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An investigation of the chip formation process by applying Finite Element Method in orthogonal machining

Arvind kaushal[1], Ajay vardhan[2], R. S. Rajpoot[3], S. K. Saluja[4]
[1]Contract lecturer Deptt. Of mechanical engineering I. G. E. C. SAGAR (MP)
[2] M-tech scholars, [3]Professor mechanical engineering
[4]Associate professor Deptt. Of mechanical engineering I. G. E. C. SAGAR (MP)

ABSTRACT:- In present scenario , metal cutting is the most famous and widely used manufacturing technique, whose aim to predict the various variable such as cutting speed ,feed , temperature etc. there are so many investigation is performed on this technique in the academic and industrial candidates in order to predict .distribution of temperature ,type of chips & forces associated with the process also, if these variable calculated experimentally then it is very time consuming & very expensive , these variable could be predicted without doing any experiment A new tool is employed in processing the metal cutting which acronymed by F. E. M. (finite element method) in present , the work is carried out for two- dimensional orthogonal machining which was applied and its analysis is done by FE method for both continuous aswellas segmented chip , machining is performed on EN-24 alloy tool steel by carbide cutting tool , then finite element software ABAQUS/Explicit used for simulating the model for continuous & segmented chips both . The numerical aspect of this analysis deals with the distribution of developed stress, strain rate, temperature distribution, associated forces, and the result also compared with experimental result.

Keyword:- FE modeling & simulation, orthogonal machining, continuous chip, segmented chip, FE software code

I. INTRODUCTION

Metal machining is the process of removing foreign material from a block of metal to get desired shape & size as per design specification of the article, removed part of the metal comes out in the form of chips due to the effect of relative motion of wedge shaped tool, however, the knowledge of the process of chip formation is required for understanding the behavior of chips & new work-surface (1) . The formation of chips is main constitute of whole mechanism & integral part, whose study is performed in mechanics of machining process. The mechanism of metal cutting process has been studied since the early of 1940s and various models were proposed by various authors, researchers & scientist. Ernst and merchant(2) and merchant (3,4) develop a model that well known as orthogonal cutting and known as straight-edge cutting moving relative to the work-piece in a direction perpendicular to its cutting edge this model gives a clear vision of three parameter of machining , as shear plane angle(ϕ) , tool rake angle (α) , coefficient of friction (μ) between chip & tool face .figure -1 showing the orthogonal machining process . The complexity of chip formation in machining process includes of several physical phenomenon like mechanical, thermal & chemical, the prediction of chip morphology depends upon a fundamental understanding of these phenomenon accurately In addition to information regarding cutting process, behavior of chips, behavior of work-piece material properties. cutting condition. The main chip morphologies observed in cutting process are continuous and cyclic or segretted chips.

