Scientific Journal Impact Factor (SJIF): 3.518
International Journal of Modern Trends in Engineering and Research
IJMTER
ISSN (ONLINE) : 2349 - 9745
ISSN (PRINT) : 2393 - 8161

INVESTIGATION OF CUTTING TEMPERATURE DISTRIBUTION DURING HARD TURNING OF AISI 4340: A NUMERICAL APPROACH

O. N. Bandal[1], O. Y. Ghodekar[2], S. S. Bhanage[3], P. M. Gorwadkar[4], A. P. Kulkarni[5] and F A Shaikh[6]

[1,2,3,4]*Student, Department of Mechanical Engineering, Vishwakarma Institute of Information Technology, Pune 411048, INDIA*

[5]*Associate Professor,Department of Mechanical Engineering, Vishwakarma Institute of Information Technology, Pune 411048, INDIA*

[6]*Assistant Professor,Department of Mechanical Engineering, Vishwakarma Institute of Information Technology, Pune 411048, INDIA*

Abstract— Temperature is in of interest in machining because cutting tools often fail by thermal softening or temperature-activated type of wear whereas workpiece fails when stress on it exceeds its yield stress. In this study, a numerical model was developed to obtain the cutting temperature distribution during hard turning of AISI 4340 steel. Temperature model as a function of heat generation is developed using ABAQUS explicit and with an Arbitrary Lagrangian-Eulerian (ALE) formulation approach. Johnson cook plastic flow material model was used to model the work piece material properties. FEM results clearly shows the heat generated at PSDZ and SSDZ. However temperature in PSDZ is more compared to SSDZ. Increase in cutting speed, leads to increase in cutting temperature. The simulated results of the present study showed a good agreement with the experimental results and hence, the model developed could be used to predict the temperature distribution during hard turning of AISI 4340.

Keywords- Temperature distribution, J-C model, Abaqus Explicit, ALE formulation

I. INTRODUCTION

Research in the field of metal cutting has traditionally been based on experimentation and prototyping, which means it has been expensive and rather slow. Nevertheless, the study of metal cutting has been going on for decades, due to the interest of the manufacturing sector in having a better understanding of this process and solving specific problem. Hard turning as it is widely used now a days, the understanding of the material removal considering the effect of work material, tool material and cutting conditions on the machining performance is very essential to ensure the quality of the products. The tool-material interactions not only changes the physical state of the material but also changes the properties of the near surface layer which changes the behaviour and durability of the material. This paper involves the study of cutting temperature distribution which is important as it is responsible for changes in the properties of the material after its tool interactions.

During chip formation process, all the mechanical energy during the tool-material interactions gets converted into heat which tends to increase the temperature at the cutting zones to vey high value. This has an adverse effect on the strength, hardness and wear resistance of the cutting tool resulting in rapid wearing of tool which in turn reduces the life of the tool. Estimation of cutting temperature is a crucial aspect in the study of metal cutting because high temperatures in work piece material may cause dimensional inaccuracy of the machined shaft and can also damage the shaft properties of the component by oxidation, corrosion, burning etc. A lot of investigations and modeling attempts have been made by the researchers to optimize and to study the effects of cutting parameters on various performance measures such as cutting forces, cutting temperature, tool wear during machining of hardened steel. Detailed works to determine cutting temperature using analytical approach began in 1951 by Hahn followed by Chao and Trigger[4], Leone[5] and Rapier[6]. Various methods have been found to experimentally measure the machining temperature. Thermocouples, radiation methods, metallographic techniques and application of thermal paints, fine powders and physical vapour deposition(PVD) are to name a few. Although, metal cutting tests have been carried out for the past 150 years on a large scale, it sometimes referred to as one of the least understood manufacturing processes due to the complexities associated with the process.

During machining of the material, heat is generated in the cutting zones. These cutting zones are classified in three distinct zones: Primary Shear Deformation Zone(PSDZ), Secondary Shear Deformation Zone(SSDZ) and Tertiary Shear Deformation Zone(TSDZ). These zones are shown properly in the Figure 1 for proper understanding. Major part of heat generation is due to severe plastic deformation is in the narrow zone called Primary Shear Deformation Zone(PSDZ). Furthur heating is generated in Secondary Shear Deformation Zone(SSDZ) due to friction between tool and chip as well as shearing at the chip tool interface. It is considered that both tools account for almost 99% of the heat generated. The heat generated in the TSDZ is mostly due to rubbing between flank of the tool and machined surface. The heat so generated is shared by the chip, cutting tool and the workpiece. The major portion of the heat is carried away by the flowing chip. As chip is meant for disposal only, focus should be on the chip to take as much as heat possible with it so that small amoun of heat gets retained in the cutting tool.

