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Chip Formation Process using Finite Element Simulation "Influence of Cutting Speed Variation"

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ABSTRACT

The main aim of this paper is to study the material removal phenomenon using the finite element method (FEM) analysis for orthogonal cutting, and the impact of cutting speed variation on the chip formation, stress and plastic deformation. We have explored different constitutive models describing the tool-workpiece interaction. The Johnson-Cook constitutive model with damage initiation and damage evolution has been used to simulate chip formation. Chip morphology, Stress and equivalent plastic deformation has been presented in this paper as results of chip formation process simulation using Abaqus explicit Software. According to simulation results, the variation of cutting speeds is an influential factor in chip formation, therefore with the increasing of cutting speed the chip type tends to become more segmented. Additionally to the chip formation and morphology obtained from the finite element simulation results, some other mechanical parameters; which are very difficult to measure on the experimental test, can be obtained through finite element modeling of chip formation process.

Keywords: FEM simulation; Johnson Cook model; Abaqus explicit; Chip formation; Cutting process.

1 INTRODUCTION

METAL machining involves two basic processes; namely the creation and the evacuation of chip. These processes involve two basic physical mechanisms: plastic deformation in the chip itself and chip-tool contact. The modeling of chip formation is based on the understanding of these two mechanisms and is aimed at predicting chip geometry, cutting forces and heating from the cutting conditions and thermomechanical properties of both machined material and tool material. It should therefore allow to assist in the rational management of cutting databases and to provide information on various practical problems; such as the machinability of materials, cutting forces, length and shape of the chip, elastic and plastic deformations, residual stress... etc. Numerical modeling of chip formation has been developed to highlight and estimate the parameters which cannot be measured precisely by experience such as cutting temperature, deformations and stresses. It's based on the finite element method (FEM),

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finite volumes or discrete elements. Significant progress has been made by these models in understanding the mechanical, thermal and physicochemical phenomena of metal cutting [1-5].

However, the vast majority of these numerical models are limited to chip formation in orthogonal cutting configuration and are based on one of the three known formulations in finite element theory: Lagrangian, Eulerian or Arbitrary Lagrangian-Eulerian formulation (ALE formulation) [6-9].

2 CONSTITUTIVE MODELS OF MACHINED MATERIAL AND TOOL

The cutting tool is often modeled by a thermo-rigid or thermoelastic constitutive model. Therefore, the variation of the temperature in the tool is described by the equation of heat, considering the two main sources of heat:

- The heat generated by friction at the tool-work piece contact interface.
- The heat resulting of the plastic deformation generated in the main shear zones and transferred by conduction to the tool-material contact interface.

Unlike the simple behavior of the cutting tool, the behavior of the machined material remains one of the major difficulties encountered in the simulation of machining. The use of an adequate and representative constitutive model remains essential to effectively simulate the chip formation process.

To properly represent the behavior of machined materials, various phenomena related to metal cutting process should be considered, such as sensitivity to work hardening, deformation rate and temperature, as well as to the physical properties of the machined materials (thermal, thermo-physical, chemical properties, etc.).

In machining, the behavior of machined materials is often described by the following constitutive equations [10]:

$$\overline{\sigma} = f\left(\overline{\varepsilon}, \dot{\overline{\varepsilon}}, T\right) \tag{1}$$

with $\overline{\sigma}$ is the equivalent flow stress of the machined material, $\overline{\varepsilon}$ is equivalent plastic deformation, $\dot{\overline{\varepsilon}}$ is the plastic strain and T is temperature of the machined material.

In the literature, there is a wide variety of constitutive models that consider the previously mentioned effects; such as Johnson-Cook constitutive model [11], Zerrili-Armstrong Model [12], Marusich and Ortiz Model [13].

