Numerical simulation of orthogonal hard turning operation of AISI 4340 workpiece using Al_2O_3 coated carbide tool

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Abstract

Machining is one of the most widely used manufacturing processes across all industries. It involves removal of metal to achieve desired shape from the work piece. Because of its versatility and large extent of applications, it is one of the most studied manufacturing processes. However, machining is one of the most complex manufacturing processes with several process parameters like cutting speed, feed rate, and depth of cut etc. In the present study, hard turning operation of AISI 4340 work piece is modeled using finite element method while subjected to given loads or boundary conditions to accurately determine the responses. The model created is an idealization of the real physical system to yield accurate solutions. This advancement in technology helps in fast creation, analyze and production of products satisfying demands. It is difficult to obtain output responses at the deformation zone through practical experiments. In the present work, the cutting force and temperature for the orthogonal cutting of AISI 4340 steel with Al_2O_3 coated tungsten-based cemented carbide cutting inserts are predicted for different cutting speeds with a fixed feed rate and depth of cut. For the simulation purpose, ABAQUS® finite element based package is used. To study the plastic deformations that occurs into the workpiece, Johnson-cook materials model is used.

Keywords:FEM simulation, Johnson-cook model, AISI 4340, hard turning, Al_2O_3 coated carbide tool insert.

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1. INTRODUCTION

Machining is considered to be the best way for manufacturing and producing of many items. Most of the industries manufacture parts through machining process. Machining is preferred for its high dimensional accuracy and high productivity [1]. It contains many material removal processes like turning, milling, drilling, grinding, boring, chamfering, polishing and so on. Each process has its own cutting tool and machining setup. The suitable machining process among these lists is chosen according to the need. Hard turning, a process of single-point cutting of materials with hardness above 45 HRC, has emerged since modern ceramics were first made available for continuous roughing and CBN tools for continuous finishing [2]. Finish hard machining has been a beneficial practice for machining industries due to its high productivity. AISI 4340 steel alloy of medium carbon steel isknown for its hardness and endurance limit and is used for wide varieties of applications. AISI 4340 serves as a viable substitute for AISI 4140 steel due to its high tensile and yield strength [3]. Finite element method (FEM) is capable of providing both qualitative and quantitative aspect of the machining process and can also correctly predict the difficult-to-measure variables associated with hard turning process such as shear strains, deformation etc. Numerous FE codes such as ABAQUS®, DEFORM, Ansys/LS-DYNA have come up that are currently being used by researchers for hard turning simulation.

2. MATERIALS AND METHOD

2.1 Experimental Procedure

All the hard turning experiments are performed on AISI 4340 steel using a NH26 Lathe machine with Al_2O_3 coated (coating thickness is 5µm) carbide insert. The diameter and the length of the workpieces are 80 mm and 200 mm, respectively. Kistler cutting force dynamometer (model 9272) is used to measure the cutting forces. Hard turning operation is carried out at0.2 mm/rev fixed feed rate, 0.1 mm depth of cut and at a varied cutting speeds as follows: 100, 120, 140, 160, and 180 m/min.

2.2 2D FEM Formulation of Orthogonal Cutting

ABAQUS® 6.13 explicit package employing coupled temperature-displacement module is used in the present study to simulate 2D metal cutting process. The geometric model consists of two numbers of 2D deformable solid bodies. The workpiece is considered as a rectangular block. The cutting tool is having zero degree rake and clearance angle considered during simulation. Workpiece length and height are considered as 2 and 0.4 mm, respectively. Tool and workpiece geometry are maintained same as per model by Akbar et al. [4].The thickness of coating on carbide insert is 5 µm. Figure 1 shows the ABAQUS® model with proper dimensions.

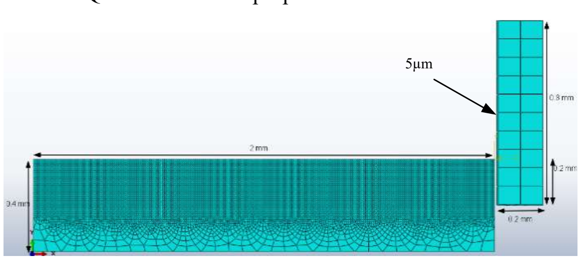

Fig. 1. Mesh configurations with dimensions in the computational domain

2.3 Boundary Conditions

The cutting tool is given velocity in the negative X direction and it is constrained in the y direction while the workpiece is kept fixedand constrained workpiece in the base in all directions. Workpiece dimensions are kept such that it will attain a steady state condition while machining. Figure 2 shows the boundary conditions.