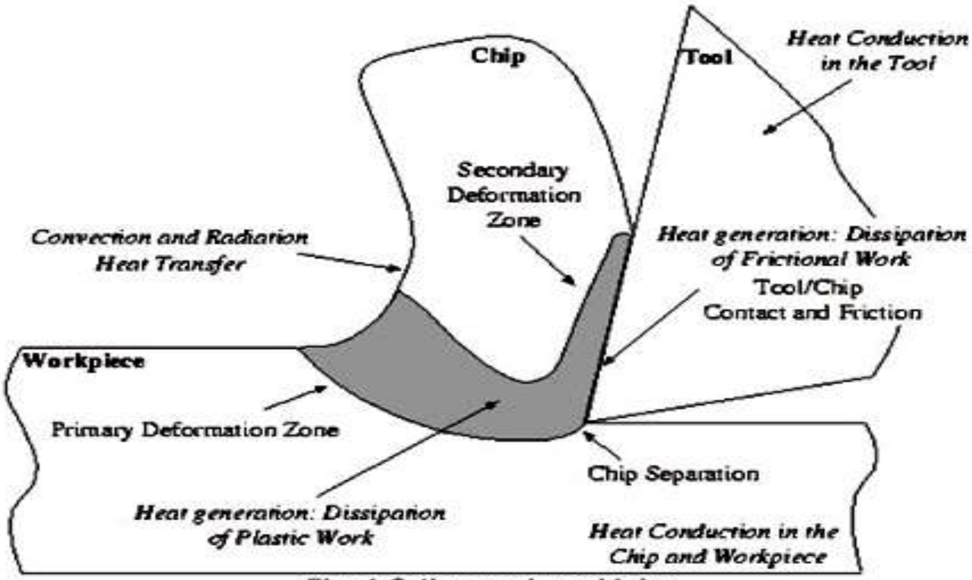

Fig. 1 Orthogonal machining

Basically, various parameters , like cutting forces, temperature, tool wear, machining power , friction between tool- chip interface and surface finish is directly influence the chip morfology .for economical & effective machining operation , process simulation performed , various analytical & numerical model in order to predict the optimum cutting condition , if accurate model is considered the optimal process parameter can be calculated , since we livng in technological ages , having various types of tools & techinique is available for supporting and solving the complicated task like computer is greater invention of science containing a commercial software packages. Finite element method application has effective and power tool for for simulating and analyzing the metal cutting proces ,this predict to permits all the parameters associated with process very effectively and accurately which is time saving and cost saving method it also gives information regarding material properties and non- linearity better then analytical analyses . In this research work a finite element method simlation method for chip formation process is used to investigating about continuous & segmented chip by FE- software ABAQUS/Explict, at very initial stage of machining the metal cutting process takes place and continuous chip is formed ,during the course of segmentation of chip shearing achieved called adiabatic shearing and model is constructed for both fe model help in investigating the speed and the evalution of various parmeter associated with metal cutting operation like sterss, the strain, foces that acts , temperature distribution also

II. LITERATURE REVIEW

A literature review is a heart beat of any operational process which associated with the previously invented technique , that is proposed by various industrial candidate , researchers , scientist and scholers of concernd technological process .following are very important review & prestigious thoghts regarding the metal cutting process .

Pioneering work in analyses of metal cutting by using FEM hasbeen carried out by Klameekr [1973] and Tay et. al. [1974] generally , application of finite element modelling to cutting process involve Eulerian , lagrangian or Arbitrary Lagrangian Eulerian [ALE] formulation , in eulerian apporach the reference frame is fixed in space that allows for the material to flow through the grid [Raczy et al , 2004] as the mesh is fixed in the space , the numerical difficulties associated with the distortation of element are eliminated further also reduced to lagrangian form on free boundary where deformation occurs . to overcome various difficulty in machining processes the scholers of all over the world applying many software package of FEM like , NIKE-2D , DEFORM, FORGE-2D , ABAQUS /standard , ABAQUS/Explict , ANSYS / LS-DYNA, ALGOR and FLUENT

Shih [4] developed a model to analyses the orthogonal metal cutting with continious chip formation , using a eulerian description , shih found that the lack of complete material properties and friction parameters directly influnced the accuracy of finite element simulation also, shih [5] studied the effect of the rake angle in the cutting processes . kalhori [6] investigated different modeling apporaches for the chip seperation, the physical model of chip formation was found to be more suitable in simulation according the notion

Stevenson , wright and chow [7] developed the finite element program for calculating the temperature distribution in the chip and tool in metal cutting they compare the temperature estimated with the temperature obtaind with previously described metallographic method . stevenson assumed that the form of the chip and cutting tool initially and then obtained the required parameter from the without simulating the separation of the chip for the current cutting condition.

Iwata , osakada and terasaka [8] develop a rigid- plastic finite element model for orthogonal cutting in a steady state condition, the method for determining the material and frictional properties to be used in the model are discussed , the shape of the chip and distribution of the stress and strain are calculated fracture of the chip is predicted by ductile fracture. In this work, an initial model is generated by giving the cutting condition and the shape of the cutting tool , and then the model is modified by using the result of the plan strain finite element analyses.

