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A COMPARATIVE STUDY OF MATERIAL FLOW MODELS FOR FINITE ELEMENT SIMULATION OF METAL CUTTING

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Abstract

IIn recent years, finite element method (FEM) has been widely used for studying metal cutting process. The reliability of FEM simulation however depends considerably on the assumed material model. Hence, it is imperative to compare and verify the matreial model before further application. In this study, a series of simulations are carried out to compare 3 popular types of material model: high-speed compression, split Hopkinson pressure bar, and machining. The simulation results are compared with experiment to identify the best suitable method of determining flow stress data for high-speed machining.

1. INTRODUCTION

Metal cutting is a common process for manufacturing parts of required dimensions and shapes. To understand the mechanism of the process, considerable effort has been devoted toward analysing metal cutting operations. To achieve this goal, besides experimental and analytical techniques, finite element method (FEM) has been broadly used in recent years [1, 2].

The reliability of FEM simulation however depends considerably on the assumed material model. Material in cutting is subjected to large plastic strain

Key words: finite element; flow stress data; metal cutting; simulation;

(1 and higher) coupled with high temperatures (200^0C to 1000^0C or more) at high strain rates (10^4 to 10^6). Moreover, in cutting there is a steep stress gradient in front of the tool and a strong stress concentration in the form of the relatively sharp cutting edge. Thus, replicating machining conditions in material testing is not an easy task. Using of flow stress data determined by conventional testing showed that the results of simulations consistently failed to match the experimental ones [3,4,5]. The lack of material property data for metal cutting has forced many researcher to simplify FEM models of machining. Zhang and Bagchi [6] simulated the machining of copper at velocities that were lower than production conditions. Ceretti et al. [7] assumed the flow stress to be constant for values higher than the test data and as a function of strain, strain rate and temperature for values in the range of the test data. Ng et al. [8] neglected the effect of strain rate on flow stress in their fem model.

To obtain the flow stress data for various materials at high strain rates and temperatures encountered in machining, some researchers have used the split Hopkinson pressure bar (SHPB) method [9-12]. Despite of special apparatus required for this complicated method, the strain rate and strain is still considerably lower than the ones in machining. Moreover, specimen in SHPB is subjected to compressive deformation in contrast with shearing dominating in machining. As an alternative approach to increasing strain rates in testing, Oxley [13] suggested that high-speed compression tests results at a large range of temperature could be extrapolated to obtain flow stress at high strain rates. This approach based on the premise that the effect of strain rate on flow stress could be equivalent to those of temperature. The testing conditions were certainly not comparable with machining conditions. Others [14] proposed that machining could be used to determine flow stress data for FEM simulations. The disadvantage of this method is that the model of cutting mechanics should be assumed for relating cutting force and shear angle to stress, strain and strain rate. Unfortunately, all known models provide only a first order approximation of metal cutting parameters [15].

None of the above methods could be claimed to successfully determine flow stress data of materials in machining [16]. Thus, it is imperative to compare and verify these methods for further application in FEM simulations. In this paper, a finite element model is presented using a commercially available FEM software package ABAQUS/ExplicitTM to simulate orthogonal metal cutting. Flow stress data was obtained from three methods: high-speed compression, split Hopkison pressure bar and machining tests. A series of simulations were carried out using these flow stress data. Simulation results were compared with experiment to identify the best suitable method of determining flow stress data for high-speed machining.

2. FEM MODEL

A. Mesh and Boundary Condition

The model consists of a cutting tool and a workpiece, which has dimension of 7.5 mm x 2.5 mm x 4 mm. The workpiece is meshed with four-node plane strain elements. The chip layer of the workpiece has the height of 0.5 mm and is divided into 10 sub-layers of elements. The chip layer is meshed with smaller element size (height 0.05 mm x length 7.14 mm). The rest of the workpiece has a length of 7.5 mm and a height of 2 mm, and is divided into 10 layers, each having 105 elements along the cutting path. The elements have the same width, but the heights increase towards the bottom of the workpiece with the ratio of 1.25 between the layers. The elements of the chip sub-layer along the cutting path are defined so that they will fail and be removed from the model when the chip separation criterion is reached. The above model has, in total, 2100 four-node plane strain elements and 2333 nodes. The undeformed mesh is shown in Fig. 1. The workpiece is constrained at the left, bottom and right. The simulated cutting conditions are given in Table I.

