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Finite Element Simulation of Orthogonal Cutting Process for Steel

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***Abstract*— The process of orthogonal metal cutting is analysed using the commercial FEA package ABAQUS/Explicit 6.11. The focus of the results presented in this paper is on the effect of friction and rake angle on the cutting forces in a metal cutting process. A number of finite element simulations have been done with the Johnson-Cook Damage model being used to initiate the damage and simulate chip separation from the workpiece .A tool rake angle varying from 20^o to 30^o and a friction coefficient varying from 0.05 mm to 0.15 mm in steps of 0.05 mm have been considered in the simulations. The results of these simulations provide insight as to how cutting forces are influenced by rake angle and coefficient of friction.**

Keywords* —Component; formatting; style; styling; insert (key words)

I. INTRODUCTION

In a metal cutting process unwanted material is removed from a workpiece in the form of chips for producing finished parts of required dimensions and accuracy. Metal cutting is a highly non-linear process in which plastic deformation is involved during chip formation. Early studies of metal cutting were based on simple models, such as the shear-angle approach proposed by Merchant [1, 2], Piispanen [3], and Oxley [4], and the slip-line field theory by Lee and Shaffer [5] and Kudo [6] based on rigid-perfectly plastic material behaviour. These models were later extended to include the effect of work hardening [7, 8], friction [9] and built-up edge [10].In the past 20 years, the finite element method has been applied to study and simulate metal cutting processes and different finite element simulation techniques have been developed. One of the finite element model by Usui and Shirakashi [11] treated steady-state metal cutting based on empirical data and assuming rate-independent deformation behaviour. A later study by Iwata et al. [12] considered the effect of friction between the chip and the tool rake face but was restricted to very low cutting speeds and strain rates and assumed rigid-plastic deformation. Perhaps the early comprehensive finite element studies of metal cutting were those by Strenkowski and Carroll [13] and Carroll and Strenkowski [14]. They used the general-purpose finite element code NIKE2D and employed an updated Lagrangian formulation to model the orthogonal metal cutting procedure. A technique for element separation in front of the tool tip and an element-separation criterion based on the magnitude of plastic strains was developed. This technique was used to simulate the cutting process from the incipient stage to the steady state and to predict cutting force, chip geometry, plastic deformation and residual stress in the workpiece. Shet and Deng [15] have extensively studied the machining of AISI 4340 steel by means of simulation using ABAQUS and their results provide much insight into the cutting forces involved in chip formation. Alternatively, Strenkowski and Moon [16] proposed a steady-state metal cutting technique based on an Eulerian formulation. Their technique was used to predict chip geometry and temperature distribution. A good correlation between model predictions and metal cutting measurements was found. The finite element study by Komvopoulos and Erpenbeck [17] focuses its attention on chip formation in orthogonal metal cutting and on the effect of such factors as plastic flow properties of workpiece material, friction at the tool–workpiece interface, and wear of the tool, on the cutting process. The simulation of chip separation was achieved by using the “distance tolerance” criterion. From the point of view of numerical simulations, the friction between the tool–chip interface has been modelled in the literature according to the Coulomb Friction Law. The purpose of this study is to address the issue of the effect of friction along the tool–chip interface and its effect on the cutting forces with various tool rake angles. To achieve the stated purpose, this study adopts the finite element method to simulate the orthogonal metal cutting process and to obtain parametric evaluations of the effect of friction. The general-purpose finite element code ABAQUS is adopted to study orthogonal metal cutting with continuous chip formation.

II. SIMULATION

The purpose of this section is to discuss the modelling options in the commercial FEA code ABAQUS/Explicit 6.11.A schematic diagram of the model problem in 2D is given below.