Kompvopolos and Erpen beck [9] modelled orthogonal chip formation process by using finite element method , they analyzed the effect of important factors plastic flow of work piece material , frictioon at the tool-work piece interface and wear of tool on the cutting process. To simulate separation of chip from the work-piece distance tolerance criterion was used by super positioning two nodes at each nodel location of the parting line of initial mesh elastic , perfectly plastic and elastic-plastic with isotropic strain hardening and starain rate sensitivity constitutive law was used in the analyses .

Strenkowaski and carrol [1985] introduced the chip separation criterion based on the effective plastic at the node nearest to the cutting edge, arbitrary lagrangian eulerian [ALE] apporach was introduce by the end of the last decades which takes best part of both the formulation [obikawa et al. 1997]

Olovsson et al. [1999] stated that implementation of ALE into the special purpose computer code Exhale -2D allowed flow boundary condition where by a small part of the work-piece in the vicinity of tool tip needs to be modelled movaheddy et al.[movahhedy et al.2008] presented the ALE model for continuous chip to study the effect of tool edge preparation .

Attanasion et al.[2008] predicted flank wear and crater wear evolution by utilizing an ALE numerical simulation of turning operation on AISI-1045 tool steel by uncoated WC tool. From the recent review of machining process modeling authored by EHMANN et al. [8] , generally the gist of current research in modelling the mechanism of machining process are emphasized on chip formation investigate , distribution of stress, strain, strain rate, temperature and residual stress with majority assumption the cutting tool is rigidbody.

1. Model formulation

For a problem solution right formulation must be chosen to describe FE mesh associated with the workpiece material. There are four main formulations: Lagrangian, Eulerian, arbitrary Lagrangian-Eulerian (ALE) and the SPH method. In this work arbitrary lagrangian euler method is applied for modeling

Arbitrary Lagrangian-Eulerian (ALE) formulation:- The ALE formulation is an extension of the Lagrangian formulation that, with additional computational steps, moves the grid and remaps the solution onto a new grid. One advantage of this technique is that the freedom in dynamically defining the mesh configuration so allows a combination of the best features of Lagrange and Eulerian. For metal cutting simulations, the Eulerian approach is convenient for modeling of the area around the tool tip, while the Lagrangian approach can be used for modeling the unconstrained material flow at the free boundaries [Özel 2005, Guo 2004, Movahhedy 2000, Pantalé 2004].

2.1 WORK MATERIAL MODELING:-

Accurate and reliable flow stress models are considered highly necessary to represent work material constitutive behavior under high-speed cutting conditions especially for a new material. The constitutive model proposed by Johnson and Cook [28] describes the flow stress of a material with the product of strain, strain rate and temperature effects that are individually determined as given in Equation (1). In the Johnson-Cook (JC) model, the constant *A* is in fact the initial yield strength of the material at room temperature and a strain rate of 1/s and ε represents the plastic equivalent strain. The strain rate ε& is normalized with a reference strain rate ε&0 . Temperature term in JC model reduces the flow stress to zero at the melting temperature of the work material, leaving the constitutive model with no temperature effect. In general, the constants *A*, *B*, *C*, and exponents *n* and *m* of the model are fitted to the data obtained by several material tests conducted at low strains and strain rates and at room temperature as well as split Hopkinson pressure bar (SHPB) tests at strain rates up to 1000/s and at temperatures up to 600 °C. JC model provides good fit for strain-hardening behavior of metals and it is numerically robust and can easily be used in FEM simulation models. Many researchers used JC model as constitutive equation for high strain rate, high temperatures deformation behavior of steels (see equation 1 & Table 1).

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

STEEL	REF.	A (MPa)	B (MPa)	n	c	m
AISI - 4340	29	950.0	725.0	0.375	0.015	0.625
AISI - 4340	30	792.0	510.0	0.26	0.014	1.03
AISI - 1045	31	553.1	600.8	0.234	0.013	1.000
EN-24T	---	700.0	508.0	0.24	0.09	1.002

Table 1. Johnson-Cook model constants for various steel

A dilatation of the element is based on the value of equivalent plastic strain at element integration points. Failure is done when damage parameter *D* exceeds one element. The damage parameter follows a cumulative damage law and is given by equation (2) is the increment of the equivalent plastic strain during an integration cycle and the equivalent strain to

