_{melt} , operating temperature T , and

strain rate sensitivity exponent m as shown in Equation (2); B and C are constants. This particular plasticity model is suitable for deformation of materials at high strain rates, which typically occur, in a machining process.

$$\sigma = B\epsilon^n \left[1 + C \ln \left(\frac{\dot{\epsilon}}{1000} \right) \right] \left[1 - \left[\frac{T - T_{room}}{T_{melt} - T_{room}} \right]^m \right] \quad (2)$$

Where for AISI H13, $B = 981.7$ MPa, $C = 0.023$, $n = 0.182$, $m = 2.7$, $T_{melt} = 1753^\circ\text{K}$, T = operating temperature [10]. The equation is valid for the variables range as follows:
 Strain = 0.96 to 1.66
 Strain rate = 1809 to 35682 /s
 Temperature = 53 to 1155 °K.

4 FRICTION MODELING

Zorev's sliding-sticking friction model is utilized in the simulation. The division of the sliding and sticking regions is determined by two methods: one is to prescribe the length of each region, the other is to determine the sliding and sticking region automatically by a program according to a criterion by Ng [4], given by Eq. (3)

$$\begin{aligned} s &= \mu p \text{ when } \mu p < \tau_{max} \\ s &= \tau_{max} \text{ when } \mu p \geq \tau_{max} \end{aligned} \quad (3)$$

Where s , p and τ are the friction, normal and equivalent shear stress at the tool rake face. The second approach is adopted this analysis with a μ (coefficient of friction) value of 0.5.

5 SIMULATION PARAMETERS

A continuous chip formation was considered in this analysis. A total of 1500 quadrilateral elements were designed on the workpiece and the cutting tool for ALE model. However comparatively finer mesh was used for Lagrangian models with 4050 quadrilateral elements on the workpiece and the cutting tool. FE simulations were carried out on a Celeron 2.4

GHz computer system with 248 MB RAM. FE simulations were run with a speed of 200 m/min, 0.25 mm feed rate and 2 mm width of cut. The cutting tool had a rake angle of -5° and a clearance angle of 5° .

6 RESULTS AND DISCUSSIONS

Figs. 1 and 2 outline the resultant forces obtained from the experiments and simulations by ALE and Lagrangian models. The forces obtained by ALE method are in close agreement with the experimental values as compared to the Lagrangian models. The Lagrangian method with element deletion technique under estimates the cutting forces for all the cutting parameters. It can be seen that when machining AISI-H13 with in a speed range of 200 to 300 m/min cutting forces almost remain constant, which is also confirmed by the simulation results.

Figures 3 to 5 show the temperature distributions obtained by the three methods at cutting speed of 200 m/min and feed rate of 0.25 mm/rev. The profiles are significantly different in ALE as compared to both Lagrangian models. In the ALE model temperatures obtained are higher as compared to the Lagrangian models. The shear zone temperatures are in the range of 250 to 350°C with ALE method while 180 to 250°C with the Lagrangian methods

The results with Lagrangian methods are also comparable that obtained by Ng [4]. Also the high temperature areas are confined to a narrow region in ALE. This may be due to the mechanism difference between the two methods. In ALE chip shape is obtained by indentation of the tool into the workpiece while in the Lagrangian method elements are deleted or common sets of nodes are debonded according to failure criteria as the tool advances. In this way the tool tip carries little or no stress in the Lagrangian methods and hence temperatures are lower. Comparison of both Lagrangian models

Table 1. Mechanical and physical properties of workpiece and tool materials

	Density kg/m ³	Elastic modulus GPa	Poisson ratio	Thermal Conductivity W/mK	Specific heat J/kgK	Hardness HRC
Workpiece	7800	211	0.28	37	560	49
Tool	3399.5	652	0.128	100	960	--

