

Finite Element Modelling of Chip Formation in Orthogonal Machining for AISI 1050

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Abstract: Finite element method has gained immense popularity in the area of metal cutting for providing detailed insight into the chip formation process. This report presents an overview of the application of finite element method in the study of metal cutting process. The basics of both metal cutting and finite element methods, being the foremost in understanding the applicability of finite element method in metal cutting, have been discussed in brief. In this project, thermo mechanical simulation of turning process has been developed using commercially available finite element analysis software, ABAQUS 6.10. A 2-D orthogonal cutting has been modelled using an Arbitrary Lagrangian - Eulerian (ALE) formulation. The Johnson-Cook plasticity model has been assumed to describe the material behaviour during the process. Adaptive meshing dynamic explicit is also employed in this model to avoid the severe deformation. This study is aimed at temperature and stresses distributions during machining of AISI 1050 steel with three different speed 120m/min, feed 0.1 mm/rev. and depth of cut 1.5 mm. The results showed for speed 120 m/min, feed 0.1 and depth of cut 1.5 that the maximum stress for -7°C rake angle is 1.35 GPa while the maximum temperature results shown that 699°C .

Keywords: Arbitrary Lagrangian-Eulerian (ALE); Adaptive Meshing; Dynamic Explicit; Finite Element Model; Johnson Cook (JC); Orthogonal Cutting; Thermo mechanical.

I. INTRODUCTION

Metal cutting involves large deformations and very high strain rates. During cutting, the chip is formed by deforming the work material on the surface of the job using a cutting tool. In this process, mechanical work is converted to heat through plastic deformation. The knowledge of basic mechanism of chip formation helps understanding the physics governing the chip formation process. This enables one to solve the problems associated with metal cutting so that the metal removal process can be carried out more efficiently and economically. In recent years, finite element analysis (FEA) has reached the major percentage among researchers to simulate the metal cutting processes. These models range from simplified analytical models to complex, computer-based models using Finite Element Method. FEM allows the coupled simulation of plastic and thermal process and is capable of considering numerous dependencies of physical constants on each other.

II. BASICS OF MACHINING

Metal cutting process involves various independent and dependent variables. Independent variables are the input variables over which the machinist has direct control. These include type of work piece material and tool material, shape and size of work piece material, cutting tool geometry, type of machining process, cutting parameters (speed, feed and depth of cut) and cutting fluids.

A. Orthogonal Machining:

In orthogonal cutting, also known as two-dimensional cutting, the cutting edge is perpendicular to the cutting velocity vector. Analysis of oblique cutting is much more difficult, so focus has been mainly given on the orthogonal cutting. The important theories based on orthogonal cutting model which have paved the way for the analysis of chip formation process include Merchant's model, Lee and Shaffer's model, Oxley's model etc.

B. Cutting Forces:

Cutting force is a result of the extreme conditions at the tool-work piece interface and this interaction can be directly related to many other output variables such as generation of heat and consequently tool wear and quality of machined surface as well as chip formation process. Cutting and Thrust force affects majorly while machining. These forces act on the cutting tool during machining process and can be measured directly using tool force dynamometers.

C. Heat Generation Zone:

Heat has a critical influence on machining process. It is found that almost all of the mechanical energy during machining is converted into heat during chip formation process that tends to increase the temperature to very high values in the cutting zone. The heating action is known to pose many of the economic and technical problems of machining. During machining heat is generated in the cutting zone from three distinct zones: Primary heat generation zone in shear plane (80-85%), Secondary heat generation zone in tool-chip interface (15-20%) and Tertiary heat generation zone (1-3%).

III. FINITE ELEMENT MODELLING**A. Geometry Modelling:**

Creating the geometry of the problem domain is the first and foremost step in any analysis. The actual geometries are usually complex. The aim should not be simply to model the exact geometry as that of the actual one, instead focus should be made on how and where to reduce the complexity of the geometry to manageable one such that the problem can be solved and analyzed efficiently without affecting the nature of problem and accuracy of results much. It is generally aimed to make use of 2D elements rather than 3D elements since this can drastically reduce the number of degrees of freedom (DOFs).

