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MODELLING AND SIMULATION OF METAL CUTTING BY FEM

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ABSTRACT

Metal cutting is one of the most widely used manufacturing techniques in the industry and there are lots of studies to investigate this complex process in both academic as well as industrial world. Predictions of important process variables such as temperature, cutting forces and stress distributions play significant role on designing tool geometries and optimizing cutting conditions.

Researchers find these variables by using experimental techniques which makes the investigation very time consuming and expensive. At this point, finite element modelling and simulation becomes main tool.

These important cutting variables can be predicted without doing any experiment with finite element method. This covers a study on modelling and simulation of orthogonal metal cutting by finite element method.

For this purpose, orthogonal cutting simulations of steel are performed and model used in simulations is validated. At first step, effects of work piece flow stress and friction models on cutting variables such as cutting forces, chip geometry and temperature are investigated by comparing simulation results with experimental results available in the literature. Then, mechanical and thermal analyses are performed. Lastly, effects of rake angle and tool tip radius on strain, temperature and stress distributions are investigated.

1. INTRODUCTION

Machining is one of the most widely used production technique in industry for converting preformed blocks of metal into desired shapes with surface quality and dimensional accuracy. The experimental approach to study machining process is expensive and time consuming especially when a wide range of parameters included like tool geometry, materials, cutting conditions and so on. Because of these difficulties alternative approaches developed as mathematical simulations where numerical methods are used. Among these numerical methods, finite element method is proved to be useful and widely used. Finite element method is basically defined as dividing a continuum system to small elements, describes element properties as matrices and assembles them to reach a system of equations whose solutions give the behavior of the total system. Finite element method has a great use in modelling orthogonal (2D) and oblique (3D) metal cutting. **Klamecki (1973)** developed one of the first finite element models for metal cutting processes by using an updated Lagrangian elasto-plastic three dimensional model which was limited to the initial stages of chip formation. **Usui and Shirakashi (1982)** developed the first two dimensional FE orthogonal machining simulation by using a special method of computation called the iterative convergence method to obtain solutions for steady state cutting. **Iwata, et al. (1984)** developed a method of numerical modelling for plane strain orthogonal cutting in the steady state on the basis of the rigid-plastic material model where temperature effects were neglected.**Strenkowski and Carroll (1985)** developed a numerical model for orthogonal cutting without a preformed chip. Their model was based on a large deformation updated Lagrangian code. **Lin and Lin (1992)** introduced a chip separation criterion using the argument of strain energy, and investigated the chip geometry, the residual stresses in the machined surface, the temperature distributions in the chip, the tool and cutting forces. **Ceretti (1996)** developed a cutting model by deleting elements having reached a critical value of accumulated damage. With the developments of hardware and commercial FE codes, modelling limitations and computational difficulties have been overcome to some extent, so many researchers focused on special topics of metal cutting. **Bil, et al. (2004)** compared three commercial FE codes used in 2D metal cutting simulations, **Özel (2006) and Filice, et al. (2007)** used Deform 2D to investigate the effects of different friction models on cutting results. **Attanasio, et al. (2008)** included an advanced approach to model heat transfer phenomena at the tool-chip interface in the numerical simulation to investigate tool wear by using Deform 3D. **Davim and Maranhao (2009)** used Msc Marc to investigate plastic strain and plastic strain rate effects during high speed machining (HSM). In this study modelling and simulation of orthogonal metal cutting is performed by using finite element method.

2. FINITE ELEMENT SIMULATION OF METAL CUTTING

2.1. Introduction

Metal cutting researchers focus on determining the best cutting conditions and tool geometries for process efficiency. Experimental works are needed to obtain results but they are expensive and time consuming. In addition to this, simplified analytical methods have limited applications and they cannot be used for complex cutting processes. At this point numerical methods become important. In last two decades, finite element method (FEM) has been most frequently used in metal cutting analysis. Various outputs and characteristics of the metal cutting processes such as cutting forces, stresses, temperatures, chip shape, etc. can be predicted by using FEM without doing any experiment.

2.2. Model Formulation

Three main formulations are used in finite element simulation of metal cutting:
Lagrangian, Eulerian and Arbitrary Lagrangian-Eulerian (ALE).