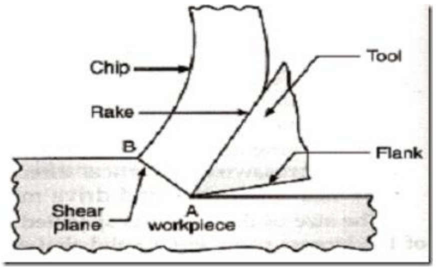


Fig 1.Schematic diagram of orthogonal metal cutting process

The material used is AISI 4340 steel with a Young's Modulus (E) of 207 GPa and density (ρ) of 7800 kg/m^3.The chip layer has a height of 50 μm, 100 μm and 150 μm for the various depth of cuts. The rest of the workpiece has a length of 2540 μm and a height of 889 μm. The tool in this study is of a parallelogram shape and has a base length of 407 μm and a height of 762 μm. The tool material properties are taken as E =207 GPa and ρ = 7800 kg/m^3. The boundary conditions for the chip-workpiece-tool system are given as follows. The upper boundary of the tool moves incrementally towards the left with a constant speed of 2.54 m/s (152.4 m/min) while it is restrained vertically. The left end and right end of the workpiece are restrained in the cutting direction but not vertically. Since the bottom boundary of the workpiece is expected to undergo very little deformation during cutting, it is assigned zero displacements in both directions. A contact pair between the chip and tool face is defined (as shown in Fig 2.) in Abaqus/Explicit 6.11 to take care of the chip sliding on the tool face during the machining.

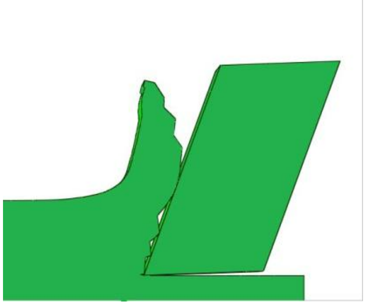


Fig 2. Position of tool and workpiece

III. MATERIAL MODEL

The workpiece material considered is AISI 1045 steel and it is modelled with the Johnson-Cook damage evolution and plasticity model available in ABAQUS/Explicit 6.11. This model is a strain rate and temperature dependent [7-8] visco-plasticmaterial model which describes the relationship of stress, strain, strain rate and temperature. It is suitable for problems where the strain rate varies over a large range (10^2 s^{-1} to 10^6 s^{-1}) . This model uses the following equivalent flow stress:

$$\bar{\sigma} = [\mathrm{A} + \mathrm{B}(\bar{\varepsilon})^n][1 + \mathrm{C}\ln(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0})][1 - (\frac{T - T_0}{T_{melt-T_0}})^m] \quad . \tag{1}$$

where $\bar{\sigma}$ is the equivalent stress, $\bar{\varepsilon}$ is the equivalent plastic strain, $\dot{\bar{\varepsilon}}$ is the plastic strain rate, $\dot{\bar{\varepsilon}}_0$ is the reference strain rate (1.0 s^{-1}), T_0 is the room temperature, T_{melt} is the melting temperature, A is the initial yield stress (MPa), B is the hardening modulus, n is the work-hardening exponent, C is a coefficient dependent on the strain rate (MPa), and m is the thermal softening coefficient. The Johnson-Cook parameter values used to simulate the behaviour of AISI 43405 workpiece are specified in Table 1.

TABLE I. JOHNSON COOK BEHAVIOUR LAW PARMETERS OF AISI 4340

A (MPa)	B (MPa)	n	C	m	$\dot{\bar{\varepsilon}}_0$ (s^{-1})	T_{melt}(δ)	T_0(δ)
792	510	0.26	0.014	1.03	1	1783	20

The material constants for Johnson-Cook model are identified through high strain rate deformation tests using split Hopkinson's bar.