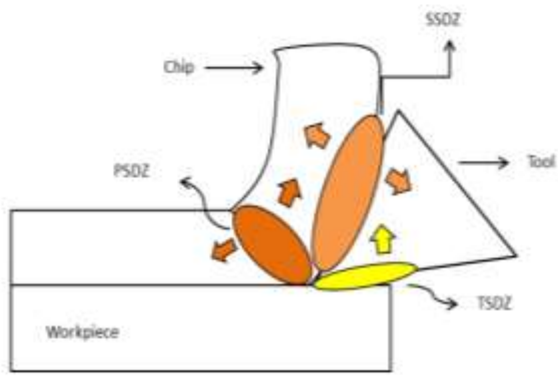


Fig. 1 Heat generation zones
i.e Shear deformation zones

Most of the researchers used Finite Element Analysis (FEA) to simulate the metal cutting processes to obtain the cutting temperature, cutting forces, residual stresses and to understand the chip formation processes. The FEA could be helpful to obtain information about the material flow and the stress, stain and temperature distribution to optimize the machining process. FEA involve simulation of short-time large deformation problems which require the use of either implicit or explicit solution techniques. Implicit methods deal with mostly non-linear system with large steps whereas explicit method deals with highly non-linear system with small steps. Therefore, the implicit solution integration methods take a longer time for simulation for fast dynamic process calculation. Therefore, processes such as material removal are calculated using explicit integration method. Numerical modeling of machining process was attempted by researchers using Lagrangian-based formulation as it is easy to implement and computationally efficient. In this formulation nodes are coincident with material points. However, elements get highly distorted as the mesh deforms with the deformation of the material in front of the tool tip. Attempts also have been made by the researchers using Eulerian-based formulation wherein nodes are coincident with spatial points. Each method discussed above has its own advantages and some limitations. Arbitrary Lagrangian and Eulerian Formulation (ALE) which was mostly attempted by the researchers to formulate the numerical model of machining process combines the

advantages of both the methods. In this formulation, the boundary nodes are moved to remain on the material boundaries, while the interior nodes are moved to minimize mesh distortion. Puri et al reviewed models and techniques for predicting the temperature distributions in heat affected zone.
In this paper, attempt has been made to develop a fully coupled thermo mechanical finite element model to obtain the temperature distribution during hard turning of AISI 4340 steel. Explicit dynamic ALE formulation which is known to be very efficient for simulating highly nonlinear problem analysis as like in machining is used to model the hard turning process. The model was developed using ABAQUS Explicit (Version 6.14) as large deformations during machining can be efficiently modelled with integrated special features in ABAQUS. Moreover, the ABAQUS includes a wide database for the effective material modeling which allows the user to minimize the model preparation time. In this paper, temperature distribution considering the effect of varying cutting speed is discussed using the developed numerical model of temperature distribution. Finally, important observations from the study are discussed and concluded.

II. NUMERICAL APPROACH

1. MODELING PROCEDURE

The 2-D model was developed in ABAQUS Explicit (Version 6.14). The modelling was done on an Intel Core i5© processor with 4GB RAM. As the depth of cut was much larger than the feed rate, this model was assumed in a plane strain. It was assumed that the work piece was a deformable body and the tool was a rigid body. The tool is considered as rigid for simplicity of the model. Work piece was modelled as a rectangle with length of 50mm and Height of 25mm. Rake angle was taken as -6^0. The simulations for temperature distributions were performed at the speeds of 180, 250, 320 m/min.

2. WORKPIECE AND TOOL MATERIAL PROPERTIES

In this study, AISI 4340 steel commonly known as EN 24 steel was used as a work piece material. The hardness of work piece material is 35 HRC .The chemical composition and the material properties of the AISI 4340 steel are shown in Table 1 and 2 respectively. The material geometry is also discussed below.