2.2.1. Lagrangian

Lagrangian formulation is mainly used in solid mechanics problems. Here the FE mesh is attached to work piece material and cover the whole of the region under analysis. This makes it highly preferable when unconstrained flow of material is involved. Lagrangian formulation is broadly used in metal cutting simulation due to ability to determine geometry of the chip from incipient stage to steady state and this

Geometry is a function of cutting parameters, plastic deformation process and material properties. Therefore, boundaries and shape of the chip do not have to be known a priori. Besides, chip separation criteria can be defined to simulate discontinuous chips or material fracture in metal cutting models which are based on Lagrangian formulation.

Although there are many advantages of Lagrangian formulation, it has also shortcomings. Metal being cut is exposed severe plastic deformation and it causes distortion of the elements. Therefore, mesh regeneration is needed. Secondly, chip separation criteria must be provided. This drawback of formulation can be eliminated by using an updated Lagrangian formulation with mesh adaptively or automatic remeshing technique.

2.2.2. Eulerian

In Eulerian formulation, the FE mesh is spatially fixed and the material flow through the control volume which eliminates element distortion during process. Besides, fewer elements required for the analysis, thereby reducing the computation time. Cutting is simulated from the steady state and therefore there is no need for separation criteria in Eulerian based models.

The drawback of Eulerian formulation is a need in determining the boundaries and the shape of the chip prior to the simulation. Also the chip thickness, the tool-chip contact length and the contact conditions between tool-chip must be kept constant during analysis which makes Eulerian formulation does not correspond to the real deformation process during metal cutting.

2.2.3. Arbitrary Lagrangian-Eulerian (ALE)

The best features of Lagrangian and Eulerian formulations have been combined and called arbitrary Lagrangian-Eulerian (ALE). In ALE formulation, the FE mesh is neither fixed spatially nor attached to the work piece material. The mesh follows the material flow and problem is solved for displacements in Lagrangian step, while the mesh is repositioned and problem is solved for velocities in Eulerian step.

The idea used in metal cutting simulation is to utilize Eulerian approach for modelling the area around the tool tip where cutting process occurs. Therefore, severe element distortion is avoided without using remeshing. Lagrangian approach is utilized for the unconstrained flow of material at free boundaries. Furthermore shape of the chip occurs as a function of plastic deformation of the material. This approach is shown in Figure 2.1.

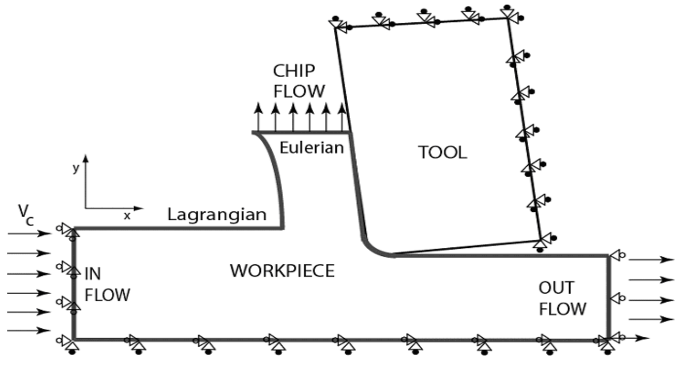

Figure 2.1. Eulerian and Lagrangian boundary conditions in ALE simulation

2.3. Meshing

A continuous region is divided discrete region called elements in FE analysis. This procedure is called discretization or meshing. Initial designed FE mesh cannot hold its original shape and it is distorted due to severe plastic deformation during metal cutting or metal forming processes. The distortion causes convergence rate and numerical errors. To handle with this problem a new FE mesh must be generated in means of changing the size and distribution of the mesh. This is called adaptive mesh procedure.

One of adaptive mesh procedure is remeshing technique and it includes the generation of a completely new FE mesh out of the existing distorted mesh. Second one is called refinement technique which is based on increasing the local mesh density by reducing the local element size as shown in Figure 2.2.