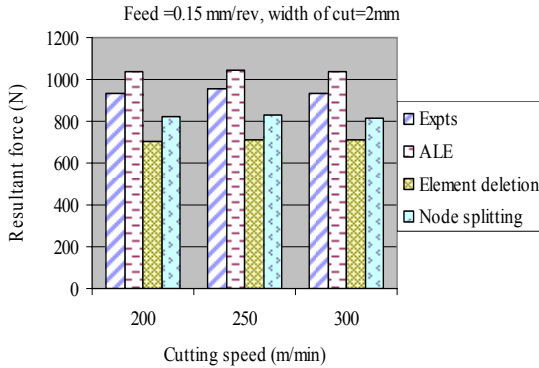


Fig. 1. Resultant forces obtained in turning operations by experiments and simulations, feed = 0.15 mm/rev, width of cut = 2mm

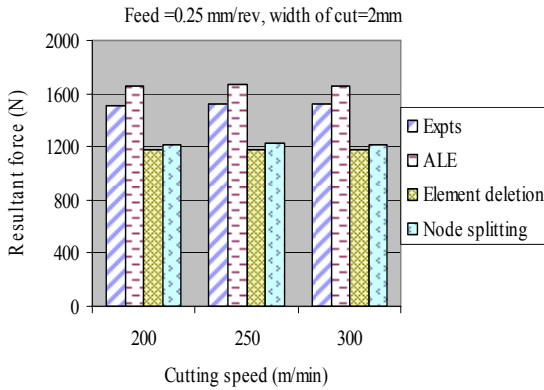


Fig. 2. Resultant forces obtained in turning operations by experiments and simulations, feed = 0.25 mm/rev, width of cut = 2mm