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

$\Delta\bar{\varepsilon}^p$ is the increment of the equivalent plastic strain during an integration cycle and the equivalent strain to fracture under current conditions of strain rate, temperature, pressure and ε^f equivalent stress, see equation (3) [Johnson 1985].

$$\varepsilon^f = \left[D_1 + D_2 \exp\left(D_3 \frac{p}{q}\right)\right]\left[1 + D_4 \ln\left(\frac{\dot{\bar{\varepsilon}}^p}{\dot{\varepsilon}^0}\right)\right]\left[1 + D_5\left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Where *p* is the pressure stress, *q* is the Von Mises stress and the failure constants are *D1–D5 as given below in table (2)*

A(Mpa)	B(Mpa)	n	m	D1	D2	D3	D4	D5	C
700	508	0.24	0.89	0.05	3.12	-2.13	0.003	0.42	0.092

III. MODELS OF CHIP FORMATION

There are several possibilities how this state of material can be implemented into the FEM algorithm. Three most often used methods are presented below: Adaptive meshing – during crack propagation a new mesh is created around the moving crack tip. All parameters have to be obtained for the new mesh and it leads to long computation time [Özel 2005, Yen 2004, MacGinley 2001, Guo 2004].

IV. FINITE ELEMENT MODELING AND MESHING

The essential and desired attribute of the FEM models for cutting is the work material model should satisfactorily represent elastic plastic and thermo-mechanical behavior of the work material deformations observed during machining process, In this paper, a commercial software code, ABAQUS/Explicit v6.7-4 and explicit dynamic ALE modeling approach is used to conduct the FEM simulation of orthogonal cutting considering, in the cutting operation , heat transfer is depends upon cutting velocity , high local heat generation doe not dissipated to atmosphere by conduction due very short period of time in process or very closeness of process thus it is a behave like a adiabatic process and hence formation of shear bands in takes place whose analyses is made which is responsible for saw- design teeth . the proper visualization of continuous & segmented chip formation, , the chip formation is simulates via adopted meshing technique .. This technique consists the features of pure Lagrangian analysis in which the mesh follows the material. Figure .(2) represent the meshing of tool & wok piece & figure (3) gives details of