TABLE I. CUTTING CONDITIONS FOR FEM SIMULATION

Rake angle of cutting tool,°	5
Clearance angle of cutting tool, °	6
Undeformed chip thickness, mm	0.5
Width of cut, mm	4
Cutting velocity, m/min	200
Workpiece material	AISI 1020

B. Friction Model

In this study, the modified Coulomb friction law option in ABAQUS/Explicit is assumed for the friction condition of the tool-chip interface. Let τ be the chip shear stress at a contact point along the tool-chip interface and σ, the normal pressure at the same point. This law states that relative motion occurs at the contact point when τ is equal to or greater than the critical friction stress τ_c. When τ is smaller than τ_c, there is no relative motion and the contact point is in a state of sticking. The critical friction stress is determined by

$$\tau_c = \min(\mu\sigma, \tau_{th}) \tag{1}$$

where μ is the friction coefficient and τ_{th} is the threshold value related to material failure. The threshold value τ_{th} should be less than the shear flow stress of the softer material at the contact interface. In this study, the friction coefficient will be assigned arbitrarily to be 0.3, 0.5 and 0.7 for investigating the effect of friction on FEM simulation.

C. Heat Model

The heat generation mechanisms are the plastic work done in the primary and secondary shear zones and the sliding friction along the tool-chip interface. In high-speed metal cutting, heat generated in the workpiece and chip does not have sufficient time to conduct away. Therefore, temperature rise in the workpiece and chip can be considered as due to localized adiabatic heating. In this simulation, adiabatic heating conditions are assumed and heat generated from friction is neglected. Each finite element integration point is treated as if it is thermally insulated from its neighbors.

Let ΔT_p be the change in temperature (local temperature rise) in the workpiece and chip induced by plastic work in a time interval Δt. Under adiabatic conditions ΔT_p can be calculated as follows

$$\frac{\Delta T_p}{\Delta t} = \eta_\pi \frac{\sigma_e \epsilon_p}{c\rho} \tag{2}$$

where σ_e is the effective stress, ϵ_p is the effective plastic strain rate, c is the specific heat, ρ is the mass density, and η_p is the percentage of plastic work that is transformed into heat. $\eta_p = 90\%$ is assumed in this simulation.

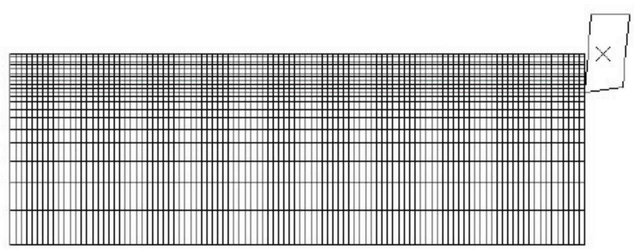


Fig. 1. Undeformed mesh for orthogonal cutting simulation

D. Chip Separation Criterion

In this study, a special option in the ABAQUS/Explicit code is used for a chip separation criterion. This criterion states that chip separation occurs when the damage parameter exceed 1. The damage parameter w is defined as

$$w = \sum \left(\frac{\Delta \bar{\epsilon}^{pl}}{\bar{\epsilon}_f^{pl}} \right) \tag{3}$$

where $\Delta \bar{\epsilon}^{pl}$ is an increment of the equivalent plastic strain, $\bar{\epsilon}_f^{pl}$ is the strain at failure, and the summation is performed over all increments in the analysis. When the shear failure criterion is met at an element integration point, all the stress components will be set to zero and the material point fails. The failed element will be removed from the models, thus, allowing part of the mesh to move as chip.

Theoretically, the critical strain at failure should be assigned based on the ductile failure characteristics of materials, which is affected by stress state, strain rate of deformation and temperature [17]. Metal cutting, unfortunately, is a complicated process, affected by the combination of high strain rates, high compressive pressure and high temperature. In light of that, it is rather difficult to assign the critical value of strain at failure from the experiment results of ductile testing, not to mention testing in the condition similar to machining is hardly available. For the purpose of this study, the effective strain at which the material fails will be assigned a value of 1 and 2 to evaluate the effect of it on the simulation results. These values are comparable with the machining results, in which strains at shear strain were measured [18]. The chip separation criterion is assumed to be independent of stress, strain rate and temperature. Studies have shown that these values affect insignificantly the simulation results .

