

Simulations of Temperatures in the Cutting Zone and Cutting Forces

Jelena Baralić^{1*}, Nedeljko Dučić¹, Aleksandra Stakić^{1,2}

¹University of Kragujevac, Faculty of Technical Sciences, Čačak, Serbia

^{1,2} PhD student at the Faculty of Mechanical Engineering, University of Belgrade, Serbia

* jelena.baralic@ftn.kg.sc.rs

Abstract: *Today, simulations are increasingly used in education and training (in mechanical engineering, medicine, army, etc.). They can be successfully used for the education of pupils and students at all levels of education, as well as for all ages. The use of this approach enables the understanding of complex processes and the development of skills in various disciplines without the use of expensive equipment or the implementation of time-consuming or dangerous experiments. This paper describes the application of simulations in order to better understand the cutting process, ie, the influence of individual cutting parameters on temperatures and cutting forces. The simulations were realized in the AdvantEdge software package. 2D simulations of turning machining were performed. In the first three simulations the feed f was varied, while in the next three simulations the cutting speed v was varied. The change in temperature in the cutting zone and cutting forces, depending on the feed f and the cutting speed v is analyzed. The results of the simulations are in accordance with theoretical and experimental data. Simulations of machining with a larger feed and higher values of the cutting speed show higher values of the temperature in the cutting zone and the cutting forces.*

Keywords: *simulation; temperature; cutting forces*

1. INTRODUCTION

The first application of computer simulations began during and immediately after World War II. Mathematicians John Von Neumann and Stanislaw Ulam used newly developed computer techniques to model nuclear detonation in the design of a nuclear bomb [1]. As this method proved to be very successful, simulations were increasingly applied in various fields, both in science and in industry. The improvement of simulation technology has led to expanded possibilities of its application. The development of the computer industry and the advent of personal computers have made this form of learning practical and accessible to the general population. Real-time simulations and 3D simulations were developed in the 90s of the twentieth century. Today, simulations are applied in all branches of industry and in education because of their advantages over the traditional method of study. The main advantage of simulations is that they save time and money. Expensive materials and equipment are not necessary for simulations. Also, the preparation of experiments is sometimes very complex and time consuming.

With the help of simulations, abstract phenomena that are not visible during the realization of the experiment can be easily understood (for example, the propagation of heat in the cutting zone). In addition, users have the opportunity to analyze a

large number of scenarios, which results in the rapid acquisition of new knowledge and skills while neutralizing risks. In the long run, investments in equipment and software package are a worthwhile investment.

2. APPLICATION OF THE SOFTWARE PACKAGE THIRD WAVE ADVANTEDGE FOR THE SIMULATION OF THE MACHINING PROCESS

The development of computers has enabled the introduction of the finite element method in everyday engineering practice. The essence of the finite element method is in the physical discretization of the examined domain (continuum) to the finite number of elements and the degree of freedom of movement. The interconnection of finite elements is defined by a finite number of nodal points whose positions are on the contour of each element.

Determining the state at each of the individual node points is enabled through known distribution functions within the elements (interpolation function) and by determining the unknown values of the function at the node points (node unknown). FEM analysis is a useful and effective method, in terms of both time and cost savings, for obtaining fast results [2]. FEM analysis is able to lower the

operational cost compared to physically conducting the machining experiment.

The Third Wave AdvantEdge software package is a commercial program for designing, improving and optimizing the machining process. It is primarily intended to simulate cutting process. The solver of this program (the part of the software that solves the mathematical problems) is adapted for metal cutting. Fig. 1 gives a graphical overview of the most frequently used software packages for simulation of the machining process with finite element method based on 116 scientific papers published in the period 2000-2014. [3]

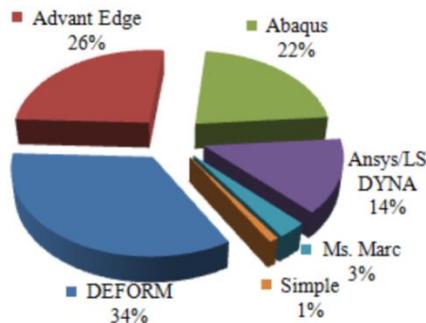


Figure 1. An overview of research activities in the area of finite element simulation [3]

The structure of the program consists of three modules: pre-process module, simulation module and post-process module. The pre-process module allows users to define the entire simulation, to define the geometry and material of the tool, the properties of the workpiece (dimensions and material) and the parameters of the machining process. The simulation module is the module where the simulation actually takes place. When the simulation is defined and started, the solver performs calculations based on the finite element method. When the calculations are completed, the results are processed in the post-process module and displayed in various forms such as graphs and images. The results that can be displayed are also chip shape, tool and chip temperature, cutting forces, tool wear and so on.

