Effect of cutting conditions on temperature generated in drilling process: A FEA approach

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Abstract

Heat generated during a drilling process has a major influence on the tool life and the workpiece material behaviour that are significantly affected by cutting conditions (cutting speed, feed rate). In this paper, the effect of cutting conditions on temperature generated in drilling process is investigated by means of finite element (FE) simulations using commercially available code MSC MARC MENTAT. A Johnson Cook material model is used to describe elasto-plastic deformation behaviour. The updated Lagrangian procedure is used to implement the transient analysis for the elasto-plastic material in the model. A modified shear friction model is employed to model friction at the tool tip-workpiece interface. The effect of friction on chip shape is investigated with FE simulations. Experiments were carried out to verify the FE results.

1. Introduction

Friction plays a very important role in metal cutting. It determines the energy required to remove a given volume of metal, as well as determining the surface quality of a finished product, chip shape, surface hardness and the rate of wear of the cutting tool. Friction is the main source of heat generated at the tool-workpiece interface, and most of the problems relating to machining are caused directly or indirectly by the amount of heat generated at the cutting edge. Of all the machining processes, drilling is one of the commonly used machining processes in creating a hole in finished components. Most of the drilling operations are normally performed at the final steps of manufacturing. Understanding thermal effects in drilling process is critical in predicting the effect of the machining technique on the workpiece as well as the consequences for the tool wear.

The finite element method (FEM) is a reliable computational technique in the modelling of mechanics of materials and drilling in particularly. In order to expedite the numerical computation most of the drilling simulations in the past were performed with a certain level of simplifications such as reducing a three-dimensional problem to a two-dimensional formulation [1] or by assuming the cutting lips as a combination of small elementary cutting tool performing orthogonal cutting operation [2].

In this study a 3D finite element model of drilling process is performed to investigate the effect of cutting condition on the temperature generated during drilling process. The three key material response are strain hardening, strain rate and thermal softening which are incorporated in the model. The influence of cutting parameter (spindle speed, feed rate), on the temperature generated during the drilling process is investigated in the model.

For the modelling of the drilling process an updated Lagrangian formulation of FEA is utilized in the model. In the updated Lagrangian formulation, the element shape changes with the material flow, and the calculation embeds a computational mesh in the material domain and solves the problem for the discrete points of the mesh in time. The formulation accounts for all non-linear kinematics effects due to large displacements and rotations.

The thermal processes in drilling comprise of heat generation due to plastic deformation, friction heating at the tool-chip interface, contact heat conduction between the tool and chip as well as convective heat transfer from the free surface of the workpiece, tool and chip to the environment which are incorporated in the FE model.

1.1. Johnson Cook Material Model

Parameters such as strain, strain rate, temperature and strain hardening have a major influence on flow stresses or instantaneous yield strength, at which the materials start to deform plastically. Accurate and reliable flow stress models are necessary to represent the material's constitutive behaviour under different cutting conditions. The Johnson Cook material model [3] is used to describe the mechanical behaviour of AISI 1010 steel at high strain, strain rate and elevated temperature in simulations of drilling process. In this model, strain, strain rate and strain hardening effects are combined in a multiplicative manner. The material response is represented as

$$\sigma_y = [A + B\left((\varepsilon_p)^n\right)][1 + Cln(\dot{\varepsilon})][1 - T^{*m}], \quad (1)$$

where σ_y is flow stress, ε_p is the effective plastic strain, $\dot{\varepsilon} = \frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_.}$, $\dot{\varepsilon}_p$ is the plastic strain rate, $\dot{\varepsilon}_. = 1\, s^{-1}$ is the reference strain rate, $T^* = \frac{T - T_R}{T_M - T_R}$ is the homologous temperature, T is the absolute temperature, T_M is the melting temperature of mild steel, T_R is the room temperature, A =250 MPa is the initial yield stress at the reference strain rate, B =275 MPa is the hardening modulus, C=0.078 is strain rate sensitivity coefficient, n =0.36 is the hardening coefficient and the term T^(*m) is assume to zero. All these parameters were determined experimentally using the Split Hopkinson Pressure Bar method and were adopted from [4].

1.2. Friction Modelling

Various friction models are available to model the interaction at the tool chip-workpiece interface: these models include the Coulomb friction model, with friction stress proportional to the normal interface stress

$$\tau = \mu\sigma_n, \quad (2)$$

where τ is the shear stress, μ is the coefficient of friction and σ_n is the normal stress [5-7]. The shear friction model

$$\tau = ku, \quad (3)$$

where k is the shear yield strength [8], the modified Coulomb friction model

$$\tau = \min(\mu p, \tau_{th}), \quad (4)$$

where τ is Coulomb shear stress, p is the normal pressure and τ_{th} is the thresholds value for conventional Coulomb model [9], stress-based polynomial model [10] and modified shear friction model [11] for friction modelling in metal cutting.