Table 1. Chemical composition and Physical Properties of AISI 4340 Steel

Element	C	Si	Mn	Cu	Cr	S	Mo	Ni	P	Fe
%	0.38	0.28	0.55	0.00	1.02	0.016	0.20	1.32	0.022	Rest

Table 2. Material properties of AISI 4340 steel (HRC 35) [14.]

Material properties	AISI 4340
Density(Kg/m^3)	7800
Inelastic heat fraction	0.9
Conductivity(W/m K)	0.0162
Specific heat(J/Kg K)	455

The tool insert used is of Kyocera with a nose radius of 0.8 mm. It has a side length of 12.70mm, thickness 4.76 mm and diameter of hole is 5.16mm. Its approach angle is 80^0.

3. MATERIAL MODEL

The work piece material was modeled as plastic with isotropic hardening and the flow stress defined as function of strain, strain rate and temperature based on Johnson-Cook (J-C) constitutive model.The Johnson-Cook constitutive model is very useful to simulate the mechanical processes involving high strain and strain rates, and the thermal softening. It has been widely used to model the cutting process. The equation of flow stress of a material is :

.......(1)

$$\sigma_s = (A + B \in_p)^n)[1 + C \log_n(\in_p / \in_o)](1 - T^{*m}) \quad where,\ T^* = (T - T_{room})/(T_{melt} - T_{room})$$

where σ_s stands for equivalent stress, $\in_p$ for plastic strain rate, $\in_o$ for reference strain rate, T_{room} for room temperature, T_{melt} for melting temperature. The five constants for the model were determined from various research papers where in A is initial yield stress, B is the hardening modulus, C is the strain rate dependency coefficient, m is the thermal softening coefficient and n is the work hardening exponent. The constants for J-C constitutive model for AISI 4340 steel are given in Table 3. Similarly, the temperature distribution property of thermal expansion is considered as $1.72*10^{-5}$ m/m^{o}C.

Table 3. Constants for J-C constitutive model and J-C failure model for AISI 4340 steel

J-C Constants	A	B	C	n	m
Values	792 Mpa	510 MPa	0.014	0.26	1.03

4. ELEMENT TYPE

The model was meshed using CPE4RT. This model has four node bilinear displacement and temperature with two degree of freedom which are temperature and displacement. The work piece is meshed with CPE4RT type elements by unstructured grid generation. ALE Adaptive Meshing has also been applied to avoid element distortion.

5. BOUNDARY CONDITION

The boundary conditions imposed in the FE model are described. Fig.2 shows a schematic diagram of the boundary conditions. The work piece was constrained along the bottom surface in the X and Y direction and also the left surface in X and Y direction. The cutting speed was assigned at the reference point of tool. The flow chart which shows the step by step procedure to model the temperature distribution is shown in Fig. 3

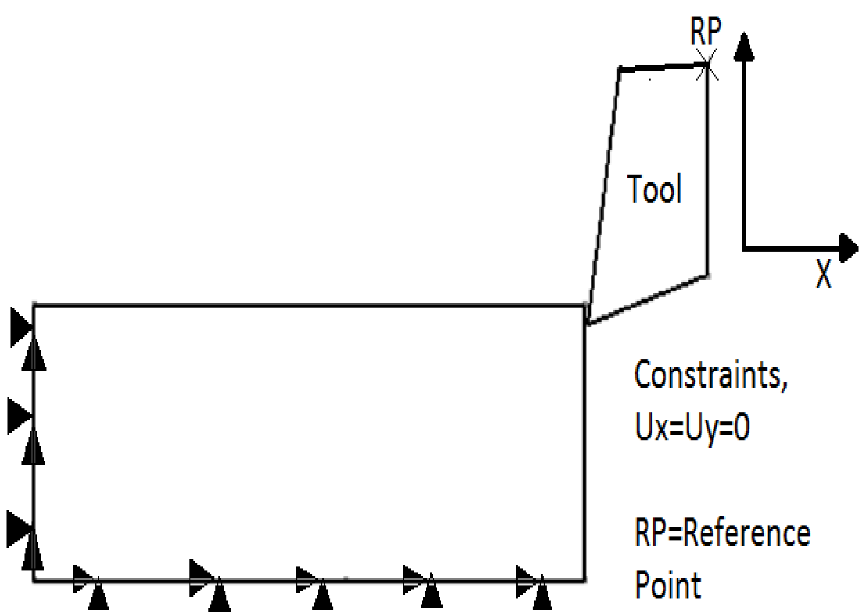


Fig. 2. Schematic representation of the boundary condition.