2.4 Element Formulation

Four-noded plane strain bilinear displacement and temperature quadrilateral element (CPE4RT) with reduced integration scheme and hourglass control are used for both workpiece and the cutting tool. Workpiece consist of 10010 elements and 10332 nodes while the tool consists of 168 elements and 200 nodes. In coupled thermo-displacement elements, the stress analysis is coupled with heat transfer. These elements have both temperature and displacement degrees of freedom. Elements can use linear or parabolic interpolation for displacement but can use only the linear interpolation for the temperature in coupled temperature displacement type elements. During machining, lots of heat is generated which affects the mechanical properties of the workpiece. Hence, coupled analysis is preferred.

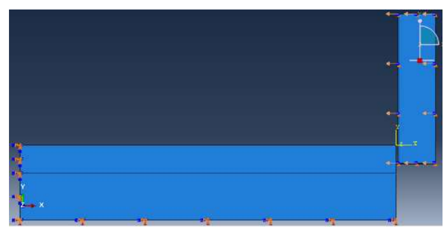

Fig. 2. Boundary conditions on cutting tool and workpiece

2.5 Material Model

For thermo-mechanical analysis of the work piece, Johnson-cook constitutive equation (1983) is used which considers the effect of strain, strain rate and temperature on the flow stress behavior of the materials [5,6]. This model is followed by most of the researchers. This model requires the value of the parameters to calculate the equivalent flow stress. The equation is given as

$$\overline{\sigma} = (A + B\overline{\varepsilon}^n)\left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{\theta - \theta_{room}}{\theta_{melting} - \theta_{room}}\right)^m\right] \qquad (1)$$

where, A is initial yield stress, B is hardening modulus, C is strain rate dependency coefficient, n is work hardening coefficient, m is thermal softening coefficient, $\dot{\varepsilon}$ is plastic strain rate, $\overline{\varepsilon}$ is equivalent plastic strain and $\dot{\varepsilon}_0$ is reference strain rate, $\theta_{melting}$ is the melting temperature of the workpiece, θ is the process temperature and θ_{room} is the ambient temperature. An equivalent plastic strain criterion is adopted to formulate the chip. Material failure depends upon the critical value of the equivalent plastic strain. This cumulative lawby Johnson & Cook (1985) is used and. It is given as

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$$D = \sum \left(\frac{\Delta \bar{\varepsilon}}{\bar{\varepsilon}_f} \right) \quad (2)$$

where, D is the damage parameter, $\Delta\bar{\varepsilon}$ is the increment of equivalent plastic strain and $\bar{\varepsilon}_f$ is the equivalent strain at failure. Equivalent plastic strain is given as

$$\bar{\varepsilon}_f = \left[D_1 + D_2 \exp\left(D_3 \frac{P}{\bar{\sigma}} \right) \right] \left[1 + D_4 \ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0} \right) \right] \left[1 + D_5 \left(\frac{\theta - \theta_{room}}{\theta_{melt} - \theta_{room}} \right) \right] \quad (3)$$

where, $\Delta\bar{\varepsilon}$ gets updated at every load step. P is the hydrostatic pressure. D_1, D_2, D_3, D_4, D_5 are the experimentally obtained failure constants. Material stiffness starts degrading after the element satisfies the damage initiation criterion. Failure is assumed to occur when D value exceeds 1. After the element is fully degraded, the element deletion in ABAQUS software completely removes the element. Johnson-cook parameters for the present workpiece are given in Table 1[7].