When the normal force or stress becomes large, the Coulomb friction model may not correlate well with experimental observations. This is due to the fact that the Coulomb model predicts frictional shear stresses to increase to a level that can exceed the flow stress or failure stress of the material. As this is not physically possible, a different friction model should be applied. There are several choices available to correct for this unphysical prediction: (i) to use a nonlinear coefficient of friction; (ii) introduce a friction stress limit in a bilinear model or (iii) to use a modified shear friction model. Therefore, the modified shear friction model is implemented using approximations of the theoretical step function [12]. Because this step function causes numerical difficulties in FE simulation of the process, the arctangent function used in the modified shear friction model is used to smooth out the step function in order to avoid numerical difficulties:

$$\sigma_{fr} \le -w\frac{\bar{\sigma}}{\sqrt{3}}\frac{2}{\pi}\mathrm{sgn}(\mathrm{V_r})\mathrm{artan}\left(\frac{V_r}{V_{\mathrm{cr}}}\right) \quad (5)$$

Where $\bar{\sigma}$ is the equivalent stress, V_r is the relative sliding velocity, V_{cr} is the critical sliding velocity below which sticking is simulated, w is the friction coefficient and $\mathrm{sgn(x)}$ is the signum function.

2. Finite Element (FE) Model Description

A commercially available FEA code MSC Marc Mentat (2007r) is used for modelling the drilling process; a schematic of this process with relative movement of the workpiece and drill bit is shown in Figure 1. The drill bit has a complex geometry and is a challenge in representing it in current FEA packages; however, it demands a significant computational cost in FEA simulations of drilling process. To reduce the computational cost, only one cutting lip of the drill bit (MZS0980S-DIN) having a diameter of 9.89 mm is considered in the FE simulation. The model is simulated for only one revolution of the drill bit. A cylindrical workpiece with outer diameter of 8 mm, with a 3 mm diameter pre hole and 1 mm thickness is used in FE simulation. Eight-nodded, isoperimetric, three-dimensional element with linear interpolation are used to model the workpiece. However, due to the poor representation of shear behaviour and lack of support for remeshing technique these elements were automatically converted into approximately 5000 five-nodded tetrahedral element. An eight-nodded isoperimetric brick element with tri-linear interpolation is used for descritization of the cutting tools. The ambient temperature is selected as 20°C for the cutting tool and workpiece.

In the present FE model of drilling process the cutting tool rotates with different spindle speeds (300 rpm, 650 rpm and 1000 rpm) and the workpiece is moved against the cutting tool with constant feed rates of 0.12 mm/rev, 0.175 mm/rev and 0.24 mm/rev (Table 1). The properties of the workpiece used in the FE simulation are that of AISI 1010 steel and those for the cutting tool are of tungsten carbide.

Chip separation is determined by the plastic flow. Due to severe deformation of the process zone and of chip, the elements near the cutting lip of a drill bit distort significantly, leading to some well-known computational problems. As a result re-meshing technique is used frequently to replace those distorted elements with geometrically consistent ones. Figure 2 shows the chip formation after the successful implementation of the remeshing technique.

In FE simulation two contact condition contact with friction ($w = 0.5$) and contact without friction ($w = 0$) is used to investigate the effect of friction on chip shape.

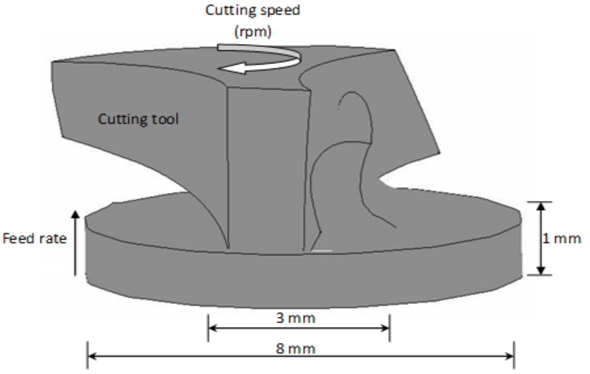

Figure 1: Scheme of relative movements of workpiece and cutting tool in 3D simulations of drilling process

3. Experimental Setup

For experimental verification of temperature distribution in the cutting region during the drilling process various experiments were conducted using CYL 6240 conventional lathe machine with a maximum spindle speed of 2000 rpm and 7.5 horse powers (HP) drive motor. The experiments were carried out in a 3 mm pre-hole drilled workpiece and the temperature values were recorded when it was reached to a steady state condition.