The work piece length was taken as 3 mm and its height as 1 mm. The cutting tool had a clearance angle of 6° , a rake angle of -7° , an edge radius of 0.08 mm, and a height 1mm and length 0.5 mm; the cutting speed V_C was set to 120 m/min. The model assembly in its initial state can be seen in Fig. 1.

As mechanical boundary conditions (shown in fig. 1), bottom of work piece is fixed in Y direction and left vertical edge of work piece is fixed in X direction. The former not only constrains the movement of work piece in the Y direction but also aids in calculating feed force during machining while the latter, not only constrains the movement of work piece in the X direction but also aids in calculating cutting force during machining. The reaction force components when added at all the constrained nodes of the left vertical edge of the work piece in X direction give the cutting force values while at bottom edge of the work piece in Y direction give the feed force. Tool is given the cutting velocity in negative X direction and top edge of the tool is constrained in Y direction. Similarly, as thermal boundary conditions the tool and the work piece are initially considered at the room temperature i.e. 25° .

Table I: Cutting Conditions

Cutting Speed, V (m/min)	120
Feed Rate, f (mm/rev)	0.1
Tool Rake Angle, α (degree)	-7°
Clearance Angle, γ (degree)	6°

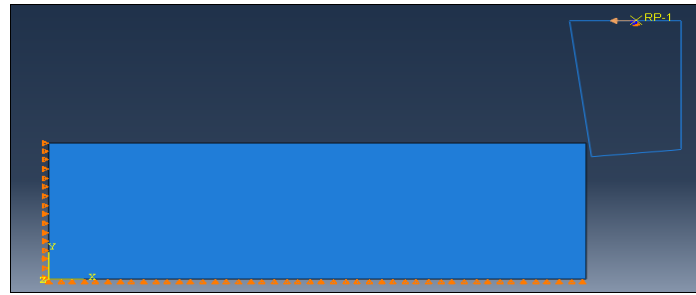


Fig. 1: 2D Geometric Model

B. Material Modelling:

AISI (American Iron and Steel Institute) 1050 is the work piece material of length 400mm and 60mm diameter. AISI 1050 was chosen as a reference material in the present study.

Table II: Material Chemical Composition

Size(mm)	%C	%Mn	%Si	%S	%P
Dia. 60	0.55	0.82	0.24	0.023	0.014

Table III: Thermo-mechanical Properties of Material AISI 1050

Properties	AISI 1050
Density, ρ (Kg/m ³)	8030
Elastic modulus, E(Gpa)	210
Poisson's ratio, μ	0.3
Specific heat, Cp(J/Kg °C)	472
Thermal conductivity, λ (W/m °C)	51.9
Expansion, ($\mu\text{m}/\text{m}^\circ\text{C}$)	13.7
T _{melt} (°C)	1460
T _{room} (°C)	25
Fracture toughness, K _{IC} (MPa m ^{1/2})	60
Conductive heat transfer coefficient h, (kWm ⁻² K ⁻¹)	10

Governing Equations:

1. Constitutive equation:

The work piece material was modelled as elasto-plastic with isotropic hardening and the flow stress defined as function of strain, strain rate and temperature, based on Johnson-Cook (JC) constitutive model [1]. Due to the large plastic deformation subjected in metal cutting process, the work piece material is subjected to strain hardening.

The JC constitutive equation is very useful to simulate mechanical processes involving high strain and strain rates, and thermal softening. It has been widely used to model cutting process as reported in. Johnson-Cook constitutive equation is one such model that considers the flow stress behaviour of the work materials as multiplicative effects of strain, strain rate and temperature, equation of flow stress is given as follows:

$$\bar{\sigma} = (A + B(\bar{\epsilon}^n))(1 + C \ln \dot{\bar{\epsilon}}^*) \left(1 - \left(\frac{T - T_{\text{room}}}{T_m - T_{\text{room}}} \right)^m \right) \quad (1)$$

Where,

T_{room} - Room temperature = 25 °C,

T_m - melting temperature of the work piece,

A - Initial yield stress (MPa),

B- Hardening modulus,

n- Work-hardening exponent,

C - Strain rate dependency coefficient (MPa),
m - Thermal softening coefficient.