2.1 Johnson-Cook constitutive model

In simulation of machining process; the Johnson-Cook model [11] is the mostly used to model the behavior of the machined material. It is an empirical model that takes into consideration the effect of hardening, viscosity and thermal softening, according to the following phenomenological equation:

$$\overline{\sigma} = \underbrace{\left[A + B\left(\overline{\varepsilon}\right)^n\right]}_{Hardening} \underbrace{\left[1 + C\ln\left(\frac{\dot{\overline{\varepsilon}}}{\dot{\overline{\varepsilon}}_0}\right)\right]}_{Viscosity} \underbrace{\left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\right]}_{Thermal\ softening} \tag{2}$$

where:

$\overline{\sigma}$	Equivalent stress
$\overline{\varepsilon}$	Equivalent plastic strain
$\dot{\overline{\varepsilon}}$	Equivalent plastic strain rate
$\dot{\overline{\varepsilon}}_0$	The reference strain rate
A	The initial yield strength [MPa] of the material at room temperature
B	The hardening modulus [MPa]
C	The coefficient dependent on the strain rate
m	The thermal softening coefficient
n	The work-hardening exponent
T_{room}	The reference ambient temperature
T_{melt}	The melting temperature of the work piece material
T	The current process temperature

To describe the damage initiation, the Johnson-Cook model [14] is often coupled to a damage law in the following form

$$\bar{\varepsilon}^f = \left(D_1 + D_2 \exp D_3 \frac{\sigma_m}{\bar{\sigma}}\right)\left(1 + D_4 \ln \frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right) \times \left(1 + D_5\left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)\right) \tag{3}$$

where:

- D_1 Initial failure strain
- D_2 Exponential factor
- D_3 Triaxiality factor
- D_4 Strain rate factor
- D_5 Temperature factor
- $\bar{\varepsilon}^f$ The equivalent strain to fracture
- σ_m The average of the three normal stresses

The damage model proposed by Johnson and Cook [14] is used in conjunction with Johnson-Cook flow stress model.

The Johnson-Cook damage model is suitable for high strain rate deformation, such as high-speed machining.

The Johnson-Cook damage model was claimed to result in more realistic simulations compared to other models such as Wilkins, the maximum shear stress, the modified Cockcroft-Latham, the constant fracture strain, and the Bao-Wierzbicki fracture models [15-17].

2.2 Zerrili-Armstrong model

This model is widely used in the context of studies of the behavior of materials subjected to high dynamic loads. The Zerrili-Armstrong model [12] is a semi-empirical model based on the theory of dislocation mobility in the microstructure. It proposes an expression of the equivalent flow stress $\bar{\sigma}$ as a function of the equivalent plastic deformation $\bar{\varepsilon}$, the plastic strain rate $\dot{\bar{\varepsilon}}$, the temperature *T*, the mean diameter of a grain *D* and the crystallographic structure of the machined material. The Zerrili-Armstrong model is then written in the following forms:

1) For a face-centered cubic material

$$\bar{\sigma} = C_1 + \frac{C_2}{\sqrt{D}} + C_3\sqrt{\bar{\varepsilon}} \exp\left(-C_6 T + C_7 T \ln\left(\dot{\varepsilon}\right)\right) \tag{4}$$

2) For a cubic centered material

$$\bar{\sigma} = C_1 + \frac{C_2}{\sqrt{D}} + C_5 \exp\left(-C_6 T + C_7 T \ln\left(\dot{\varepsilon}\right)\right) + C_4\,\bar{\varepsilon}^n \tag{5}$$

3) For a compact hexagonal material

$$\bar{\sigma} = C_1 + \frac{C_2}{\sqrt{D}} + C_5\sqrt{\bar{\varepsilon}} \exp\left(-C_6 T + C_7 T \ln\left(\dot{\varepsilon}\right)\right) + C_5 \exp\left(-C'_6 T + C'_7 T \ln\left(\dot{\varepsilon}\right)\right) \tag{6}$$

where C_1 to C_7 and C'_6 and C'_7, are constants of the model to be determined. The major disadvantage of the Zerrili-Armstrong model is the large number of parameters to be identified and which strongly depend on the crystallographic structure of the machined material.