3.1. Cutting Conditions

Table 1 shows the detail of machining parameters used in experimentation such as feed rate, cutting speed. Temperature was experimentally measured in dry drilling conditions.

3.2. Temperature Measurement

To measure the temperature of a drill bit during the dry drilling process, a standard Teflon coated K-type thermocouple is inserted into the coolant hole of a drill bit.

The diameter of the thermocouple is 127 µm and can measure temperature up to 600°C with a response time of 10 µs. HH501DK 4-channel K-type thermometer is used to record the measured temperature values; the Fourier's law is then used to calculate the estimated temperature at the centre point of the cutting lips of the drill bit. The setup used for the measurement of a drill-bit temperature is shown in Figure 3. Figure 4 demonstrate the experimental results obtained at various cutting conditions.

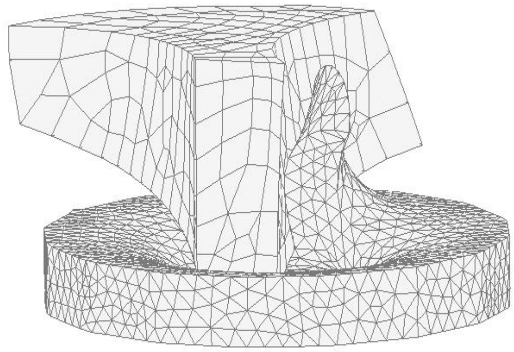

Figure 2: Chip formation

Parameters used in analysis	Magnitude of parameter
Spindle Speed (rpm)	300, 650, 1000
Feed Rate (mm/rev)	0.12, 0.175, 0.24

Table 1: Cutting parameters of drilling

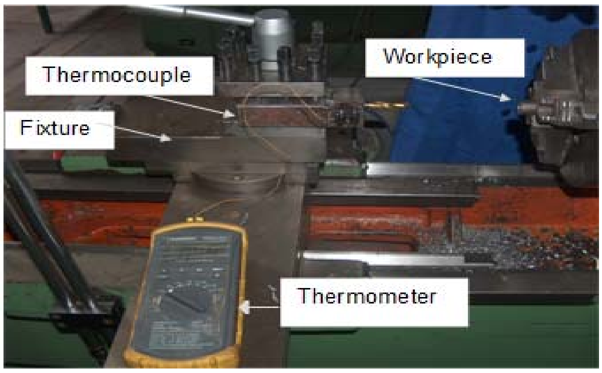

Figure 3: Experimental setup for temperature measurement

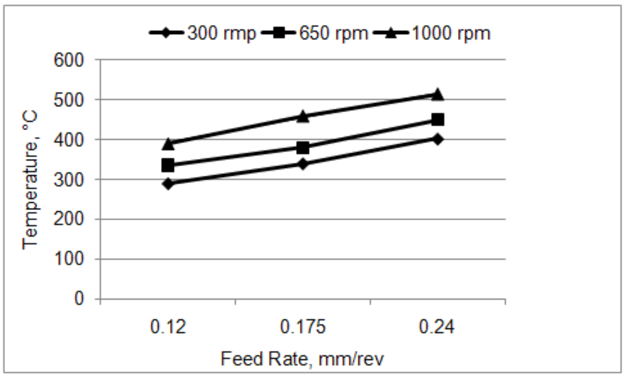

Figure 4: Experimentally measured temperature in drilling process at various cutting condition

4. Results of Simulation

In this section we present the result obtained with FE simulation of drilling process with different cutting conditions. Varying cutting speeds (rpm) and feed rates (mm/rev) are used in the FE simulation of the drilling process. The FE simulation results are in good quantitative agreement with the experimental results.

4.1 Effect of Feed Rate

Variation of feed rate has a significant effect on the temperature generated during the drilling process. In all the FE simulations the cutting speed and other parameters are kept constant and only the feed rate is varied.

From the FE simulations of the drilling process it is observed that the temperature increases with the increase of feed rate (Figure 5), which is in good agreement with [13-15]. The possible reason is that increasing the feed rate increases the penetration into the workpiece leading to higher plastic deformation resulting in a higher heat generation at the cutting region. Increasing the feed rate from 0.175 to 0.24 mm/rev (approx. by 37%) causes a 5% increase in temperature.