A, B, C, n and m used in the model are actually the empirical material constants in eq. (1) that can be found from different mechanical tests. Johnson-Cook model has been found to be one of the most suitable one for representing the flow stress behaviour of work material undergoing cutting. Besides, it is also considered numerically robust as most of the variables are readily acceptable to the computer codes. This has been widely used in modelling of machining process by various researchers.

Table IV: Johnson-Cook Parameters

JC Parameters	Value
Yield stress, A(Mpa)	880
Hardening modulus, B(Mpa)	500
Strain rate dependency coefficient, c	0.013
Strain exponent, n	0.234
Thermal softening, m	1
Melting temperature(°c)	1460
Transition temperature(°c)	25

2. Chip Separation Criterion:

Chip separation criterion to separate the chip from the machined surface in an FE analysis, there are two commonly used criteria: one geometrical criterion and one equivalent plastic strain criterion. The geometrical criterion is convenient to use but its physical meaning is not well defined since the stagnation point has to be predetermined. Therefore an equivalent plastic strain criterion was used in the present study. According to this criterion, the material fails when the equivalent plastic strain reaches a critical value with the cumulative damage D given by,

$$D = \sum \frac{\Delta \varepsilon^p}{\varepsilon_f^p}$$

Where, $\Delta \varepsilon^p$ is the increment of the equivalent plastic strain and ε_f^p is the equivalent strain at failure. According to the Johnson-Cook model, $\Delta \varepsilon^p$ is updated at every load step and ε_f^p is expressed by,

$$\varepsilon_f^p = \left[D_1 + D_2 \exp D_3 \left(\frac{p}{\sigma} \right) \right] \left[1 + D_4 \ln \left(\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0} \right) \right] \left(1 + D_5 \frac{\theta - \theta_0}{\theta_{melt} - \theta_0} \right) \quad (2)$$

Where, P being the ratio of the hydrostatic pressure to the equivalent stresses. The values of the failure constants D1, D2, D3, D4, and D5 are 0.06, 3.31, -1.96, 0.018, and 0.58 respectively for AISI 1050. Failure will occur when the damage parameter D, given by equation (2), reaches unity. When this condition is met within an element, the stress components are set to zero and remain zero for the rest of the simulation [4].

C. Element Type:

A fully coupled thermal-stress analysis module of finite element software ABAQUS/Explicit version 6.10 has been employed to perform the study of chip formation process. This makes use of elements possessing both temperature and displacement degrees of freedom. It is necessary because metal cutting is considered as a coupled thermo-mechanical process, wherein, the mechanical and thermal solutions affect each other strongly. The element type used is four-node plane strain, thermally coupled quadrilateral bilinear displacement and temperature elements with reduced integration, linear geometric order, and hourglass control (in ABAQUS CPE4RT)[4]. Tool is considered as rigid wire type explicit model. Thus tool is taken as element type of R2D2.

D. Mesh Adaptivity:

Generally speaking, mesh adaptivity can be described as the capability of the mesh to adapt according to the nature of problem in order to maintain a high quality mesh throughout the analysis. The need of such technique becomes more evident while simulating problems that involve heavy mesh distortion such as in the case of cutting process undergoing large deformations.

This is well illustrated by citing an example which considers cutting process as a purely large deformation problem comprising a rectangular block as work piece and a portion of cutting tool fig.2 (a) shows the initial mesh configuration of the work piece while Fig. 2 (b) shows the deformed refined mesh configuration as tool comes in contact with the work piece.