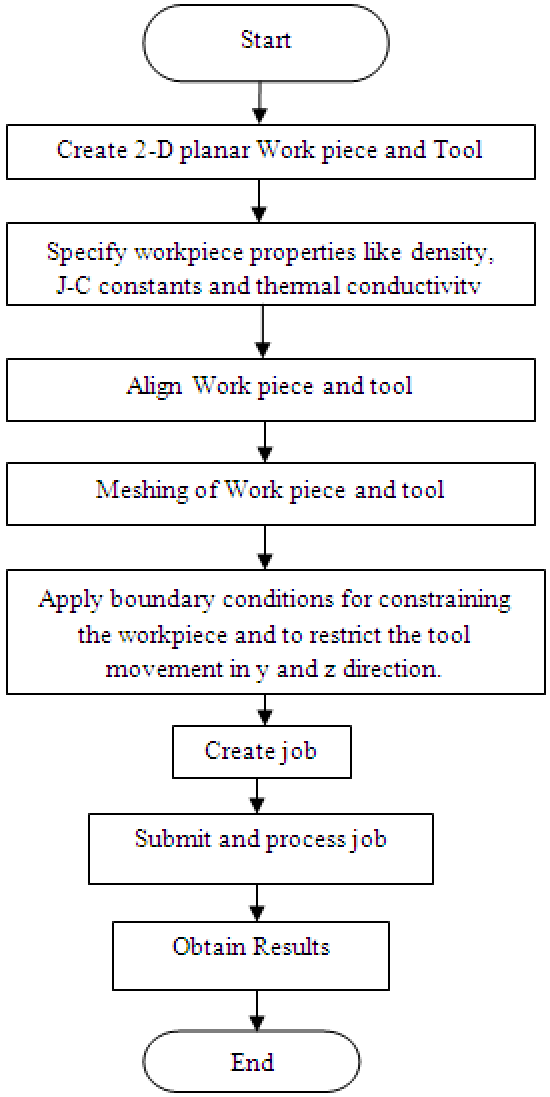
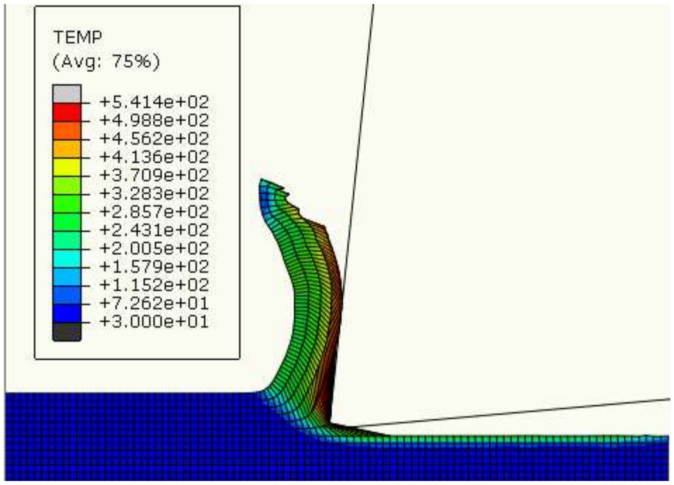


Fig. 2.Flow chart showing step by step procedure to model temperature distribution.

