Simulation analyzing the influence of cutting HT250 by self-prepared Si3N4 insert at different feed rate

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Abstract. Metal cutting process is an extremely complicated problem. Using the commercial finite element software (Deform), the process has been reliably simulated. In this paper, the process of cutting HT250 by self-prepared Si3N4 insert was simulated at different feed rate base on Finite Element Method (FEM). After simulation, the results of cutting force and temperature were availably obtained. The influence of cutting properties at different feed rate was effectively predicted through analysing these results.

1. Introduction
Metal cutting process is a very complicated nonlinear problem. The traditional cutting test method is difficult to get accurate and stable results. However, using the commercial finite element software, metal cutting process has been able to be reliably simulated and predicted. The finite element simulation by computer can achieve the required accuracy and the high reliability, avoid actual material cutting experiments, and save time, manpower and material resources.

Childs [1,2] considers that the success and reliability models are dependent upon work material flow stress. Trent et al. [3,4,5] considers that the simulation models are also dependent upon friction parameters between the tool and workpiece interfaces for accurate analysing the metal machining process. This paper studies the dynamic process of cutting HT250 by Si3N4 inserts using FEM. The numerical models (geometric model, material behaviour model, contact and friction model, heat transfer model, etc.) were created before simulation. The simulation tests were carried out at different cutting condition ($V_c=300m/min$, $a_p=0.5mm$, $f=0.1/0.15/0.2mm/rev$). The results of cutting force and tool temperature were availably obtained after simulation. The cutting properties of Si3N4 insert were effectively predicted through analysis these results.

2. Finite element models

2.1. Geometries and mesh generation
The geometric model of Si3N4 inserts was created in Deform software according to the type of MCGNR. And then the workpiece and insert were respectively meshed with 45419 and 26994 isoparametric quadrilateral elements [6]. The tool nose geometry mesh was generated with element size ratio of 6 for improving the accuracy of analysis. The geometric models and mesh generations of Si3N4 insert and HT250 workpiece were respectively shown a and b in fig.1
2.2. Material behaviour model

(1) Workpiece material behaviour model

Accurate flow stress models are considered highly necessary to represent work material constitutive behavior under high strain rate deformation conditions [7]. The constitutive law proposed by Johnson and Cook [8] provides a good description of material behavior subjected to large strains, high strain-rates and thermal softening. The Johnson-Cook model, provided in Deform software, was used in the simulation process. The law was described by Eq.1. The elastic and thermos-mechanical properties of HT250 were shown in Table2.

\[
\sigma = [A + B(\varepsilon)]^{n} 
\times [1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)] 
\times [1 - (\frac{T - T_{\text{room}}}{T_{\text{melt}} - T_{\text{room}}})^m] \tag{1}
\]

In Eq.1, \(\sigma\) is the material flow stress, \(\varepsilon\) is the equivalent plastic strain, \(\dot{\varepsilon}_0\) is the reference plastic strain rate, \(\dot{\varepsilon}\) is the plastic strain rate, \(T_{\text{room}}\) and \(T_{\text{melt}}\) are respectively the room and the melting temperatures. The coefficients \((A, B, C, n \text{ and } m)\), listed in Table 3, are obtained from tensile curves using a fitting program [9].

![Geometric models and mesh generation](image)

Fig.1 Geometries and mesh generation

Table 1 Elastic and thermal properties parameters of HT250

| Property       | Value          |
|---------------|----------------|
| Density       | 7190 Kg/m³     |
| Poisson’s ratio | 0.26           |
| Yong’s modulus | 126 10⁹ MPa    |
| Heat conductivity | 100°C: 49.1     |
|                | 200°C: 48.1     |
|                | 300°C: 47.1     |
|                | 400°C: 46.1     |
|                | 500°C: 45.1     |
| Thermal expansion | -100~20°C: 10.0 |
|                | 20~200°C: 11.0  |
|                | 200~400°C: 12.5 |

Table 2 HT250 material constants for J-C model:

| A    | B    | C    | n     | m     | \(T_{\text{room}}\) | \(T_{\text{melt}}\) | \(\dot{\varepsilon}_0\) | \(\dot{\varepsilon}\) |
|------|------|------|-------|-------|----------------------|---------------------|------------------------|------------------------|
| 573  | 380  | 0.034| 0.17  | 0.12  | 20                   | 1250                | 1                      | 1                      |

(2) Insert material behaviour model

Deform software provides different methods of defining the flow stress. In materials database of Deform software, the Al2O3 ceramic is defined by the Power Law [6], shown below Eq.2. In this study, Si3N4 ceramic was also defined by the Power law.

\[
\sigma = c \times \varepsilon^n \times \dot{\varepsilon}^m + y \tag{2}
\]