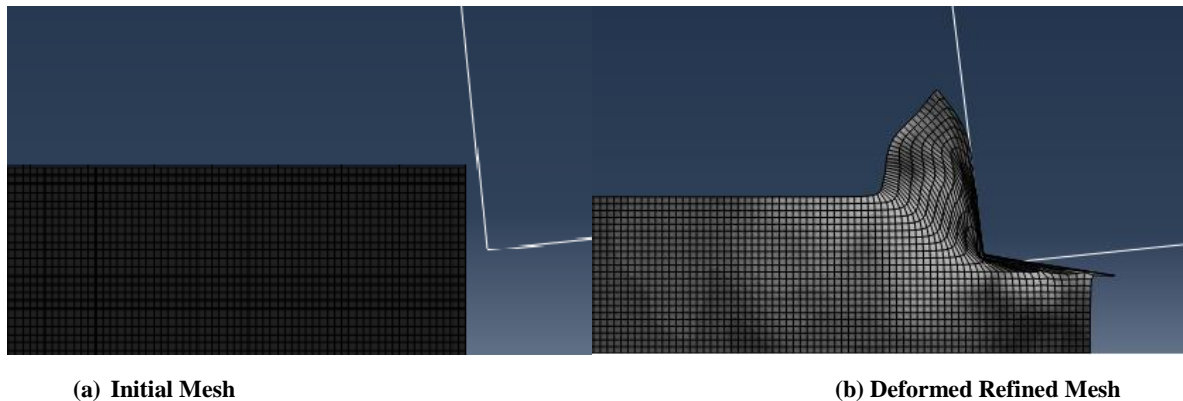


Fig. 2: Meshing of Work-piece

IV. ABAQUS SIMULATION

The type of software package chosen for the FE analysis of metal cutting process is equally important in determining the quality and scope of analysis that can be performed. There are large numbers of commercial software packages available. Some of the dominant general purpose FE software packages include ABAQUS, ANSYS, MSC/NASTRAN, SRDCIDEAS, etc. The present study selects ABAQUS as a platform to explore the capabilities of finite element method in analysing various aspects of metal cutting process. ABAQUS is known to be powerful general purpose FE software that can solve problems ranging from relatively simple linear analyses to the highly complex non-linear simulations. It is said that the strength of ABAQUS program greatly lies in the capabilities of these two solvers.

- Pre-processing Abaqus/CAE (Preprocessing) - Output file (.inp)
- Analysis - Abaqus/Standard or Abaqus/Explicit - Output file (.odb)
- Post-processing Abaqus/CAE or Abaqus/Viewer.

The subsequent subsections would discuss about various modules of ABAQUS/CAE in brief.

Part module: Individual parts are created in the part module either by sketching their geometry directly in Abaqus/CAE or by importing their geometry from other geometric modelling programs.

Property module: Property module allows assigning sections to a part instance or region of a part instance to which various material properties are defined. A material definition specifies all the property data relevant to a particular analysis.

Assembly module: The individual parts that are created in part module exist in their own coordinate system. It is in the assembly module that these parts are assembled by relative positioning with respect to each other in a global coordinate system.

Step module: The step module is used to create and configure analysis steps, as in the present case is coupled temperature displacement explicit dynamic analysis. The associated output requests can also be created.

Interaction module: Interaction module allows specifying mechanical and thermal interactions between regions of a model or between a region of a model and its surroundings. Surface-to-surface contact interaction has been used to describe contact between tool and work-piece in the present study.

Load module: The Load module is used to specify loads, boundary conditions and predefined fields.

Mesh module: The Mesh module allows generating meshes on parts and assemblies created within ABAQUS/CAE as well as allows selecting the correct element depending on the type of analysis performed (as in the present case is CPE4RT) for discretization.

Visualization: The Visualization module provides graphical display of finite element models and results. It extracts the model and result information from the output database.

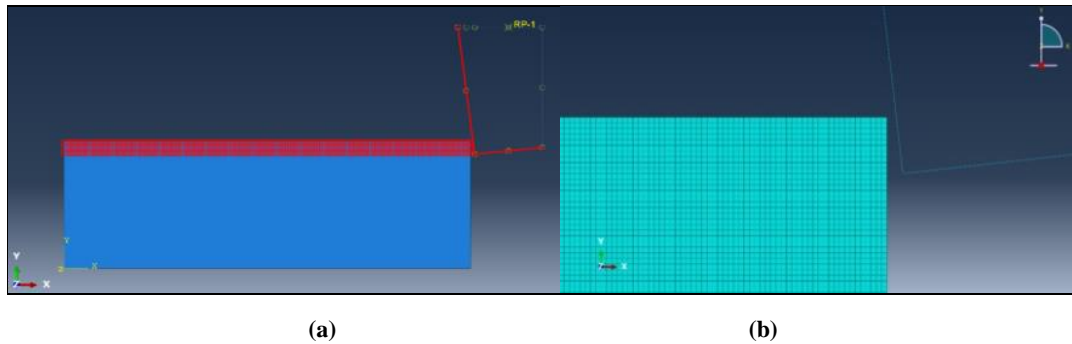


Fig. 3: Interaction (a) and Meshing (b) of Tool-Work piece Assembly

V. SIMULATION RESULTS

Figure 4 shows the distributions of stress (a), temperature (b), cutting forces (c) and thrust forces (d) while machining of AISI 1050 using uncoated carbide tool for a cutting speed of 120 m/min and feed of 0.1 mm/rev.