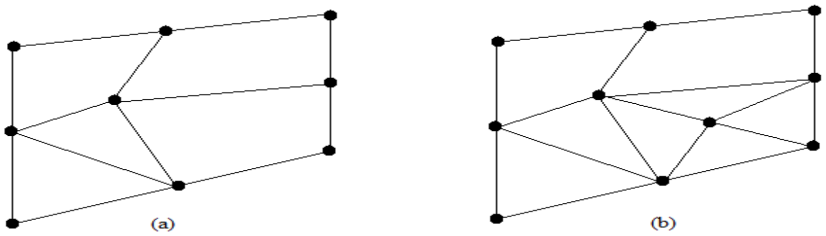

Figure 2.2. Refinement: (a) Initial local mesh, (b) Reducing element size

The last adaptive mesh technique is smoothing which includes reallocating the nodes to provide better element shapes as shown in Figure 2.3. The adaptive mesh procedure decreases solution errors during calculation therefore it increases the accuracy of the simulation. For these reasons, the adaptive mesh procedure must be used in FE simulations including severe plastic deformation such as metal cutting and metal forming.

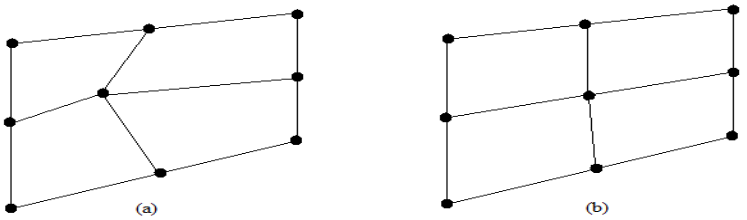

Figure 2.3. Smoothing: (a) Initial local mesh, (b) Reallocating of the nodes

2.4. Work Material Constitutive Models

One of the most important subjects in metal cutting simulation is modelling flow stress of work piece material properly in order to obtain true results. Flow stress is an instantaneous yield stress and it depends on strain, strain rate and temperature and represented by mathematical forms of constitutive equations. Among others, the most widely used ones in metal cutting simulations are Oxley, Johnson-Cook and Zerilli-Armstrong material constitutive models.

2.4.1. Oxley Material Model

Oxley (1990) and his co-workers used power law to represent material flow stress for carbon steel as

$$\sigma = \sigma\ \varepsilon\ n^{1} \qquad \text{-- I}$$

Where σ and ε are flow stress and strain, $\sigma 1$ is the material flow stress at $\varepsilon = 1.0$ and n is the strain hardening exponent. $\sigma 1$ and n depend on velocity modified temperature (T_{mod}) given by Macgregor and Fisher. T_{mod} is defined as

$$T_{mod} = T\ [1 - V \log \frac{\varepsilon'}{\varepsilon 0'}] \qquad \text{---II}$$

Where ν and 0 ε& are work piece material constants and they have values of 0.09 and 0.1 for carbon steel.

2.4.2. Johnson and Cook Material Model

Johnson and Cook (1993) developed a material model based on torsion and dynamic Hopkinson bar test over a wide range of strain rates and temperatures. This constitutive equation was established as follows:

The first parenthesis is elastic-plastic term and it represents strain hardening. The second one is viscosity term and it shows that flow stress of material increases when material is exposed to high strain rates. The last one is temperature softening term. A, B, C, n and m are material constants that are found by material tests. T_{melt} is instantaneous temperature, Tr is room temperature and Tm is melting temperature of a given material.

$$\sigma = [A + B\mathcal{E}^{n}] + [1 + C \ln (\mathcal{E}'/\mathcal{E}_0')]\ [1 - \{(T_{melt} - T_{Room})/\ (T_{melt} - T_{room})\}^{m}] \qquad \text{------------III}$$

Johnson-Cook material model assumes that flow stress is affected by strain, Strain rate and temperature independently.