IV. CHIP FRACTURE CRITERION

In order to simulate the separation between chip and workpiece, a dynamic failure model was used for the Johnson-Cook model in ABAQUS/Explicit which is suitable only for high strain-rate deformation of metals. The Johnson-Cook dynamic failure model is based on the value of the equivalent plastic strain at element integration points. The failure is assumed to occur when the damage parameter D exceeds 1. This is a physical criterion. The damage parameter D is defined as follows:

$$\mathrm{D} = \Sigma(\frac{\Delta\bar{\varepsilon}^{pl}}{\bar{\varepsilon}_f^{pl}}) \tag{2}$$

where $\Delta\bar{\varepsilon}^{pl}$ is the increment of equivalent plastic strain $\bar{\varepsilon}_f^{pl}$ is the strain at failure, and the summation is performed over all increments in the analysis. The strain at failure $\bar{\varepsilon}_f^{pl}$ is assumed to be dependent on the nondimensional plastic strain rate $\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\varepsilon}_0}$. The dependence of $\bar{\varepsilon}_f^{pl}$ is assumed to be separable and is the following relation:

$$\bar{\varepsilon}_f^{pl} = [d_1 + d_2 \exp(d_3 \frac{p}{q})][1 + d_4 \ln(\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\varepsilon}_0})](1 + d_5 \frac{T - T_0}{T_{melt-}T_0}) \tag{3}$$

where d_1-d_5 are failure parameters measured at or below the transition temperature T, and $\dot{\varepsilon}_0$ is the reference strain rate. The values of d_1-d_5 are specified in Table 2 when the Johnson-Cook dynamic failure model was defined.

TABLE II. JOHNSON-COOK DAMAGE LAW PARAMETERS OF AISI -4340

d_1	d_2	d_3	d_4	d_5
0.05	3.44	-2.12	0.002	0.61

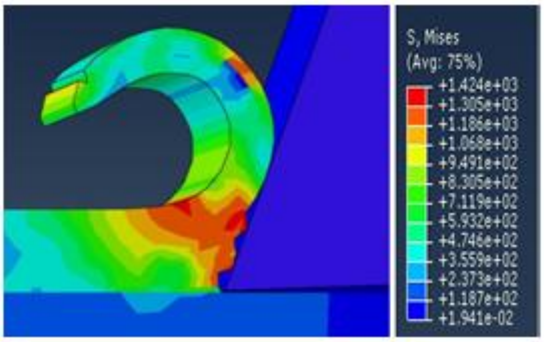
V. FINITE ELEMENT RESULTS AND DISCUSSION

A total of 9 simulation cases have been performed, which cover four rake angles and three friction coefficient values for each rake angle. This allows for a parametric evaluation of the effect of friction and rake angle on the stress and strain fields. The details of the simulation schedule are listed in Table 3.

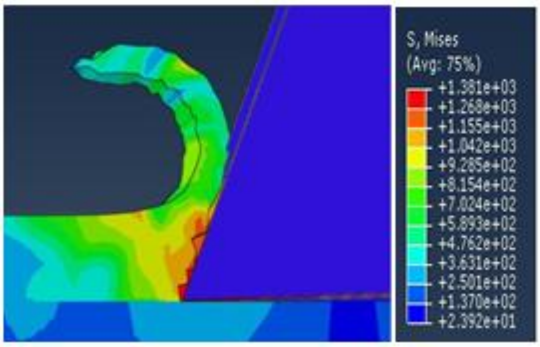
TABLE III. VARIATION INMACJINING PARAMETERS

Rake angle (α)	Depth of cut(t),(mm)	Cutting speed(v), (m/s)	Coeff. of friction(μ)
20°	0.05,0.1,0.15	2.54	0.4
25°	0.05,0.1,0.15	2.54	0.4
30°	0.05,0.1,0.15	2.54	0.4

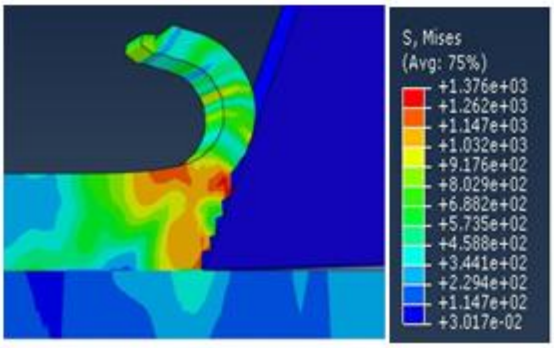
The von-Mises stress plots for the various rake angles and depth of cut are given below.