Table 1: Johnson-Cook parameters for AISI 4340 [7]

A (MPa)	B (MPa)	n	C	m	D_1	D_2	D_3	D_4	D5
950	725	0.375	0.015	0.625	-0.8	2.1	-0.5	0.002	0.61

For both workpiece and tool, thermos-mechanical properties are specified. Material properties of the AISI 4340 workpiece and tungsten carbide cutting tool insert i.e. density (ρ), elastic modulus (E), Poisson's ratio (ν), thermal expansion coefficient (α), melting temperature (θ_{melt}) and room temperature (θ_{room}) are provided in Table 2. Temperature-dependent thermal conductivity (K) values are given Table 3.

Table 2: Material properties of AISI 4340 workpiece, carbide tool and Al_2O_3 coating [7]

Material	Carbide tool	AISI 4340	Al_2O_3
C_p(J/kg-°C)	126	475	904
ρ (kg/m^3)	11900	7850	3780
E (N/m^2)	650 E9	205 E9	415E9
ν	0.25	0.3	0.22
α (μm/m-°C)	–	13.7	–
θ_{melt}(°C)	–	1520	–
Θ_{room}(°C)	25	25	25

Table 3: Thermal conductivity of carbide tool and Al_2O_3 coating [7]

Material	Property						
Al_2O_3	Temperature (°C)	50	90	300	500	1000	1300
	K* of (W/m-°C)	33	28	19	13	7	7
Carbide tool	Temperature (°C)	30	100	300	500	1000	1300
	K of (W/m-°C)	30	32	34	37	44	47.5

*K – Thermal conductivity

2.6 Contact properties

A kinematic contact algorithm is used to establish contact between tool rake face and chip. Tangential behavior effect of frictional forces are taken into consideration. Penalty contact with a constant coefficient of friction is used to model the contact.

2.7 Explicit dynamic analysis

Explicit dynamic formulation is generally used for highly non-linear problems which involves large amount of deformations. Explicit dynamic is an integration technique which uses central difference method to move the solution further in time. Explicit analysis uses the information already it has for obtaining unknown information. It does not require any iteration or convergence check for obtaining the solution. It is designed to study highly nonlinear, discontinuous and high speed dynamic problems. It requires lesser disk space as compare to standard analysis.

2.8 ALE Adaptive Meshing Technique

Arbitrary Lagrangian Eulerian (ALE) meshing technique combines the advantages of both the Lagrangian and Eulerian method. In the Lagrangian model, the mesh is locked on to the material. ALE combines the advantages of both Lagrangian and Eulerian model to fit the simulation criteria. ALE arbitrarily changes from Lagrangian or Eulerian model depending upon the need of the mesh at a point. This mean, in regions of huge plastic deformation, ALE acts more or less like the Eulerian model. While along the boundary of the material, ALE acts like Lagrangian model to facilitate easy implementation of boundary condition. In Eulerian approach, the mesh elements are locked on to the spatial points. This means that mesh remains fixed while the material flows through the mesh.

3. RESULTS AND DISCUSSION

3.1 Cutting force model validation

Figure 3 shows the simulation results of the variation of cutting and thrust force with time at 100 m/min cutting speed. The cutting and thrust forces have reached steady-state condition at 0.00016 s with a certain variation as shown in Fig. 3. The comparison between predicted and experimental results of cutting force is shown in Fig. 4 where a good agreement between the measured and predicted forces at all cutting speeds is observed. As the cutting speed increases from 100 to 180 m/min, the cutting forces decrease gradually from an average value of 330 N to 285 N experimentally and 380 N to 310 N in simulation results.

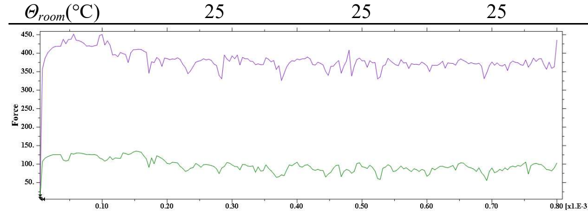

Fig. 3. Force plot for single cutting tool at a speed of 100 m/min

From Fig. 4, it can be seen that the cutting force and thrust force reduce at higher cutting speeds. Also, the cutting temperatures are significantly higher at higher cutting speeds. At higher cutting speed, the material becomes softerdue to thermal softening. Hence, the cutting force reduces.