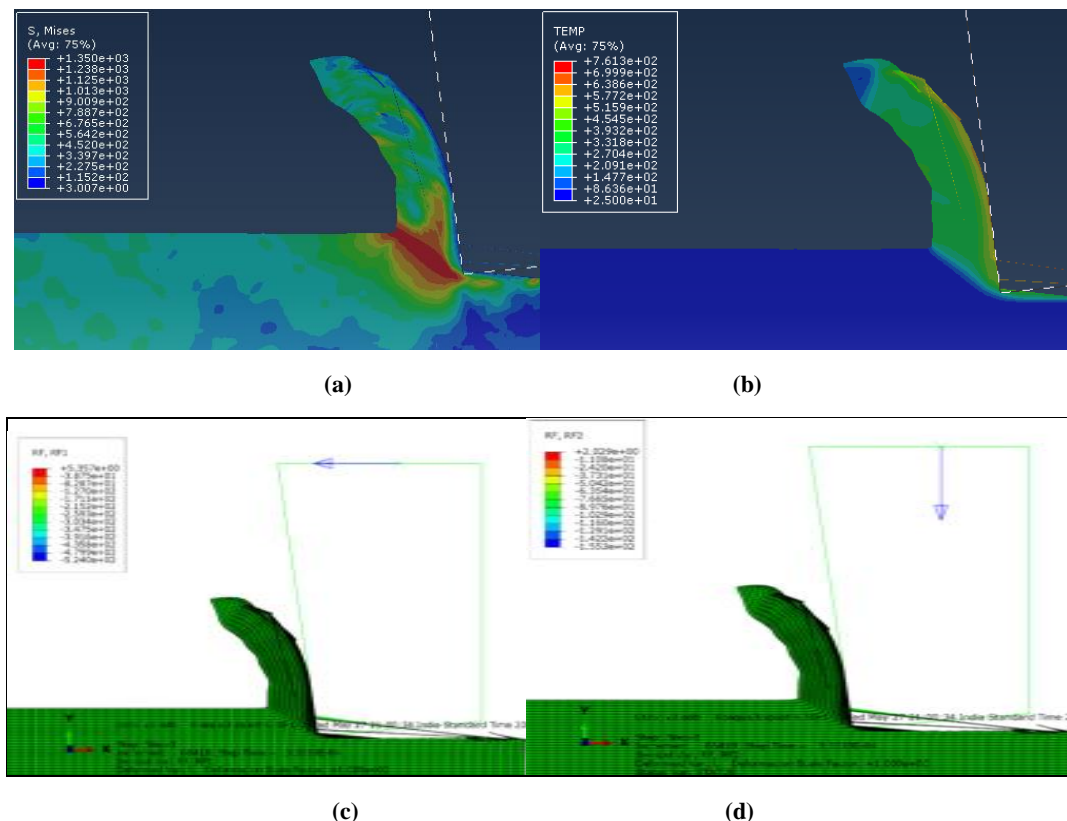


Figure 4: Distribution of stress (a), temperature (b), cutting forces (c) and thrust forces (d)

The stresses in shear plane region is as high as 1.35 GPa. is shown in simulation viewport fig 4 (a) and the maximum temperature is found along the tool–chip interface i.e. 699.9°C is shown in simulation viewport fig 4 (b). Cutting force has maximum magnitude of 524 N as shown in simulation viewport in fig. 4 (c) and thrust force has maximum magnitude of 155.3 N, shown in simulation viewport in fig. 4 (d).

VI. CONCLUSION

1. The maximum interface temperature exists in the vicinity of the cutting edge i.e. part of the tool-chip contact.
2. The maximum stress is occurred in the shear plane of the work piece.
3. The machining is safe for given feed, cutting velocity and depth of cut (i.e. stress, strain values are within permissible limit, so failure does not occur).
4. Continuous chip is formed during operation under these parameters.

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