2.3 Marusich and Ortiz model

The thermo-viscoplastic model of Marusich and Ortiz [13] is widely used in the numerical simulation of high speed machining. This model is called a two-branched law is implemented in an EF code called "Third Wave AdvandtedgeTM", it is described by the following equations:

$$\begin{aligned}
&\left(1+\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)=\left(\frac{\bar{\sigma}}{g\,(\bar{\varepsilon})}\right)^{m_1} && if \quad \dot{\bar{\varepsilon}} \le \dot{\bar{\varepsilon}}_t \\
&\left(1+\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\left(1+\frac{\dot{\bar{\varepsilon}}_t}{\dot{\bar{\varepsilon}}_0}\right)^{\frac{m_2}{m_1}}=\left(\frac{\bar{\sigma}}{g\,(\bar{\varepsilon})}\right)^{m2} && if \quad \dot{\bar{\varepsilon}} \ge \dot{\bar{\varepsilon}}_t \\
&g\,(\bar{\varepsilon})=\sigma_0\,\Theta(T)\left(1+\frac{\bar{\varepsilon}}{\bar{\varepsilon}_0}\right)^{\frac{1}{n}}
\end{aligned} \tag{7}$$

where m_1 and m_2 are respectively the sensitivities at low and high speeds of deformation and $\Theta(T)$ is a thermal function.

3 RESULTS OF FEM SIMULATION

In this paper, Chip formation simulations for aluminum alloy were performed with different cutting speeds (15, 30, 60, 90, 120 and 200 *m/min*), depth of cut a_p = 1*mm*, rake angles γ_0 = 30º, using Abaqus/Explicit FEM software. CPE4R elements, 4-node bilinear plane stress quadrilateral, reduced integration with hourglass control are used in the workpiece model. The influence of cutting speed on chip separation and plastic strain are presented in the present study. Element size in cutting region (top section of the workpiece) is 1 μm in length. A rigid body constrained is applied to the cutting tool in the simulations.

Damage criterion and element deletion is applied to entire workpiece elements, so that it might be possible to simulate crack initiation along a chip's primary shear region. Johnson-Cook flow stress parameters are given in Table 1. Element deletion technique is used to allow element separation to form a chip. The ALE adaptive meshing technique is used to maintain the mesh quality throughout the simulation and to reduce element distortion in cases of extreme deformation.

The Johnson-Cook damage parameters used for the present study are given in Table 2.

Table 1
Johnson-Cook flow stress parameters for workpiece.

A (MPa)	B (MPa)	C	m	n	Density ρ [kg/m^3]	Elastic modulus, E [GPa]	Poisson's ratio	T_{melt} [ºC]	T_{room} [ºC]
148	341	0.023	0.859	0.183	2700	73	0.33	640	25

Table 2
Johnson-Cook damage parameters.

$D1$	$D2$	$D3$	$D4$	$D5$
0.071	1.248	-1.142	0.147	0.1

3.1 Influence of cutting speed on chip separation time and plastic strain

The influence of cutting speed on chip separation is shown on Fig. 1 for the different cutting speeds using for the simulation of chip formation.

It has been noted that cutting speed influence strongly the chip separation time, it vary between 2.5E-3 sec for V= 200*m/min* and 1.75E-2 sec for V=15 *m/min*. Figs. 1 and 2 show respectively the Von Mises stress and equivalent plastic strain (PEEQ) variation with the different cutting speeds, it has been noted that the values of stress and plastic deformation evolve accordingly with the increase of cutting speed

The values shown on Table 3., and histograms of Fig.3 represent the variation of Mises stress and equivalent plastic strain (PEEQ) at chip separation time for the different cutting speeds used in our simulation.