2.4.3. Zerilli and Armstrong Material Model

Zerilli and Armstrong (1987) developed two micro structurally based constitutive equations. They worked on face-centred cubic (f.c.c.) and body-centred cubic (b.c.c.) metals to analyze their temperature and high strain rate responds and noticed a significant difference between these materials. Therefore, they developed two distinct models. The constitutive equation for b.c.c. metals can be written as follows:

For BCC

$\sigma = C_0+C_1 \exp(-C_3T_3+C_4T \ln \varepsilon'/\varepsilon_0') +C_5\varepsilon^n$ ---------------------------IV

For FCC

$\sigma = C_0+ C_2\varepsilon^{-1/2} \exp(-C_3T_3+C_4T \ln \varepsilon'/\varepsilon_0')$ --------------------V

In these equations, C_0 is component of stress that accounts for dislocation density on the flow stress, C1 - C5, n are material constants and T is the absolute temperature. In Equation IV, it is assumed that the strain dependence on flow stress is not affected by strain rate and temperature while it opposite in Equation V

2.5. Friction Models

Friction modelling plays significant role on results such as cutting forces, temperature and tool wear in metal cutting simulation. Hence, researchers focused on determining a friction model to represent the real behavior of process. The most widely used ones in metal cutting simulation can be listed as follows.

2.5.1 Constant Coulomb

In early metal cutting simulation, the simple Coulomb friction model was used on the whole contact zone with a constant coefficient of friction.

This model is defined as

$\tau = \mu\sigma_n$ ---------------------------------VI

Here, τ is the frictional stress, σ_n is the normal stress and μ is the coefficient of friction.

2.5.2 Constant Shear

In shear friction model, frictional stress on rake face of tool is assumed to be constant and the low stress variation of τ and σ_n are neglected.

This can be expresses by means of the following formulation:

$\tau = m k$ -- *VII*

Where m is friction factor and k is shear flow stress of the work material.

2.5.3 Constant Shear in Sticking Zone and Coulomb in Sliding Zone

According to Zorev (1963), two friction regions occur on rake face of tool. The first region is sticking zone where the frictional stress is constant. The next one is sliding zone where the normal stress is small. Therefore, constant shear friction model in sticking zone and Coulomb's theory in sliding zone can be used to model friction phenomenon.

The important thing in using this model is to determine the length of sticking and sliding zones. According to Shatla, et al. (2001), it was assumed that the length of the sticking region was equal to two times of the uncut chip thickness. However, it was noticed that the sticking region covered all the contact length in this way. Thus, Ozel (2006) suggested that the length of the sticking zone was equal to the uncut chip thickness.

2.6. Chip Separation Criteria

In machining operations, continuous, discontinuous or segmented chips may occur. Two basic methods are used to provide real chip formation in a numerical method. Fist one is to define chip separation criteria along a pre-defined line and the next one is to use continuous remeshing which is based on large plastic deformation.

A number of separation criteria can be grouped as geometrical and physical. According to geometrical criteria, chip separation is started when the tool tip approaches a node along the parting line within a critical distance. Then that node is separated from the work piece and it becomes part of the chip.

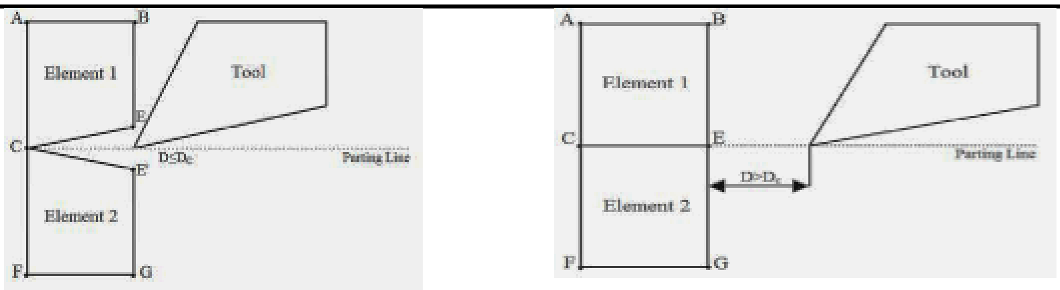

Figure 2.4. Geometrical Separation

According to the physical criteria, separation of nodes occurs when the value of predefined critical physical parameter is reached at a node or element. This critic physical parameter can be selected as strain, stress or strain energy density depending on work material properties and cutting conditions.

Strenkowski and Carroll (1985) used effective plastic strain criterion to simulate orthogonal cutting. When the effective plastic strain at a node closest the tool tip is reached the predefined critical value, it is allowed to move from the work piece.

Physical criteria seem to be more accurate in modelling chip separation because they are based on work piece properties. However, the problem is to determine critical physical values for real process.