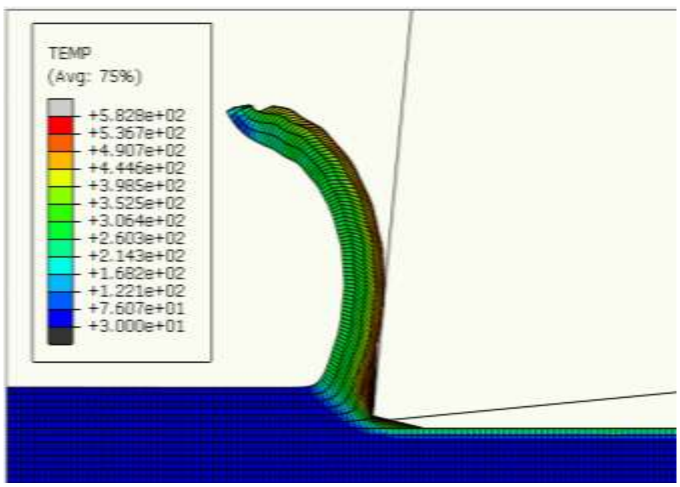
III. RESULTS AND DISCUSSIONS

The simulation was carried out for different speed 180, 250, 320 m/min with a depth of cut of 1mm and feed of 0.4 mm/rev. The results of the simulation are as shown in the following figures 3(a), 3(b) and 3(c). In this study we are only interested in the temperature distribution. As the cutting tool cuts the workpiece, the cutting temperature increases and reaches the maximum at a particular location on the cutting tool. The heat is generated due to severe plastic deformation in a very narrow zone (PSDZ), friction offered by the cutting tool to the flowing chip and shearing of the flowing chip at the chip tool interface(SSDZ). As seen from the figures 3(a), 3(b) and 3(c)

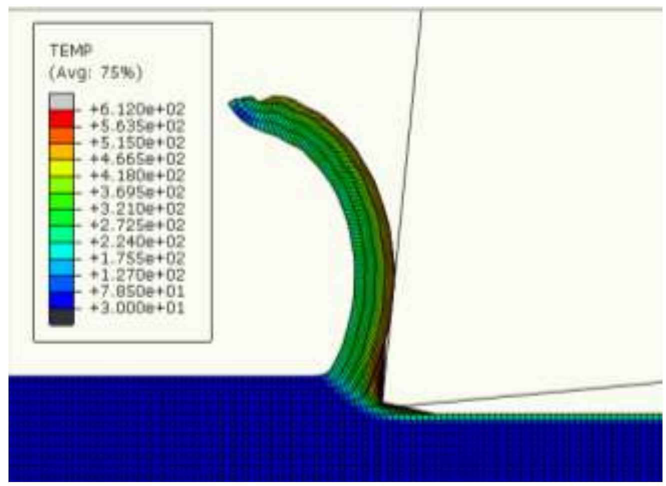
As chip is generally disposed in the end, it is favoured that the chip carries as much heat as possible so that tool retains small amount of heat.From the Figs. 3(a)-(c), it can be seen that the maximum amount of heat is carried away with the flowing chips as shown by red color segments in the chip. However, at higher cutting speeds the temperature is higher in comparison to temperature obtained at lower cutting speeds. These simulated results confirm that large portion of heat is penetrated into the tool at higher cutting speeds as compared to lower cutting speeds or large portion of heat is carried away with the flowing chip at lower cutting speed in comparison to higher cutting speeds which can be seen from Figs. 3(a)-(c).



3(a)



3(b)



3(c)

Fig. 3.Temperature distribution at cutting speedsof (a) 180 m/min; (b) 250 m/min; (c) 320 m/min.

Table 3. Maximum temperature at respective cutting speeds.

Cutting Speed (m/min)	Temperature (°C)
180	541.4
250	582.80
320	612.6

Table 4.Comparison of temperature of simulated and Experimental observation:

Cutting Speed (m/min)	Experimental value of temperature (°C)	Simulated value of temperature (°C)	% Error
180	596.34	541.40	-10.14
250	625.66	582.80	-07.35
320	632.80	612.00	-03.34

Further, the developed numerical model to obtain temperature distribution was validated with the experimental results. The calibration of the K-type Thermocouple were taken from the experiment done by Pranav et al.[14] The simulations were carried out at different cutting conditions reported above. The results obtained from simulations in the present study are compared with the experimental observations. The cutting conditions along with the experimental and simulated results are shown in Table 3 . Percentage error in experimental and simulated results is also shown in the same Table 3. It can be seen that simulated results are not in complete agreement with the experimental results. The variations to the extent of an average error of 6.94% can be seen. Observed values of errors in experimental and simulated results can be attributed to the variations in the work piece and tool material properties, tool geometry and boundary conditions considered in the present study while simulating the temperature distribution. However, experimental values shown may also have some variations as it was measured by a thermocouple. Thermocouple measures temperature at a location wherever it is installed. In the present study, reported results are compared with the maximum temperature obtained by simulation. Therefore, some variations in the experimental and simulated results are expected to occur. However, average error obtained in the range of 7% shows that the developed numerical model could be used to get an idea of temperature distribution and to locate the point of maximum temperature during hard turning of AISI 4340 steel.