The Mises stress shows a gap (variation) of 1.51*E*+07 between the higher and the lower registered values, the higher value has been registered for cutting speed V = 120 *m/min*; where the lowest value has been registered for V = 60 *m/min* (Fig.3(a)).

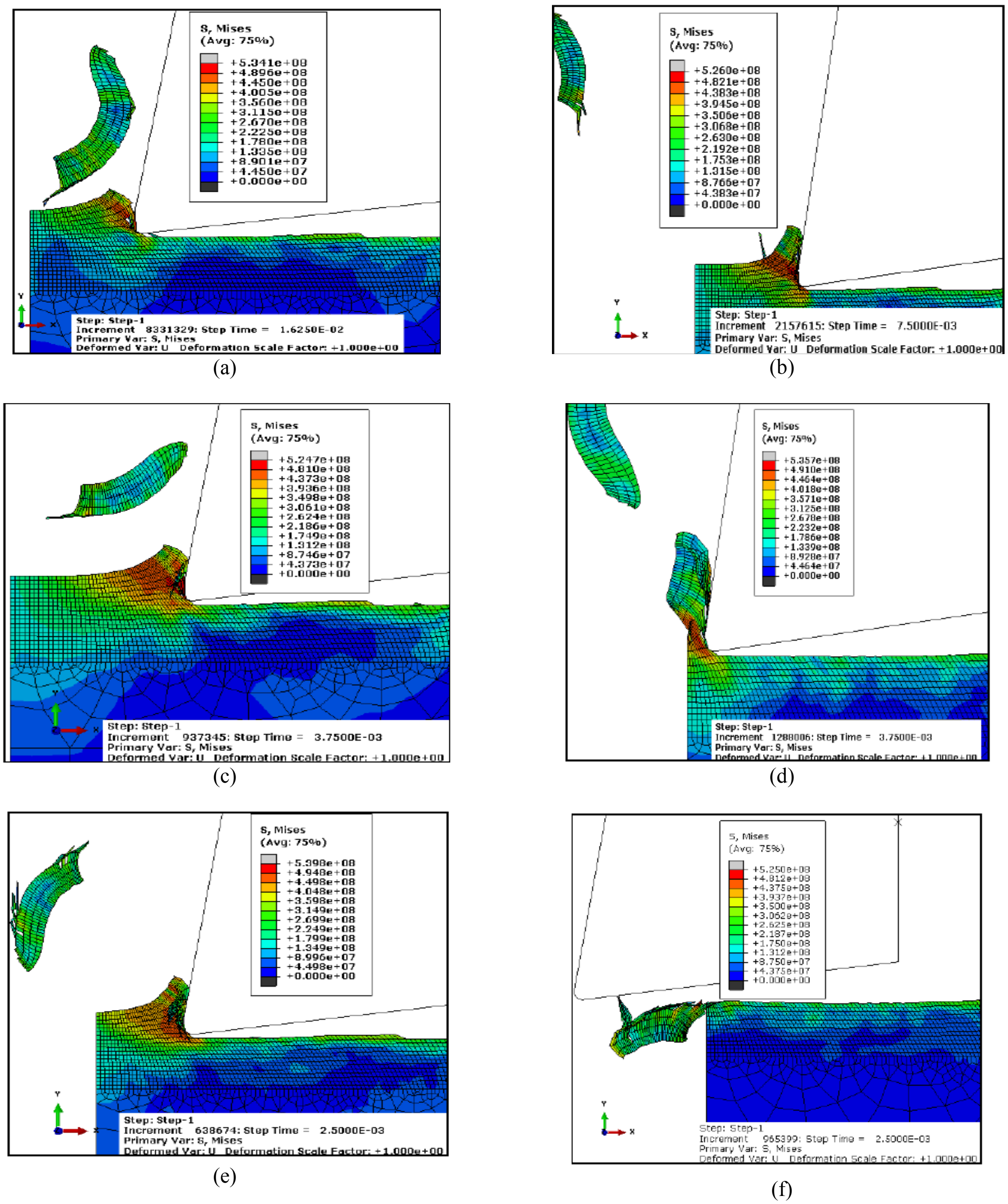


Fig.1
Mises criterion variation for different cutting speeds: (a) V= 15 *m/min*, (b) V= 30 *m/min*, (c) V= 60 *m/min*, (d) V= 90 *m/min*, (e) V= 120 *m/min*, (f) V= 200 *m/min*.