2D quadrilateral element

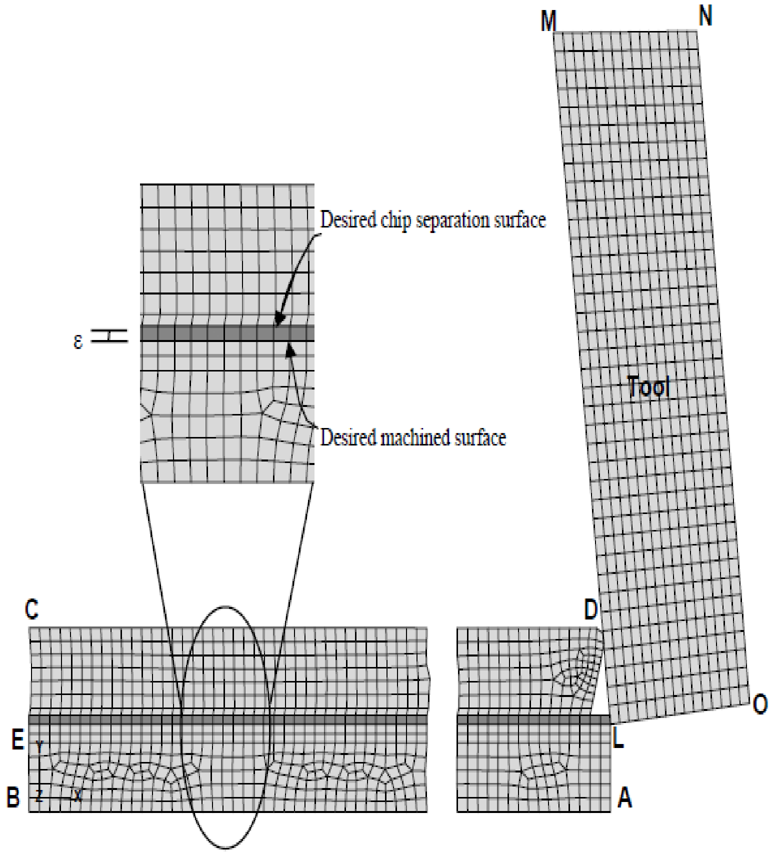

Figure.2. Geometric meshing configuration of tool & work piece

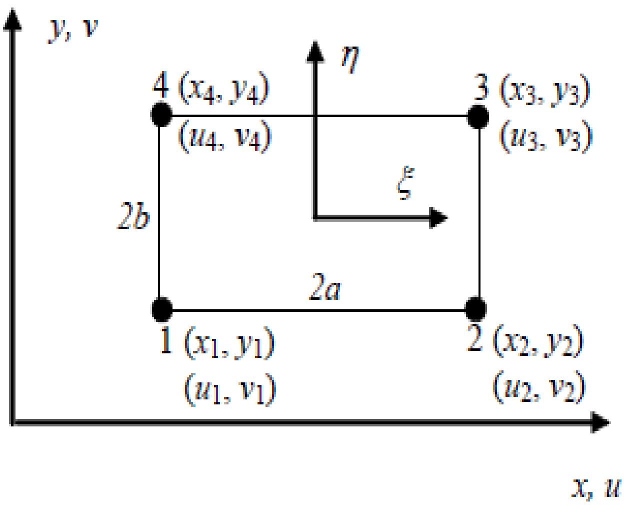

Figure.3. 2D quadrilateral element details

Four-node plane strain bilinear quadrangle (CPE4RT) elements with reduced integration scheme and hourglass control are used for the discretization for both the work piece and the cutting tool. The work piece is meshed with 2172 CPE4RT type elements by unstructured grid generation which utilizes advancing front algorithm in ABAQUS/Explicit.

4.1 Cutting tool :- Cutting tool is modeled with a with a negative rake angle , clearance angle is about 6 a complete details of cutting tool & work piece is given below in table (3)

Description	Orthogonal cutting parameter	Adopted value
Cutting tool geometry	Rake angle Clearance angle	-8 6
Work piece geometry	Length in (mm) Width in (mm) Damage zone width(mm)	15 0.3 0.02
Cutting parameter	Feed (mm) Cutting velocity (v)	0.2 110

The element geometry and displacement field are defined in terms of nodal coordinates and DOF by the following functions

$$\begin{cases} x = \sum_{i=1}^{4} N_i(\xi,\eta)x_i \\ y = \sum_{i=1}^{4} N_i(\xi,\eta)y_i \end{cases} \qquad \begin{cases} u = \sum_{i=1}^{4} N_i(\xi,\eta)u_i \\ v = \sum_{i=1}^{4} N_i(\xi,\eta)v_i \end{cases} \qquad \Rightarrow \mathbf{u}=\mathbf{Nq}$$

where

x_i, y_i = global x-y coordinates at i-th node

u_i, v_i = displacements at i-th node along global X, Y axes, respectively

$N_i(\xi,\eta)$ = interpolation or shape function for i-th node defined in the natural coordinates

ξ_i, η_i = natural coordinates of the i-th element node

The nodal interpolation function $N_i(\xi,\eta)$ for quadrilateral elements is of the form (Liu & Quek, 2003):

$$N_i(\xi,\eta) = \frac{1}{4}(1+\xi_i\xi)(1+\eta_i\eta) \text{ for } i = 1,2,3,4$$

The strains at any point within element can be expressed as follows:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial v}{\partial y}+\frac{\partial u}{\partial x} \end{bmatrix} = \begin{bmatrix} \frac{\partial}{\partial x} & 0 \\ 0 & \frac{\partial v}{\partial y} \\ \frac{\partial}{\partial y} & \frac{\partial}{\partial x} \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} \frac{\partial}{\partial x} & 0 \\ 0 & \frac{\partial v}{\partial y} \\ \frac{\partial}{\partial y} & \frac{\partial}{\partial x} \end{bmatrix} \begin{bmatrix} N_1 & 0 & N_2 & 0 & N_3 & 0 \\ 0 & N_1 & 0 & N_2 & 0 & N_4 \end{bmatrix} \begin{bmatrix} u_1 \\ v_1 \\ \vdots \\ u_2 \\ v_3 \end{bmatrix} \quad (3)$$

$$\therefore \varepsilon = \mathbf{du} = \mathbf{dNq} = \mathbf{Bq} \quad (4)$$

where $\mathbf{B}$ = strain-displacement matrix and $\mathbf{q}$ =vector of nodal displacements.