2.7. FE Software Utilization

Researchers usually wrote their own FE codes for specific process such as metal cutting analysis commercial FE packages such as Deform 2D/3D, Abaqus, Advantedge, Ls-Dyna and etc. have been used excessively for process analysis. This is because different FE packages have different capabilities and solver techniques. Deform, Design Environment for Forming, is a Finite Element Method based system that can be applied to several manufacturing processes such as forging, rolling and machining. Deform has a specific machining module to quickly set up turning, software allows the user to adjust specific modelling variables such as mesh size, boundary conditions, and tool work piece interface conditions. The program has a material library including different types of steel, super alloy, aluminum, titanium. New materials can be created by using material models.

Advantedge was developed for metal cutting operations such as turning, milling, drilling as shown in Figure 2.6. The software has got simple input interfaces to supply work piece and tool geometries as well as the cutting conditions. Advantedge also has extensive material library. The user control on solver and material inputs are not allowed in this program.

Cylindrical Milling Ls-Dyna is an explicit and implicit finite element program used to analyze safety analysis and crash, forming problems. However, this program does not include machining module and it is time consuming to model metal cutting operations. In addition to this, Ls-Dyna does not have ability to do remeshing at tool and work piece contact area affecting the results in metal cutting simulations.

3 STEPS FLLOWED BY SIMULATION OF METAL CUTTING

The modelling part of metal cutting simulation is very important step to achieve accurate results. In this Part, details of modelling tool, work piece and cutting system are presented.

3.1. Tool Modelling

For Example, In analysis, cutting tool is assumed to be a rigid body. Tool material was selected uncoated tungsten carbide (WC). Thermal and mechanical properties of WC are given in Table 3.1

Table 3.1 Thermal and mechanical properties of WC Elastic

Elastic Modulus, E (MPA)	650000
Poisson’s Ratio	0.25
Thermal Expansion (1/ºC)	5.10^6
Thermal Conductivity (N/sec/ºC)	50
Heat Capacity (N/mm2 ºC)	4

Mesh density of tool tip and a part of rake face are modelled high with using mesh windows in the software to obtain more accurate temperature distribution results. This design is shown in Fig.

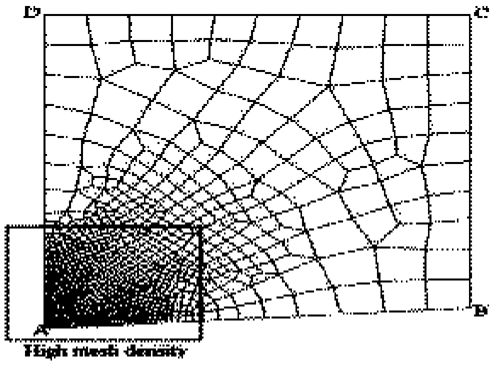

Figure 3.1. Mesh design of the tool

Heat exchange is defined on the boundaries D-A and A-B. Boundaries B-C and D-C are sufficiently away from cutting edge therefore their temperature is fixed 20 ºC.

3.2. Work piece Modelling

Flow stress modelling of work piece material is very important to achieve satisfactory results from metal cutting simulation. In the analysis, For Example AISI 1045 is selected as work piece material. Oxley, Johnson-Cook and Zerilli-Armstrong material constitutive models are used to model the plastic behavior of AISI 1045. Due to high strain, strain rate and temperature in metal cutting, the material data is represented by flow curves at 11 different strain (0.05, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5), 7 different strain rates (1, 10, 100, 1000, 10000, 100000, 500000 s-1) and 7 different temperature (20, 100, 300, 500, 700, 900, 1200 ºC).Material coefficients listed in Table 3.3. And Table 3.4.re used in calculating Johnson-Cook and Zerilli-Armstrong flow stress values.