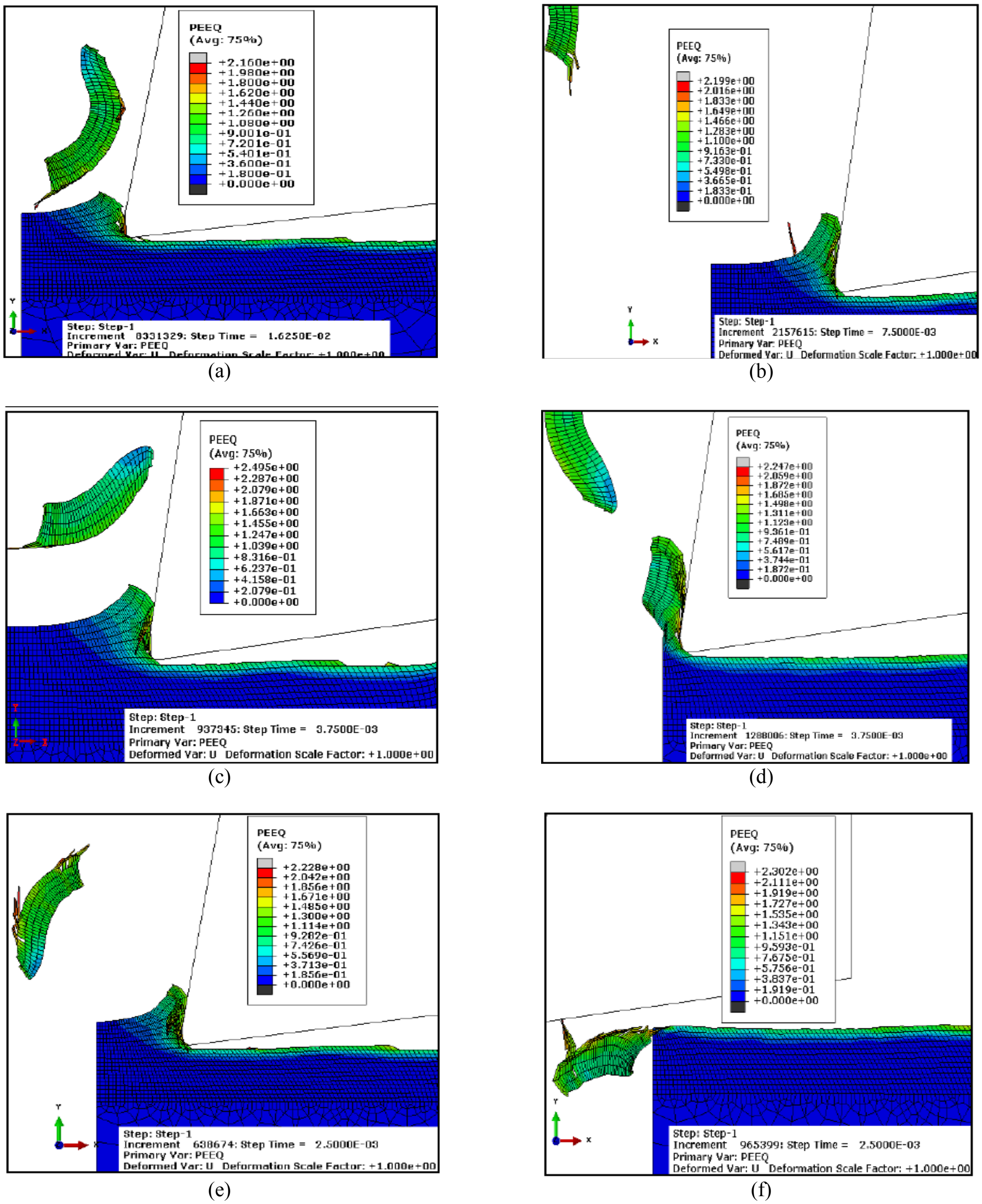
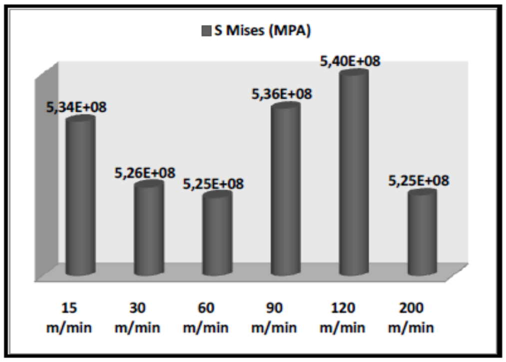
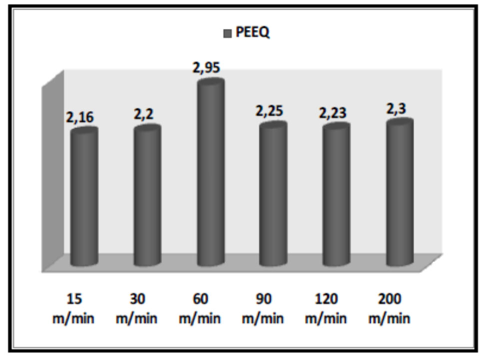