4.2 Effect of Cutting Speed

Temperature generated during the drilling process is also greatly affected by the cutting speed. In the following FE studies, the feed rate is kept constant and the cutting speed is varied. A rise in temperature is observed with an increase of cutting speed (Figure 5). For instance, an increase in cutting speed from 300 to 650 rpm (approx. by 116%) can cause an average increase of about 15% in temperature during the drilling process [2, 13, 14, 15].

4.3. Chip Shape

A visible difference in chip shape is observed in numerical simulations for dry and frictionless drilling conditions. Figure 6 shows chip shape for both cases. The radius of curvature of a chip under frictionless contact condition was approximately 60% smaller than that for contact condition with friction at the tool tip-workpiece interface. The ratio of thickness of the uncut chip to that of the deformed one is equals to 0.7 with friction ($w = 0.5$) and 0.45 without friction ($w = 0.5$).

5. Conclusions

A numerical study of the process of drilling is carried out to analyse the effect of various cutting conditions on the temperature generated. A comparison of feed rate shows that temperature grows with its increase. A 37% increase in the feed rate causes a 5% increase in temperature.

The effect of cutting speed on temperature generated during drilling process is also studied. A 116% increase in cutting speed causes a 15% increase in temperature.

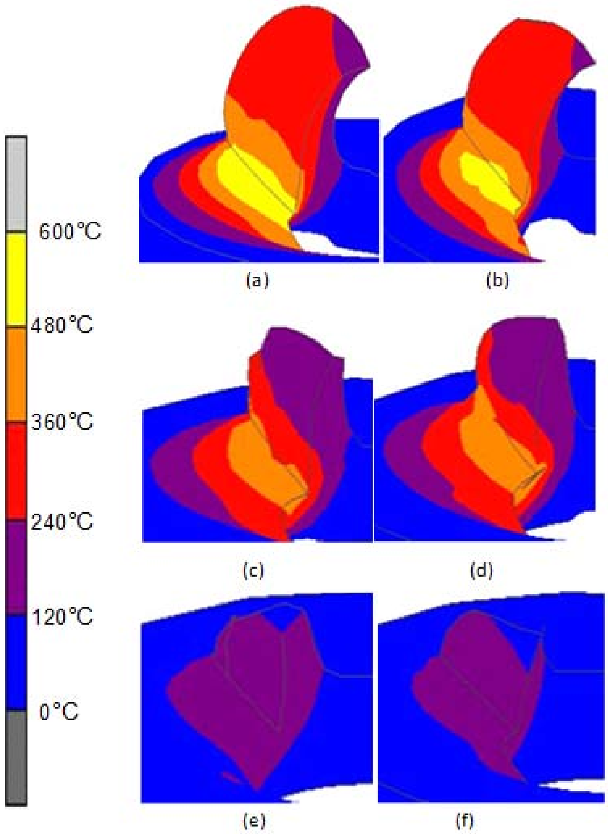

Figure 5: Effect of feed rate and cutting speed on temperature generated in drilling process: (a) 1000 rpm, 0.24 mm/rev, (b) 1000 rpm, 0.175 mm/rev, (c) 650 rpm, 0.24 mm/rev, (d) 650 rpm, 0.12 mm/rev, (e) 300 rpm, 0.24 mm/rev and (f) 300 rpm, 0.12 mm/rev, at t = 0.035 s.

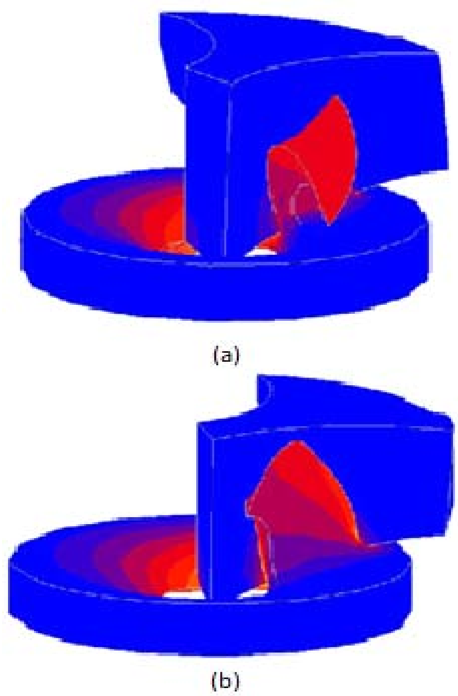

Figure 6: Effect of friction on chip shape (a) without friction (w=0), (b) with friction (w=0.5)

The chip shape in drilling is affected by the friction condition on the tool tip-workpiece interface. The radius of curvature of the chip in dry drilling condition is approximately two times larger than that for frictionless condition. The chip thickness is also higher.

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