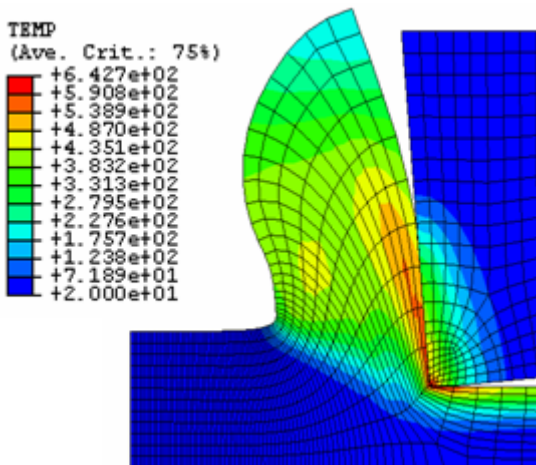


Fig. 3. Temperature contours by arbitrary Lagrangian eulerian method

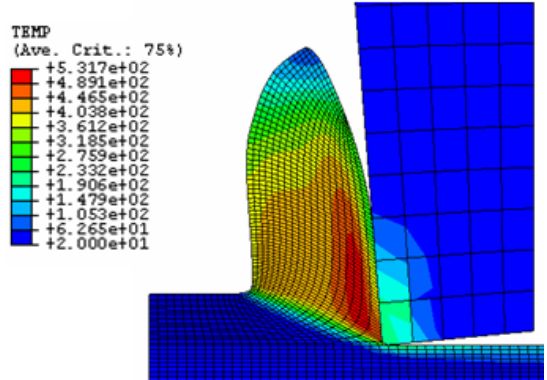


Fig. 4. Temperature contours by element deletion method

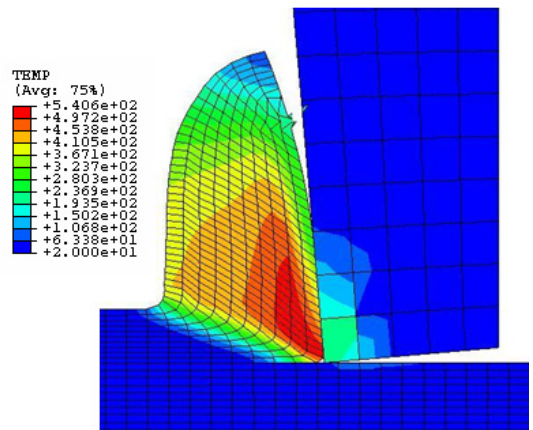


Fig. 5. Temperature contours by node debond method

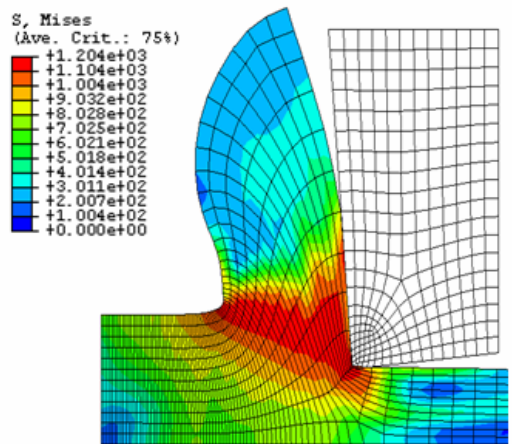


Fig. 6. Mises stress contours by arbitrary Lagrangian eulerian method

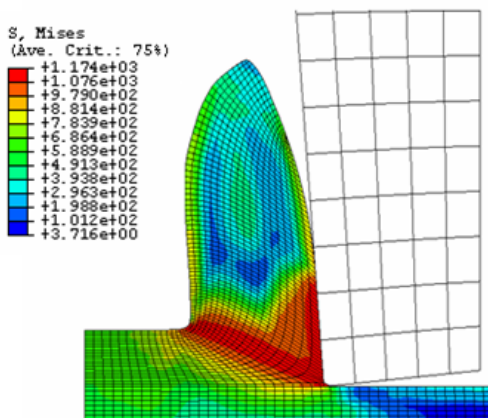


Fig. 7. Mises stress contours by element deletion method

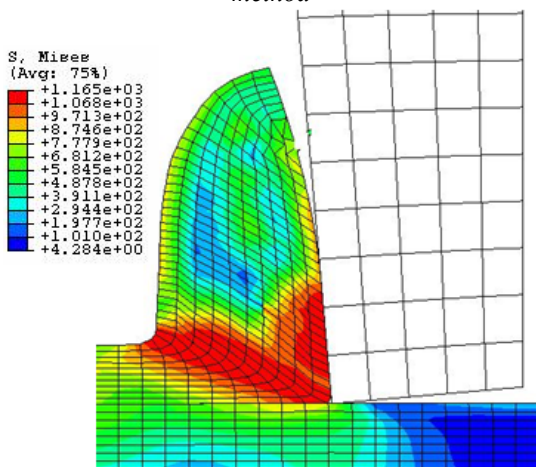


Fig. 8. Mises stress contours by node debond method

show that chip separation is better simulated by node debond method which provides minimum overlapping of the tool and workpiece. This may be one of the reason of higher temperatures with the node debond method.

Figs. 6 to 8 show the Mises stress distributions obtained by ALE and Lagrangian methods at cutting speed of 200 m/min and feed rate of 0.25 mm/rev. The stress distributions are quite similar except that the Lagrangian methods show a little lower value of mises stress. This may be again due to the chip formation technique adopted by the two models. It seems that indentation of the tool into the workpiece produces greater deformation that results in

higher value of Mises stress in contrast to the element deletion and node debond methods in the Lagrangian approach. With all three models the high mises stress comprises of the areas including primary shear zone, workpiece area in front of tool tip and the chip tool interface. However the ALE method also shows high Mises stress beneath the flank face (tertiary shear zone) which is in accordance with the experimental findings.

7 CONCLUSIONS

- 1) Cutting forces obtained by ALE and Lagrangian models show that ALE results are in good agreement with the experimental ones.
- 2) High forces with ALE results due to the indentation of the tool into the workpiece as the model works without any damage criterion.
- 3) Temperatures profiles are significantly different obtained from the two methods and Lagrangian models show overall lower temperatures.
- 4) ALE model also show tertiary shear zone which is not found in both Lagrangian models.

8 REFERENCES

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