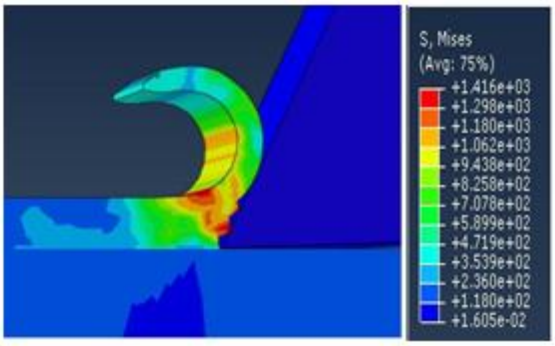
α=20°,t =0.05 mm



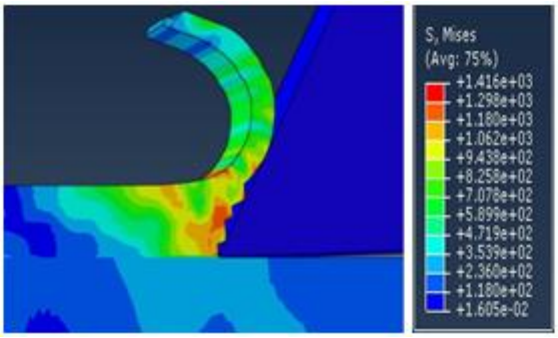
α=20°,t =0.1 mm



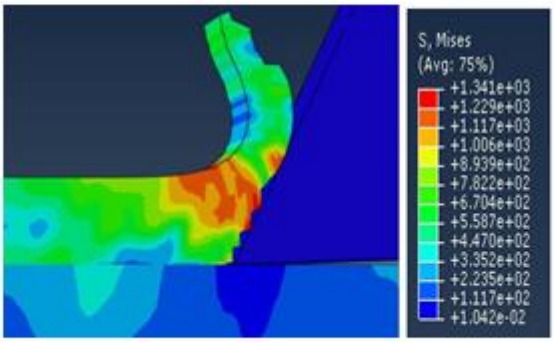
α=20°,t =0.15 mm



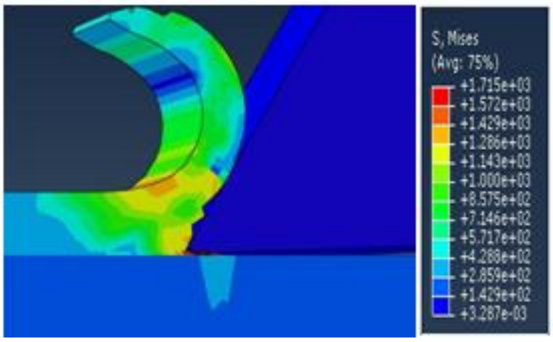
α=25°,t =0.05 mm



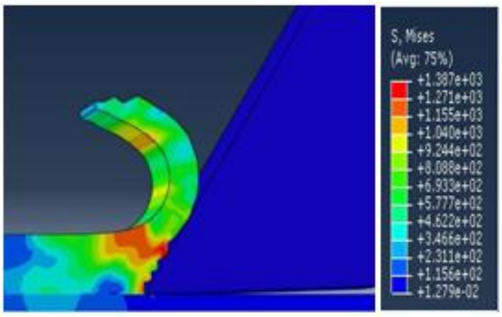
α=25°,t =0.1 mm



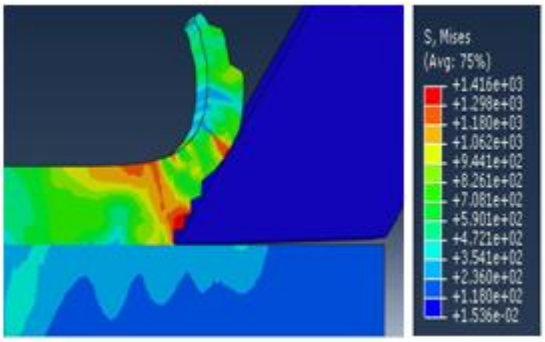
α=25°,t =0.15 mm



α=30°,t =0.05 mm



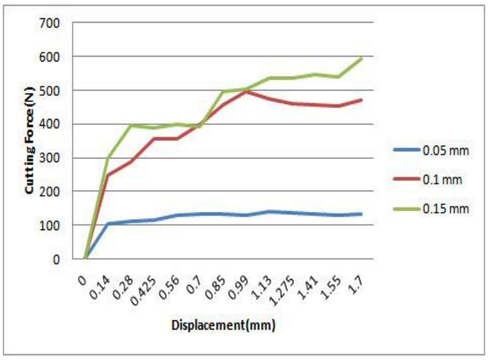
$\alpha=30^{o}$,t=0.1mm



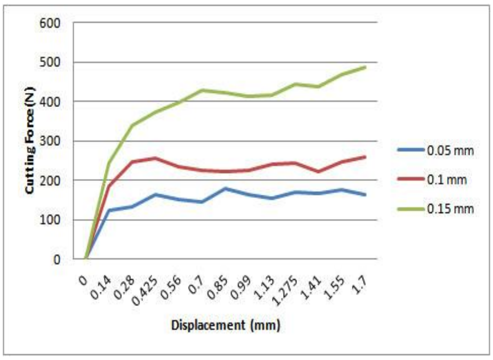
$\alpha=30^{o}$,t =0.15 mm

Fig 3. Plots of Von-Mises stress developed in the chip at various rake angles and depth of cut.

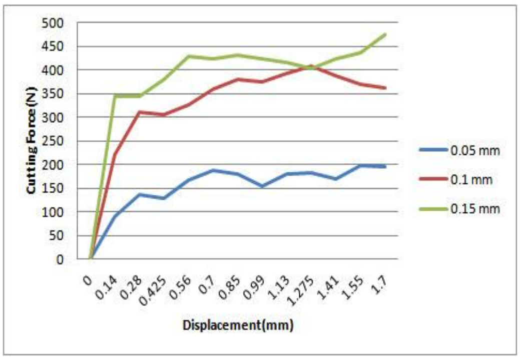
The von-Mises stress distributions in Fig 1 help us to observe the plastic flow behaviour. Upon close observation it can be seen that the stress contours are parallel to the tool chip ahead of the tool tip and aligned slightly towards the left in a forward direction. The peak contour is seen to connect the tool tip and the turning point on the chip's free boundary, forming the ``shear" angle (Shet and Deng) [1].



$\alpha = 20^{o}$



$\alpha = 25^{o}$



$\alpha = 30^{o}$

Fig 4. Variation of cutting force with varying rake angles and depth of cut

Fig 2 shows the variation of horizontal cutting forces with the tool tip displacement for varying rake angles and depth of cut. For each value of depth of cut, the cutting force is seen to increase with increase tool tip displacement. For each rake angle, the cutting force for a particular depth of cut is seen to decrease with tool tip displacement.

VI. CONCLUSION

Finite element simulations of the machining of AISI 4340 steel have been successfully carried out using the commercial FEA code ABAQUS/Explicit 6.11.Chip separation was properly simulated under dry friction condition. Steady-state finite element solutions for the cutting forces and von-Mises stress have been presented. This study shows that the simulation can be extended to parameters like friction and cutting speed and for various materials so as to optimise the machining process for that particular material.

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