Fig.2
PEEQ variation for different cutting speeds: (a) *V*= 15 m/min, (b) V= 30 m/min, (c) V= 60 m/min, (d) V= 90 m/min, (e) V= 120 m/min, (f) V= 200 m/min.



(a)



(b)

Fig.3
Mises stress and equivalent plastic strain (PEEQ) at chip separation instant for the different cutting speeds.

Table 3
Mises and PEEQ Simulation results for different cutting speeds.

Cutting Speed	Time (Second)	S Mises (*MPA*)	PEEQ
15 *m/min*	1.75*E*-02	5.341*E*+08	2.160*E*+00
30 *m/min*	7.50*E*-03	5.260*E*+08	2.199*E*+00
60 *m/min*	3.75*E*-03	5.247*E*+08	2.945*E*+00
90 *m/min*	3.75*E*-03	5.357*E*+08	2.247*E*+00
120 *m/min*	2.50*E*-03	5.398*E*+08	2.228*E*+00
200 *m/min*	2.50*E*-03	5.250*E*+08	2.302*E*+00

4 CONCLUSIONS

With the latest FEM models, a set of new results has been presented on the effects of influential material parameters and processing parameters on chip formation.

The morphology of cutting chips (continuous chip) is simulated in Abaqus/Explicit finite element software. The Johnson-Cook constitutive material model is used in conjunction with the Johnson-Cook progressive damage model by using damage evolution criterion.

According to simulation results, the variation of cutting speeds is an influential factor in chip formation. The lower values of cutting speed lead to longer time for chip formation and separation, whereas the increasing of cutting speed lead to accelerate the process of chip separation which leads to a discontinuous chip form. According to simulation results in this paper, with the increasing of cutting speed chip type tends to become more segmented. However, some difficulties were encountered in the simulation with smaller cutting speed due to the excessive distortion of mesh elements and computational power.

Additionally to the chip formation and morphology obtained from the finite element simulation results, some other mechanical parameters such as stress, strain, strain rate and plastic deformation; which are very difficult to measure on the experimental test, can be obtained through finite element modeling of chip formation process.

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