Table 3.2 Constants for Johnson-Cook constitutive model

A [MPa]	B [MPa]	C (-)	n (-)	m (-)	Tm (K)
553.1	600.8	0.0134	0.234	1	1733

Table 3.3 Constants for Zerilli-Armstrong constitutive model

Co [MPa]	C1 [MPa]	C3 (K-1)	C4 (K-1)	C5 (MPa)	n (-)
159.2	1533.7	0.00609	0.000189	742.6	0.171

During analysis, it is assumed that work piece does not undergo elastic deformation and it is allowed to show only plastic behavior. Finite element mesh of work piece is modelled using 3130 nodes and 3005 isoperimetric quadrilateral elements. The work piece is created at least 20 feeds long and 10 feeds high therefore the predicted results are not sensitive to the displacement boundary conditions and steady state can be reached. Mesh of deformation zone is modelled very dense in order to reduce calculation time and obtain more accurate results.

Heat exchange is defined on the boundaries A-D and D-C. Boundaries A-B and B-C are sufficiently away from cutting edge therefore their temperature is fixed 20 ºC. In addition to plastic properties of work piece, its thermal properties depending on temperature have to be given to the software for heat transfer calculation. Thermal conductivity, thermal expansion and heat capacity of AISI 1045 are shown.

3.3. System Modelling

After modelling metal cutting components one by one, the next step is to assembly them due to cutting conditions. Cutting conditions are shown in Table 34.

Table 3.4. Cutting conditions

Cutting Velocity, Vc (m/min)	Feed Rate, f (mm/rev)	Width of Cut, b (mm)
100	0.1	3

Displacement boundary conditions of the system are shown in Figure 3.2. The tool is supported by fixing the nodes on the boundary C-D-E in both x and y direction. The work piece is fixed at y direction and it is moved against the tool by applying a constant cutting velocity at the bottom boundary A-B

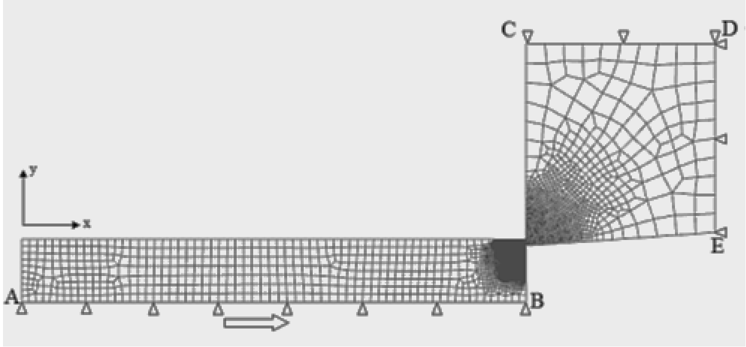

Figure 3.2. Displacement boundary conditions of the cutting system

For the heat transfer calculations, the following assumptions are made:
i) The contact between the tool and the chip is thermally perfect. Hence a very large value of the interface heat transfer coefficient (hint) is used and it is fixed to 1000 kW/m2K (Filice, et al. 2007).
ii) The boundaries are sufficiently away from the cutting zone remain at room temperature (T∞=20 ºC)
iii) The chip and tool loss heat due to heat convection (h=20 W/m2 ºC) on the free surfaces on the W/P
iv) Heat loss due to radiation is very small and it is neglected.

Thermal boundary conditions of the system can be defined as

$$T = T\infty \text{ --------------------}3.1$$

$$-k\frac{\partial T}{\partial n} = h_{inter}\ (T - T_C) \text{ ---------------------- }3.2$$

$$-k\frac{\partial T}{\partial n} = h\infty(T - T\infty) \text{ -----------}3.3$$

$$-k\frac{\partial T}{\partial n} = 0 \text{ ------}3.4$$

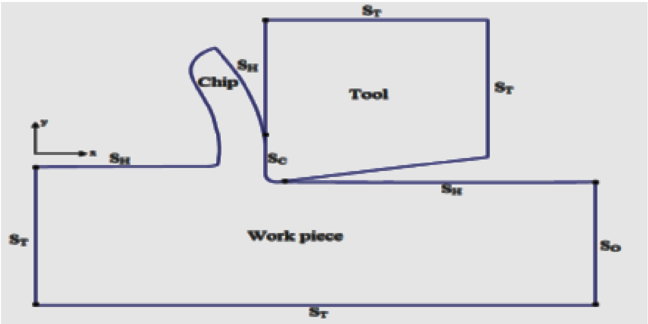

Figure 3.3. Thermal boundary conditions of the cutting system

Another important step is to define contact between the work piece and the tool. The tool is selected as master object because it was defined as a **rigid** object. The work piece is defined as slave object. Then, friction type, friction coefficient and interface heat transfer coefficient is defined. Therefore, contact is generated as shown in Figure 3.4.