3. MATERIAL MODEL

A. Flow Stress Data

The material constitutive equations used in the FEM simulations were derived from the three method high-speed compression, SHPB and machining tests [10,13,14]. Flow stresses are calculated for a range of strains from 0 to 2; the strain rates for calculation are 10 s^{-1}, $10^4 s^{-1}$, 10^5 s^{-1} and $10^6 s^{-1}$; and the temperatures are 27 ^{0}C, 300 ^{0}C, 600 ^{0}C, and 900 ^{0}C. The strain rates and temperature are chosen to cover the range of strain rates and temperatures in machining. For other strain rate and temperature values, the data is interpolated by the FEM code. The representative data of flow stress is shown in Fig. 2. From the comparison of the models, it is clear that the machining test model underestimates flow stress at low strain rate. Thus, it is decided to substitute the flow stress data of the machining test model at strain rate $10^{-1} s^{-1}$ by the data from the compression test model.

B. Physical Properties

The specific heat $S(Jkg^{-1}K^{-1})$ is calculated as follows:

$$S = 420 + 0.504T \tag{4}$$

where T is temperature ^{0}C. The physical properties of AISI1020 are summarized in Table II.

TABLE II. PHYSICAL PROPERTIES OF AISI 1020

Physical property	**Temperature, C**			
	27	**300**	**600**	**900**
Elastic modulus, GPa	205	171	130	88.5
Specific heat, J/kg.K	432	571	722	873
Density, kg/m^3	7800			

IV. RESULTS AND DISCUSSION

A total of nine simulations have been carried out. The results of the simulations with friction coefficient =0.3 are shown in Fig. 3 to Fig. 6. The comparison reveals the strong influence of underlying models on the simulated results. The chip geometries are distinctly different for each case. The dimension of the secondary shear zone in case b (with the impact test model) is markedly larger than in case a (with the compression test model). The difference is more significant when comparing case c (with the machining test model) with the other cases.

On the whole, the simulations with the compression test model (case a) and the impact test model (case b) give comparable results in terms of equivalent stress, equivalent plastic strain and temperature. The maximum equivalent stress in both cases is around 890 MPa at the primary shear zone. Similarly, the equivalent plastic strain reaches about 2.7 in the secondary shear zone and 0.7 in the primary zone while the values for the temperature are approximately 500 ^{0}C and 130 ^{0}C respectively.

For the simulation with the machining test model, the maximum equivalent stress is approximately 1020 MPa. Similarly, equivalent plastic strain and temperature reach higher magnitudes (3.4 and 700 ^{0}C respectively) than the other cases. The high values of strain and temperature are consistent with the level of mesh distortion in case c.

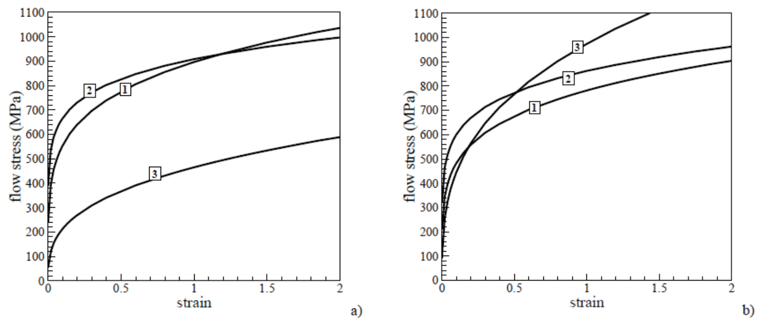


Fig. 2. Flow stress- strain data for AISI1020: (a) flow stress at 27^0C and strain rate 10-1 s-1, (b) flow stress at 300^0C and strain rate 10-5 s-1. Line (1): impact test model, (2): compression test model, (3) : machining test model.

TABLE III. COMPARISON OF CUTTING FORCES AND CHIP THICKNESS BETWEEN SIMULATIONS AND EXPERIMENT

Case	Cutting force, N			Chip thickness, mm		
	0.3	0.5	0.7	0.3	0.5	0.7
A	2931	3069	3215	1.01	1.07	1.13
B	3299	3513	3526	1.29	1.35	1.36
C	4075	failed	3729	1.42	failed	1.28
Experiment	3200			1.1		

Compared with experimentation by Hastings et al. [19], the simulations with the impact and compression test models closely match the experimental results in terms of cutting force and chip thickness (Table III). The model derived from the compression test data seems to underestimate the cutting forces while the model with the impact test overestimates the results. The highest discrepancy is observed for the case with the machining test model.

The effect of friction on FEM simulations is investigated by varying the friction coefficient. In the nine simulations, the simulation with the machining test model has failed at the friction of 0.5 due to excessive mesh distortion. The increase in the friction coefficient insignificantly affects the distribution of equivalent stress, strain and temperature. Increasing friction tends to increase the magnitude of the three parameters while the chip geometries are quite similar. The maximum equivalent stress in 3 cases is at approximately 890 MPa. The temperature and strain at the tool-chip interface are 530^0 C and 3 respectively for the cases of friction 0.5 and 0.7 in contrast with 490^0 C and 2.8 for the friction of 0.3. The higher value can be explained by the higher friction stress at the interface. The equivalent stress, strain and temperature at the primary shear zone are the same for 3 cases of friction.

