FINITE ELEMENT ANALYSIS OF HARDENED STEEL CUTTING

Received: 01 November 2010 / Accepted: 17 April 2011

Abstract: Hard machining, as attractive replacement for many rough and finish grinding operation, generates high cutting forces and temperature that enhance tool wear when act together. Therefore, the tool geometry and machining parameters have to be carefully optimized for a given material. Because of high cost and time consuming experimental work up-to-date advanced software for modeling and simulation brings quick and adequate solution. The aim of this contribution is to study the influence of cutting parameters on accompanying phenomena when hard turning process with mixed oxide ceramic inserts. Hardened steel with hardness of HRC 55 has been employed in modeling and trials. In order to better understand dynamics of cutting hardened steel, investigation has been performed making use finite element simulation in two dimension, and experimental analysis of cutting force. The potentiality of the model as well as the experimental results are compared and discussed.

Key words: Hard turning, cutting force, temperature, Advant Edge modelling.

1. INTRODUCTION

Hard turning is a complex process with chip formation occurring at tool nose radius and relative small feed and depth of cut. Most research on hard turning in the literature is limited to experimental work, while practical theoretical models including FEA (finite element analysis) of this promising machining process are scarce, due to the inherent complexity of a hard turning process. In order to improve the fundamental understanding of hard turning and process optimization for producing favourable surface integrity, theoretical modelling of a hard turning process has economic as well as scientific importance [1, 2]. The finite element method seems to be the right tool to predict cutting performance including chip flow and morphology, cutting forces, and complex residual stress and cutting temperature fields which are often beyond the capability of current measurement methods. A 2D FEA modelling of temperature and forces in orthogonal cutting of hardened steel was reported more times [3, 4, 5, 6]. Nowadays variety of applicable FEM modelling software is available. The choice of finite element software for machining analysis is an important factor in determining the quality and scope of analysis that can be performed.

One of this software ThirdWave System’s AdvantEdge is a machining specific FEM package. It has pre-programmed modules for both 2D and 3D machining operations including turning and milling. AdvantEdge also comes with a workpiece modeller as well as a material property library. As AdvantEdge has been explicitly written with machining operations in mind, its solvers have been optimized specifically for metal-cutting processes. Also, the software has a very user friendly interface with simple input screens to supply the tool and workpiece geometries as well as the process parameters. AdvantEdge has a built-in editor for simple tool and workpiece geometries and allows for the import of more complex geometries. AdvantEdge also has a very extensive material library with models of many engineering metals and alloys, including several aerospace alloys [4]. Specifying new materials is relatively simple and the user has the capability to enter the properties of the material using different models. The program also uses adaptive meshing to handle increase the accuracy of the solution in the areas of high deformation and allows a reasonable degree of flexibility in the meshing controls [7, 8, 9].

On the other hand AdvantEdge does not give the user much flexibility in configuring the controls of the solver. While this may be preferable in some cases, this means that the user is restricted to the preset controls of the software. If a quick, easy to setup machining simulation is needed, then the preferable software packages would be AdvantEdge. This package allows quick setup of simulations and has built in modules to specify material properties, tool and workpiece geometries and process parameters, Fig 2.

Fig. 2 Example of one of the input set up window

In this study a general practical 2D model has been applied to analyze hard turning steel with of HRC 55
using mixed oxide ceramic cutting tool. The goal of this study is to investigate the influence of cutting parameters on the accompanying phenomena of hard turning process – cutting force and temperature. Experimental evidence and simulation results are compared.

2. HARD TURNING – DEFINITION OF INPUT PARAMETERS FOR MODELLING

Machining conditions in hard turning are different from conventional turning. Depth of cut, feed rate, and cutting tool nose radius are typical finishing conditions in hard turning. Because of the low depth of cut and the large cutting tool nose radius, chip formation usually takes place in the nose radius or on the chamfer of a cutting tool. Thrust force appears to be the largest force component, while the feed force component is the smallest one using a worn tool. By increasing the tool flank wear, a significant rise of the thrust force component can be observed. Considering a very small contact area on the tool-chip interface, extremely high stresses and temperatures develop on the area. A numerical simulation may provide a powerful tool to analyze the contact mechanics on the tool/chip and tool/workpiece interfaces [1].