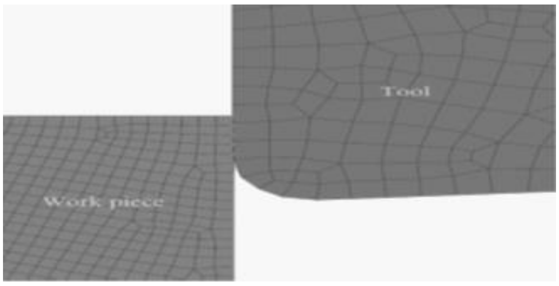

Figure 3.4. Contact generation between the tool and the work piece

In the analysis, updated Lagrangian model formulation with automatic remeshing method is used. Chip flow is achieved by remeshing hence there is no need to use a separation criterion.

4 Analysis of Mechanical and Thermal Parameters

In this part, the distribution of strain, strain rate, stress and temperature in the deformation zone, which are hard to measure experimentally, are proposed. In the analysis, Oxley's material constitutive model and Shear friction model are used. Mesh of work piece consists of 4938 nodes and 4792 iso-parametric quadrilateral elements. All parameters are collected after a 3 mm tool stroke where steady state has reached. First analysis is carried out with 0º rake angle as pervious works. The distribution of temperature in the work piece, chip and tool are shown in Figure 4.1. The maximum temperature is located on the secondary shear zone due to friction between the chip and the rake face of the tool. The highest temperature in the tool is achieved just above the tool tip.

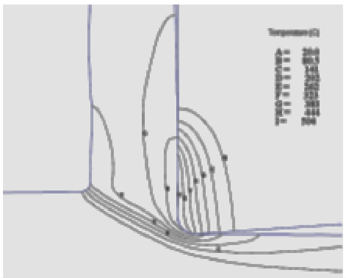

Figure 4.1. Temperature distribution

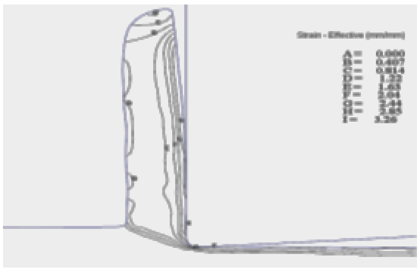

Figure 4.2. Plastic strain distribution

Plastic strain is shown in Figure 4.2. It can be seen that as an element of the work piece passes though the deformation zones, its magnitude of plastic strains increases. High plastic strain appears in the secondary shear zone where the maximum temperatures are located, with a maximum value and it remains constant away from the deformation zone. High plastic strains are also observed underneath the machined surface with the maximum value. Plastic strain value is also equal to the primary shear zone. This value is smaller in contrast to plastic strain in the secondary shear zone due to high strain hardening and low temperature in this area. High strain rates are obtained along the primary shear zone which is a very small area. The maximum value of about is obtained at the ahead of the tool tip. Strain rate starts to decrease gradually from the tool tip then it remains almost constant in the shear zone.

It can be seen that effective stress reaches the maximum value at the primary shear zone due to increase in both strain and strain rate. Then it starts to decrease towards the secondary shear zone due to decrease in strain rate and increase in temperature. A maximum value of is obtained in the primary shear zone and less in the secondary shear zone.

5 CONCLUSION

Thermo-mechanical model of plane strain orthogonal metal cutting with continuous chip formation is presented. The developed model is able to predict cutting and thrust forces, chip shape, chip thicknesses, contact lengths, shear angles as well as temperature, strain, strain rate and stress distributions. In the first part of this study, three different material constitutive equations, two different friction models implemented, and results of model are compared with the experimental data available in the literature. It is seen that flow stress models have a major effect on calculated results. The results of the simulations show that Oxley material model is able to give more accurate results for used cutting conditions in the analysis, however errors in calculating shear angle and thrust force are higher than Johnson-Cook and Zerilli-Armstrong material models. In addition, friction models and friction coefficients have a strong influence on cutting forces, thrust forces, chip shape and temperature in the cutting zone.

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