In Eq.2, \(\sigma\) is Flow stress, \(\varepsilon\) is effective plastic strain, \(\dot{\varepsilon}\) is effective strain rate, \(c\) is material constant, \(n\) is strain exponent, \(m\) is Strain rate exponent, \(y\) is initial yield value. The properties of Si3N4...
inserts were shown in Table 3.

| Properties of Si3N4 ceramic inserts |
|------------------------------------|
| Bending strength (MPa) | HV hardness (GPa) | Fracture toughness (MPa·m1/2) | Poisson’s ratio | Yong’s modulus 10³MPa | Heat conductivity (W/(m·K)) | Heat capacity (J/(kg·K)) |
|-------------------------|-------------------|-------------------------|----------------|----------------|-------------------|-------------------|
| 905                     | 14.3              | 9.02                    | 0.25           | 310            | 31                | 550               |

2.3. Contact and friction model

Zorev [10] proposed the most realistic description of normal and frictional stress distribution at tool-chip interface. The author assumed that the tool-chip interface was subdivided into two zones: sticking zone and sliding zone [11]. In the sticking zone, the shear stress reach the saturation values $\tau_{max}$. In the sliding zone, the frictional shear stress does not reach the saturation values $\tau_{max}$. The frictional stress can be expressed as Eq.3, $\mu = 0.45$ [12].

$$
\begin{align*}
\tau_f &= \mu \times \sigma_n \quad \text{if} \quad \mu \times \sigma_n < \tau_{max} \quad \text{(Sliding)} \\
\tau_f &= \tau_{max} \quad \text{if} \quad \mu \times \sigma_n \geq \tau_{max} \quad \text{(Sticking)}
\end{align*}
$$

2.4. Heat transfer model

In machining process, the temperature increases in cutting zone results from material plastic deformation and friction at tool-workpiece interface. Most of the heat is taken away by chip, parts of the heat is transferred into the air. In order to improve the accuracy of analysis, the heat transferred into air is expressed as Eq.4[13].

$$
Q_h = h \times (T_w - T_0)
$$

In Eq.4, $h = 0.02$ and is convection coefficient, $T_w$ is the surface temperature of insert and workpiece, $T_0 = 20^\circ C$ and is environment temperature [6].

3. Finite element simulation and discussions

Using the aforementioned models, the simulation tests were carried out with specific cutting parameters. The cutting parameters were listed in Table 4. The number of simulation steps was defined to 500. The simulation process was shown in Fig.2.

| Table 4 Cutting parameters |
|---------------------------|
| Cutting speed $V_c$ (m/min) | Depth of cut $a_p$ (mm) | Feed rate $f$ (mm/rev) |
|---------------------------|---------------------------|---------------------------|
| 300                       | 0.5                       | 0.1/0.15/0.2              |

Fig.2 Simulation process
3.1. Cutting force analysis
Cutting force is main analysis parameter, which is related to cutting heat generation, tool wear, machining accuracy. The simulation results of cutting force were shown in Fig. 3. The cutting force were gradually rising from zero up to the maximum, stabilize within a certain range finally. Accompany with chip separation, when node number was increasing, cutting force was increasing. On the contrary, cutting force is reduced. So cutting force appeared wave.

The max cutting force was respectively 403/648/535(N) while feed rate was respectively 0.1/0.15/0.2 (mm/rev). The cutting force was the maximum at f=0.15 than others.

![Fig.3 Results of cutting force](image)

3.2. Temperature fields analysis
Temperature is another main analysis parameter. Heat generation is mainly caused by metal deformation in cutting process. The results of temperature analysis were shown in Fig. 4. The highest temperature focused on the nose of insert, which was the interface of insert and workpiece, where was the most severe shear zone of materials. However, Fig. 8 showed that the temperature of Si3N4 insert was only more than 23°C. The most of heat generated caused by deformation was taken away by chip. The low thermal conductivity of ceramic material prevented heat from passing on the insert, which effectively ensured tool life.

The highest temperature was respectively 23.1/24.9/24.4(℃) while feed rate was respectively 0.1/0.15/0.2 (mm/rev). The tool temperature was the highest at f=0.15 than others.
Fig. 4 Temperature fields analysis

4. Conclusions
This paper simulated the cutting HT250 process by self-prepared Si3N4 ceramic insert at different feed rate. Depended on analyzing the results of cutting force and tool temperature after simulation, the cutting properties of self-prepared Si3N4 insert were predict. The simulation results concluded:

1) The cutting force was the maximum at f = 0.15 mm/rev.
2) The tool temperature was the highest at f = 0.15 mm/rev.
3) Other factors (cutting speed, cutting depth) should be taken into account for predicting accurately the cutting properties of self-prepared Si3N4 insert.

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