From Table III, it can be observed that the augmentation of the friction coefficient increases the simulated results of cutting force and chip thickness for the compression and impact test models but reduces for the machining test model. In terms of cutting force and chip thickness, the model with compression test material model and friction of 0.7 is closely matched with the experiment. It is also noted that higher friction causes more mesh distortion, which in turn reduces the time increment and in some cases stops the simulation prematurely.

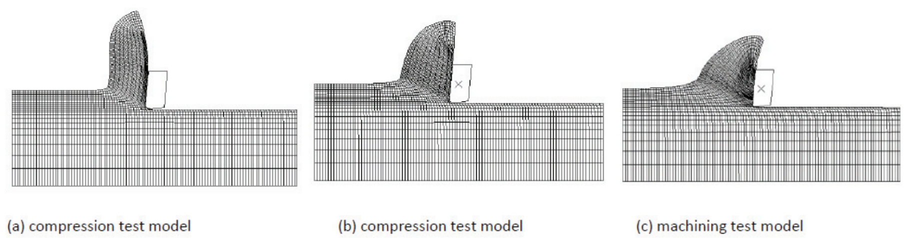


Fig. 3. Deformed meshes in simulations with $\mu = 0.3$.

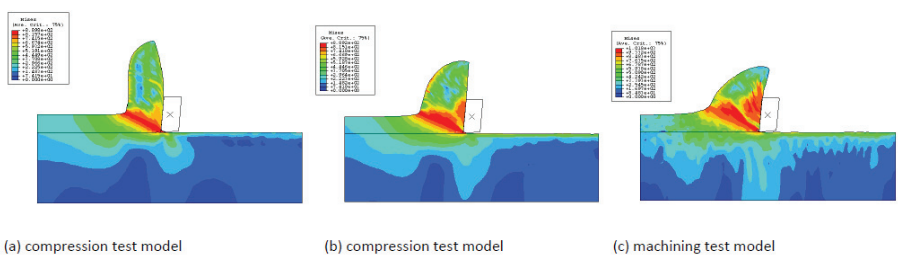
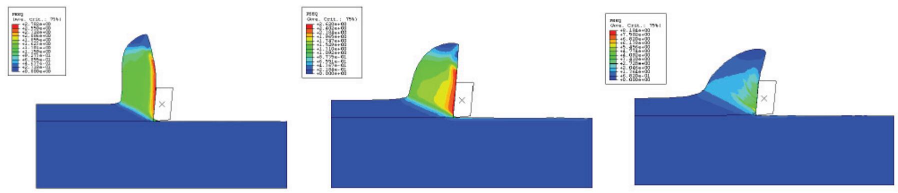


Fig. 4. Equivalent stress in simulations with $\mu = 0.3$ (MPa).

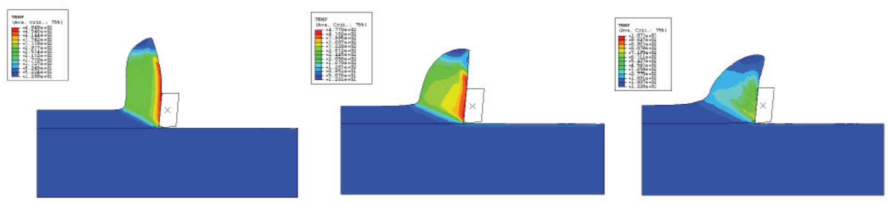
V. CONCLUSION

In conclusion, the study shows the strong influence of material models on FEM simulation of machining. It highlights the importance of the selection of appropriate material model for correct and effective FEM simulation. The investigation reveals the material models obtained from the compression and impact



(a) compression test model (b) impact test model (c) machining test model

Fig. 5. Equivalent plastic strain in simulations with with $\mu = 0.3$



(a) compression test model (b) impact test model (c) machining test model

Fig. 6. Temperature in simulations with with $\mu = 0.3$ (MPa).

tests as the suitable ones for further simulation. It seems to be a contradiction that material data derived from the machining tests gives poor FEM simulation of metal cutting. It also casts doubt on the appropriateness of machining as the method for obtaining flow stress-strain data in machining conditions. The magnitude of friction does not affect significant FEM results, at least in terms of equivalent stress, strain and temperature.

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