Finally the stress- strain relationship becomes

$$\sigma = \mathbf{D}\varepsilon = \mathbf{DBq} \quad (5)$$

where $\mathbf{D}$ is the elasticity matrix defining the mechanical properties of the material in terms of the Young's modulus and the Poisson's ratio.

4.2 Boundary condition:-

For the simulation of cutting operation, kinematic boundary conditions are given below –

For the workpiece:

$$u_y = 0 \text{ on AB}, u_x = 0 \text{ on BC}, v_x = V_c \text{ on ABEF}$$

where v_x is the velocity in X-direction, V_c is the cutting velocity, and AB, BC and ABEF refer to edges in Figure1.

For the cutting tool, boundary conditions on sides ON and MN in Figure1 are:

$$u_x = 0 \text{ on ON}, u_y = 0 \text{ on MN}$$

The thermal boundary conditions are given below , In case of adiabatic analysis

$$\frac{\partial T}{\partial n} = 0 \qquad \text{………………………………………….. (6)}$$

The convective heat transfer boundary conditions, with the overall heat transfer coefficient (*h*) , thermal conductivity (*k*) and ambient temperature (*o T)* given as

$$-k\frac{\partial T}{\partial n} = h(T_o - T) \qquad \text{…………………………………………..(7)}$$

In the present work, simulations at a particular speed-feed combination were done for *h* varying within a range of 100-1000 kW/m2 K. Since the difference in temperature was found to be very less with the change in heat transfer coefficient, *h* = 500 kW/m 2 K was considered as a fair compromise. Moreover, this value has also been used by Coelho (2006) for machining EN-24T alloy steel and thus, taken as the reference value for the entire set of simulations.

4.3 Thermo-mechanical properties of work piece and cutting tool

The physical properties of the EN-24T Alloy steel work piece and the tungsten carbide cutting tool such as, density (ρ), Elastic modulus (*E*), Poisson's ratio (ν), specific heat (*p C*), thermal conductivity (*k*) and thermal expansion coefficient (α) are mentioned in Table 3 (Ozel & Zeren, 2006). *Table 4. Work piece and cutting tool properties* (Ozel & Zeren, 2006)

Material	□ **(kg/m3)**	***E*** **(GPa)**	□ **Poission ratio**	***C*** **(J kg□1 K□1)**	***k*** **(W m□1K□1)**	□ **(□mm□1K□1)**
AISI 4340	7850	205	0.30	475	44.5	13.7
CARBIDE TOOL	11900	534	.022	400	50	----
EN-24 T	7700	200	.015	428	38.6	----

When the thermal conductivity of the work piece material was considered in the coupled temperature displacement analysis, continuous chips were obtained in contrast to the previous section where segmented chips, as found experimentally (Belhadi et al., 2005), were produced under the same cutting conditions. Figure (4) shows the deformed finite element mesh for the continuous chip formation & segmented chip.