Cutting temperature is of fundamentals importance in hard turning. Cutting temperature may cause thermal damage and even white layer when machining hardened steels. The influence of cutting temperature on the surface integrity may be more important than the tool life. However, the fact that temperature is most difficult to measure explains the numbers of different methods used over the years [2].

The applied software employs well-known Johnson-Cook material model to describe material behaviour. Friction on the tool-chip interface is a major input determining the dependent variables such as chip morphology, cutting forces, residual stresses, and temperatures. Therefore, an accurate determination of the friction condition is of considerable importance for finite element analysis of metal cutting. Friction conditions at the tool/chip interaction was modelled by using an average friction coefficient only determined by Coulomb’s friction law as a value of 0.5. It limits application of the model and reduces FEA model efficiency significantly [2, 10].

A Lagrangian finite element-based machining model is applied in the simulation of cutting force components and temperature in two-dimensional turning of hardened steel. The cutting force $F_c$ force in X direction ($F_X$) and transverse force in Y direction ($F_Y$) on the tool are displayed as functions of time. In simulation with AdvantEdge, there is no separation criteria defined since chip formation is assumed to be due to plastic flow; therefore the chip is formed by continuously re-meshing the workpiece. Adaptive re-meshing of the model is used to avoid extreme element distortions due to the strong deformations. It re-meshes the workpiece periodically to refine large elements, re-mesh distorted elements, and coarsen small elements. Heat transfer to the tool is allowed, Fig.3, but heat transfer by radiation, convection or conduction was considered as negligible. The model iscredited by triangular elements and uses maximum 12000 elements, depending on the chip configuration [11]. The length of cut was set to 5 mm. The simulation was conducted with coolant off and initial temperature was fixed at 20°C. The simulation was conducted in rapid mode.

3. EXPERIMENTAL CONDITIONS AND MODEL VALIDATION

For simulation, workpiece material AISI 1045 hardened at hardness 55 HRC have been employed. Turning process was conducted with mixed oxide ceramics insert D310 (70% Al$_2$O$_3$+30% TiC) with a SN geometry, nose radius $r_n = 0.8$ mm, and chamfered edge $0.2 \times 20^\circ$, $\gamma = -6^\circ$, $\alpha = 6$. Set of cutting conditions are follows: cutting speed $v_c = 90$, 120, and 150, 240 and 350 m/min, feed rate: $f = 0.047$, 0.1, 0.15 and 0.2 mm, depth of cut: $a_p = 0.5$ mm.

In this study, external longitudinal turning of hardened steel of hardness 55HRC had been employed for measurement of cutting force components $F_x$, $F_y$, $F_z$ by triaxial dynamometer. The difference between the simulated values and the experimental ones did not exceed 10% [11]. These differences could be caused by different way of cutting 2D in simulation and 3D in measurement. 2D simulation is unable to make punctual estimation of thermo mechanical stress induced on the material/tool interface therefore and simulated outputs from software has only informative character [8]. Comparisons of measured and simulated data are illustrated graphically in Fig. 4.
Fig. 4 Comparison of experimental and simulated cutting force values $F_c$, $F_f$ for $v_c = 120$ m/min, workpiece hardness 55 HRc

Figure 4 illustrates the cutting force behaviour in function of the feed rate, while the other parameters remain constant. It is interesting to note the linearity of the cutting force within the feed rate range considered. Simulation results have been processed graphically. AdvantEdge software shows simulation results in different way such as a table or graph or color area, Fig.5.