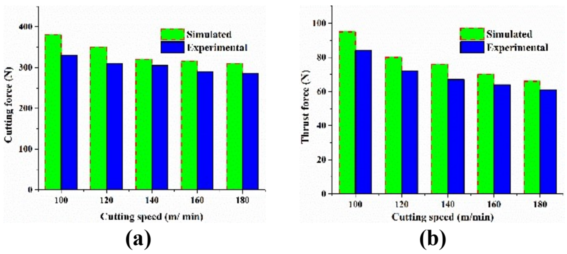

Fig. 4. Effect of cutting speed on (a) cutting force and (b) thrust force

3.2 Variation of shear angle

This section shows the simulated variation of shear angle with respect to cutting speed. Figure 5 shows the simulated shear angle at 100 m/ min cutting speed. From Fig. 6, it can be seen that shear angle increases with increased cutting speed. At high speed, the cutting temperature increases. Hence, chip thickness reduces which lead to increased shear angle.

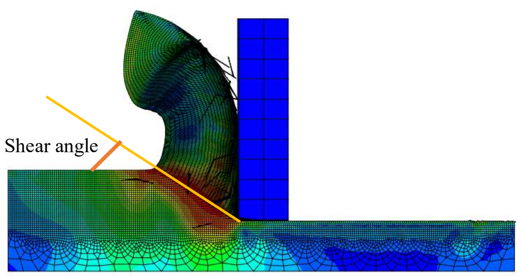

Fig. 5. Shear angle measured at 100 m/min cutting speed and 0.2 mm/rev feed rate

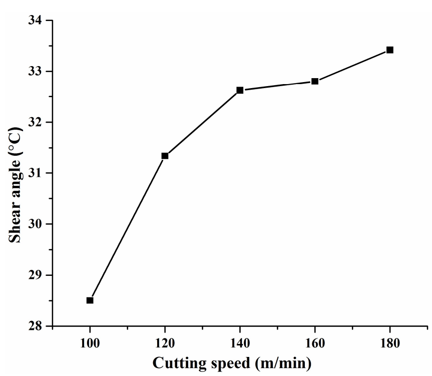

Fig. 6. Simulation results of the effect of cutting speed on shear angle

4. CONCLUSIONS

A FE based simulation is carried out to model orthogonal cutting of hard steel with a single-layer coated carbide tool. The effect of coating on cutting force, thrust force and shear angle during machining of AISI 4340 steel is studied. The experimental results are very close to the simulated results of cutting force and thrust force. The pattern of shear angle closely matches with the results available in the literature. Hence, from above results it is clear that ABAQUS® can be used for the prediction of forces and shear angle for 2 D orthogonal hard turning operation.

References

[1] A.B. Sadat, M.Y. Reddy, and B.P. Wang, Plastic deformation analysis in machining of Inconel-718 nickel-base superalloy using both experimental and numerical methods, *International Journal of Mechanical Sciences* **33** (**10**) (1991) 829–842.

[2] H. Bensouilah et al., Performance of coated and uncoated mixed ceramic tools in hard turning process, *Measurement* **82** (2016) 1–18.

[3] 4340 Steel | 36CrNiMo4 | 16511 | EN24 | SNCM439 - Otai Special Steel, (n.d.).

[4] F. Akbar, P.T. Mativenga, and M.A. Sheikh, An experimental and coupled thermo-mechanical finite element study of heat partition effects in machining, *The International Journal of Advanced Manufacturing Technology* **46** (**5**–**8**) (2010) 491–507.

[5] F.J. Zerilli, Dislocation mechanics-based constitutive equations, *Metallurgical and Materials Transactions A* **35** (**9**) (2004) 2547–2555.

[6] Johnson, GR and Cook, WH (1983) A Constitutive Model and Data for Metals Subjected to Large Strains, High Strain Rates, and High Temperatures Proceedings 7th International Symposium on Ballistics, The Hague, 19-21 April 1983, 541-547 - References - Scientific Research Publish, (n.d.).

[7] İ. Ucun and K. Aslantas, Numerical simulation of orthogonal machining process using multilayer and single-layer coated tools, *The International Journal of Advanced Manufacturing Technology* **54** (**9**–**12**) (2010) 899–910.