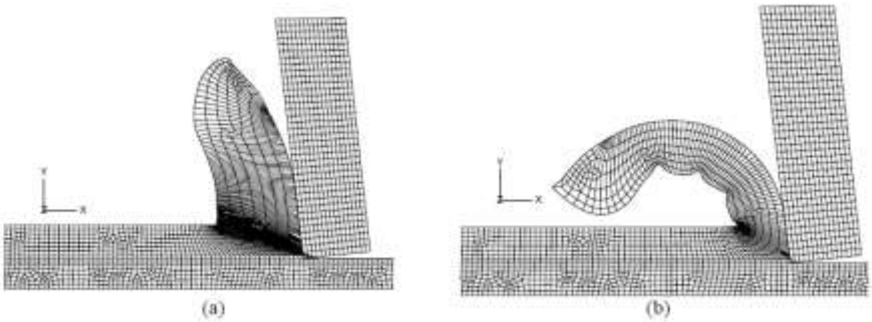

Figure.4. continuous chip formation & segmented chip

Since adiabatic conditions allow maximum amount of heat to be retained on the chip surface, adiabatic shearing was very prominent; thus reproducing saw-teeth due to thermal softening on the back of the chip. Following Figure. (5) & Figure. (6) Clearly depict the variation in distribution of equivalent von Mises stresses, equivalent strain and the temperature over the chip surface when the chip morphology changes

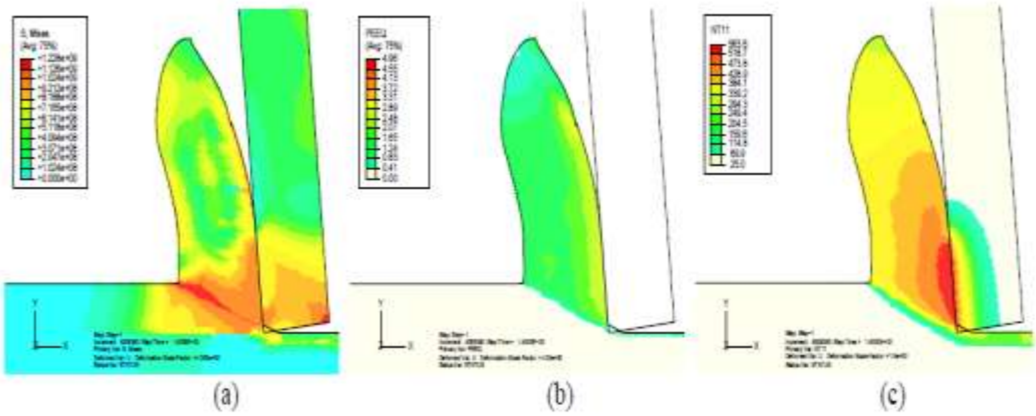

Figure 5.(a) von Mises equivalent stresses, 5(b) von Mises equivalent strains and 5 (c) Temperature distribution (°C) for continuous chip formation

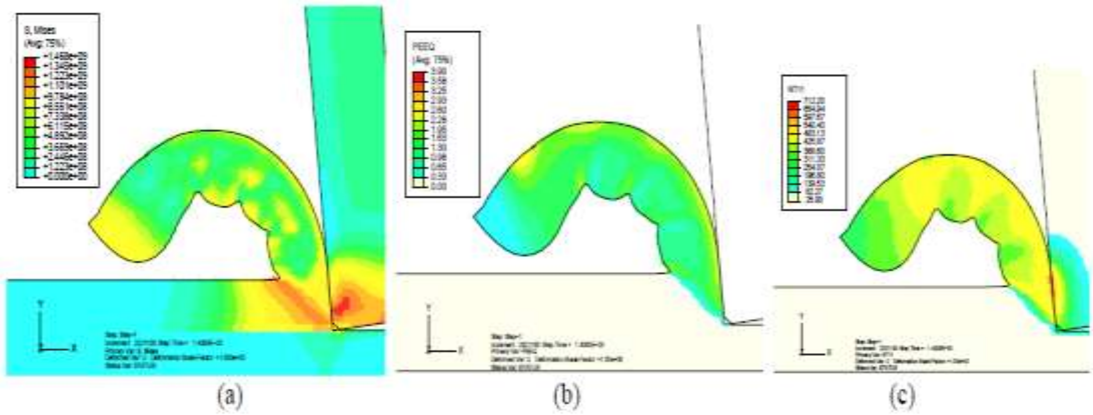

Figure 6 (a) von Mises equivalent stresses (Pa), 6 (b) von Mises equivalent strains and 6 (c) Temperature distribution (°C) for segmented chip formation