Fig. 5 Example of graphical output from cutting force simulation

4. SIMULATION RESULTS AND DISCUSSION

Effect of cutting parameters and material hardness on cutting forces

Ceramic cutting tools have an advantage in the machining of hard work piece materials at high speed. The variation of main cutting force with cutting speed has been modelled. It can be noted that the cutting forces of the ceramic cutting tool slightly decreases with cutting speed, Fig 6. The decrease of cutting force with respect to cutting speed when using mixed alumina ceramic cutting tool shows that this type of ceramic cutting tool can machine the work piece material with high speed and at low cutting forces. The lower cutting forces result in a lower distortion of work piece, which improves the surface finish while machining with the ceramic cutting tools and particularly by using mixed oxide ceramic cutting tools.

Effect of cutting parameters on chip deformation

Besides the cutting and transverse force it is possible to extract from the proposed model predictions for values that it would be very work-intensive or even impossible to obtain otherwise. Examples for such cases are: plastic strain rate, chip deformation, von Misses stresses, and temperature distribution and heat rate.

Effect of cutting parameters on cutting temperature and heat flow

The knowledge of maximum temperature and of the distribution of the temperature field in the rake face of the tool is of great interest because of high temperature in ceramics tool are connected to wear mechanics that reduces the tool life. With the simulated results provided by model it is possible to minimize unwanted effects and to choose suitable cutting condition in order to optimise the process [8].

In Fig.7 plastic strain rate in shear zone for cutting speed 120 m/min, is shown. This figure demonstrates the model at a step analysis, for length of cut $l = 1.2$ mm, where cutting is well into the steady-state region.

Fig. 6 Numerical results of cutting force component for different cutting speed, HRC 55, $a_p=0.5\text{mm}, f=0.15\text{mm}$

Fig. 7 Example of graphical output from cutting force simulation HRC55

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Considering of low thermal activity of ceramics it is assumed that the temperature distribution on the rake face of the cutting tool is mainly determined by sources of plastic deformation of the metal on the shear plane and by the friction on the tool-chip interface. Depth of cut $a_p = 0.5$ mm and feed per revolution $f = 0.15$ mm
were fixed. Simulation results are processed in figure 8. Graphs show variation of temperature for three values of cutting speed. Figure 9 represents the temperature distribution on rake face of cutting inserts. Rake face temperature is growing with increasing of cutting speed.

Fig. 8 Temperature distribution on tool rake face

Fig. 9 Temperature vs distance along the tool rake face for 55HRC material hardness

5. CONCLUSION

Summarizing the results reported above it can be concluded that hard turning has many advantages in comparison to other processes in machining of hardened steels. The finite element methods have been extensively used for modelling machining operations. This method is also used in the present paper and the software AdvantEdge is employed. Simulation of 2D orthogonal cutting model is provided. The modelled results for cutting and transverse force components have been compared with experimentally achieved values. However, other results such as temperature distribution, chip thickness and chip deformation as well as plastic strain rate had been only predicted; because of measuring these data is more time consuming and very work intensive.

From the analysis provided in this contribution can be concluded that the proposed model fits quite well and is suitable for practical application mainly in industry. Therefore FEM simulation software provide very important role in research work because of a minimum amount of experimental work is needed and produce reliable results, allowing for industrial use of optimal production.

ACKNOWLEDGEMENT

Presented results were carried out within Research Grant Projects VEGA No. 1/0279/11 supported by Scientific Grant Agency of the Ministry of Education of Slovak Republic and the Slovak Academy of Science.

6. REFERENCES


Authors: Ildiko Maňková1, Pavel Kovac2, János Kundrak3, Jozef Beňo4

1Full professor at TU Košice, KTaM SJF TU, Masiarska 74 04001 Košice, Slovakia,
2Full professor at University Novi Sad, Serbia
3Full professor at University Miskolc, Hungary
4Associate professor at TU Košice, Slovakia

E-mail: ildiko.mankova@tuke.sk, pkovac@uns.ac.rs, kundrak@gold.uni-miskolc.hu, jozef.beno@tuke.sk