IV. CONCLUSION

In this study, a numerical model was developed to obtain temperature distribution in hard turning of AISI 4340 steel. Temperature distribution model as a function of heat generation was developed using ABAQUS explicit and with an Arbitrary Lagrangian-Eulerian (ALE) formulation approach. A series of thermal simulations were carried out to obtain the value and region of maximum temperature at various cutting conditions. The simulated results of the temperature distribution showed a good agreement with the results available in the literature which showed that it is possible to carry out the complex FE model of cutting process using general purpose advanced commercial code. Based on the simulation results, at cutting speed of 180 m/min lower temperature is obtained and at 320 m/min higher maximum temperature is obtained. This is because as the cutting speed increases friction between tool and work piece also increases. The model developed could be used to predict the temperature distribution and to choose correct process parameters during hard turning of AISI 4340 steel.

REFRENCES

[1] J. Paulo Dawim; Statistical and Computation Techniques in Manufacturing”; 101-110.
[2] S. Chinchanikar and S.K. Choudhury, “Hard turning using HiPIMS-coated carbide tools: Wear behavior under dry and minimum quantity lubrication (MQL),” Measurement, 55 (2014), 536- 548.
[3] A.P. Kulkarni, G.G.Joshi, A. Karekar and V.G. Sargade, “Investigation on cutting temperature and cutting force in turning AISI 304 austenitic stainless steel using AlTiCrN coated carbide insert,” in IJMMM 15(3/4), 2014, 147-156.
[4] T. Chao, and K..J. Trigger,“An analytical evaluation of metal cutting temperature,” in Trans. ASME 73, 1951, 57–68.
[5] W.C. Leone, “Distribution of shear-zone heat in metal cutting,” in Trans. ASME 76, 1954, 121-125.
[6] A.C. Rapier, “A theoretical investigation of the temperature distribution in the metal cutting process,” Br. J. Appl. Phys. 5,1954, 400-405.
[7] J.E. Ceretti, P. Fallbohmer, W.T. Wu and T. Altan, “Application of 2D FEM to chip formation in orthogonal cutting,” in Journal of Materials Processing Technology, 59 (1996)169-181.
[8] J.S.Strenkowski and K.J. Moon, “Finite Element Modelling prediction of chip geometry and tool/work piece temzerature distributions in orthogonal metal cutting,” in ASME Journal of Engineering for Industry 112, 1990, 313-318.
[9] K. Li, X. Gao and J.W. Sutherland, “Finite element simulation of the orthogonal metal cutting process for qualitative understanding of the effects of crater wear on the chip formation process,” in Journal of Materials Processing Technology 127, 2002, 309-324.
[10] Y. M. Puri, A. P. Patil and P. S. Durugkar, “Review on finite element analysis of temperature distribution in heat

affected zone by different welding process," in Advanced Materials Manufacturing & Characterization 3(1), 2013, 285-290.

[11] M. Slais, I. Dohnal and M. Forejt, "Determination of Johnson-Cook parameters," in Acta Metallurgica Slovaca, Vol. 18, 2012, No. 2-3, p. 125-132.

[12] X. Wang and J. Shi, "Validation of Johnson-Cook plasticity and damage model using impact experiment," in International Journal of Impact Engineering 60 (2013), 67-75.

[13] P.S. Bapat , P.D. Dhikale, S.M. Shinde, A.P. Kulkarni and S.S. Chinchanikar , "A Numerical model to obtain temperature distribution during hard turning of aisi 52100 steel," in 4th Internation conference for material processing and characteristics, 2014.

[14] A. Jadhav and M. S. Ramgir, "Finite element simulation of orthogonal cutting process for steel," in IJERT Vol. 4 Issue 04, April-2015, 789-793.

[15] S. Chinchanikar, S.K. Choudhury, Machining of hardened steel- Experimental investigations, performance modeling and cooling techniques: A review, International Journal of Machine Tools and Manufacture, 89(2015) 95–109.