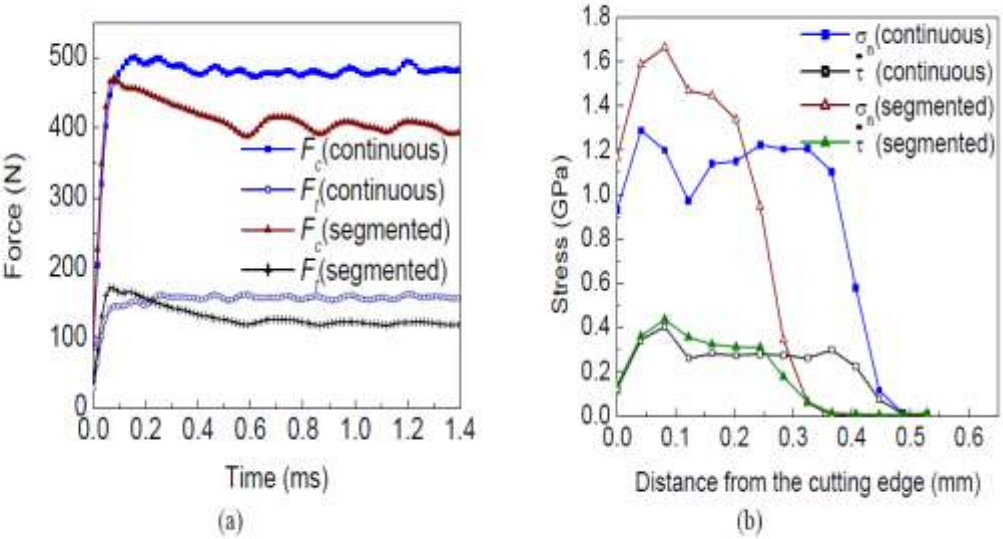

Figure 7.(a) Evolution of c F and t F over time and 7.(b) Distribution of □ and □on the surface rake for continuous and segmented chip formation

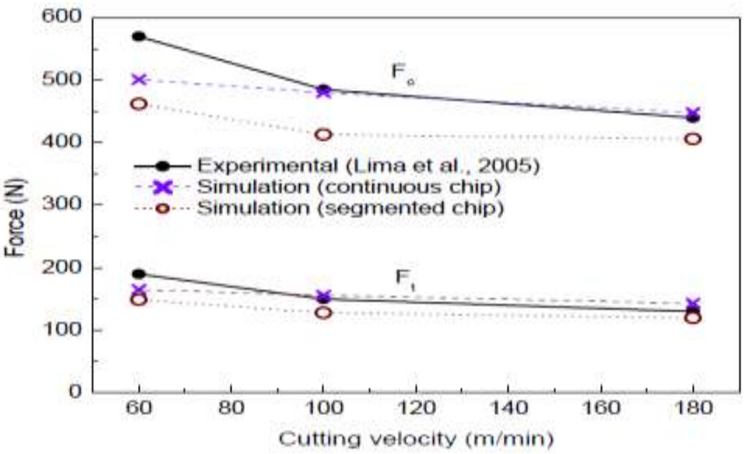

Figure 8. predicted forces during simulation of continuous and segmented chip

5. Result and Conclusion

A two-dimensional model for orthogonal cutting has been developed and simulation is performed by finite element method by finite element software ABAQUES/explicit. for a work-piece of tool steel EN-24T ,a segmented chip formation takes place due to thermal softening , and hence adiabatic shearing of metal is achieved during this course of time temperature region is very high and thus segmented chip of saw –design teeth is generated , at very initial stage continuous chip is formed & due to effect of back high temperature segmentation of chip is started , highest temperature occurs only tool-chip interface during continuous chip ,temperature affects the stress value then it also vary the strain consequently we can also predict the residual stress , cutting temperature, cutting forces associated with the machining we also observed that there is a close relationship between type of chip & cutting forces .the knowledge of cutting forces also support to calculating the power consumption , design of tool , cutting tool geometry , and concentrate a future aspect in order to optimize the cutting process, the experimental result and simulated result having a best correlation for high cutting speed .

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