The simulation can be done in demonstration and standard mode. Demonstration mode reduces the duration of the simulation, but it is less accurate, while standard mode requires more time, but it is much more accurate.

3. TEMPERATURES IN THE CUTTING ZONE AND CUTTING FORCES

The appearance of heat in the cutting zone is a consequence of the conversion of mechanical energy into heat. Temperatures at characteristic points of the cutting zone are important for studying the cutting process (Fig. 2). The temperature θ_1 occurs as a consequence of material breakage, ie rupture of the structure of the

base material of the workpiece. The temperature θ_2 occurs at the shear plane as a result of compression and deformation of the chip. Temperature θ_3 is the contact temperature of the chip surface and the rake face of the cutting tool. It reaches its maximum at half of the contact. A contact temperature θ_4 occurs on the contact of the side clearance surface of the cutting tool and the machined surface of the workpiece. The cutting zone temperature is the mean cutting temperature θ_{sr} .

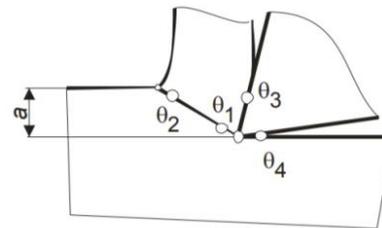


Figure 2. Cutting zone temperatures [4]

The heat in the cutting zone increases until an equilibrium state between the generated and dissipated heat is established. After the establishment of the equilibrium state, a quasi-stationary heat field is created [5]. The heat field can be considered stable only for a certain period of time. It has been experimentally determined that the establishment of the equilibrium state of the thermal field takes about 15 seconds.

The forces impacting on the cutting tool during machining process are named cutting forces. (Fig. 3) The understanding the phenomenon of the cutting forces has a significant role in the process of defining the machinability of materials, wear of cutting elements of tools, sizing of machine elements, driving power of the machine, etc. In orthogonal cutting, the resulting cutting force F_R can be decomposed into:

- tangential force (friction force) F_T , which acts in the plane of the rake surface and normal force F_N , which acts in the plane normal to the rake surface of the cutting wedge;
- shear plane force (shear force) F_S and normal force F_{SN} , which acts in the plane normal to the shear plane and
- the main force (main cutting force) F_1 and the penetration force (force F_2), which acts normally on the machined surface of the workpiece.

The equation for calculating the main cutting force F_1 is usually defined. Other components are determined based on the value of the main cutting force. The main cutting force is most influenced by the material of the workpiece and the parameters of the cutting process, above all the depth of cut and feed.

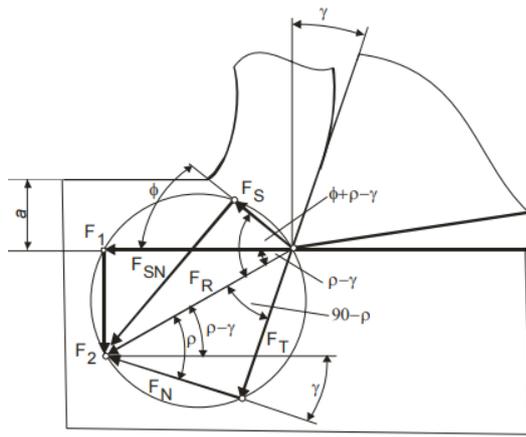


Figure 3. Cutting force components in orthogonal cutting [4]

The expression form, that is most often used to calculate the main cutting force, is:

$$F_1 = C_{k1} \cdot a^{x1} \cdot f^{y1}, \tag{1}$$

where **a** is the depth of cut and **f** is the feed, while k_1 , x_1 and y_1 are constant and exponents of the influence of the workpiece material, tool geometry and machining conditions.

4. DEFINING PARAMETERS FOR 2D SIMULATION OF TURNING

The paper presents the process of model formation and 2D simulation of the turning process in the Third Wave AdvantEdge software package. After choosing the type of machining, it is necessary to choose the dimensions and material of the

workpiece. As this is a 2D simulation of turning process, the workpiece is shown as a prismatic part. The material that is removed by turning is chip. After that, the tool is selected, and the shape, dimensions and material of the tool are defined. Finally, the parameters of the turning process are defined: cutting speed, feed, depth of cut (Fig. 4).

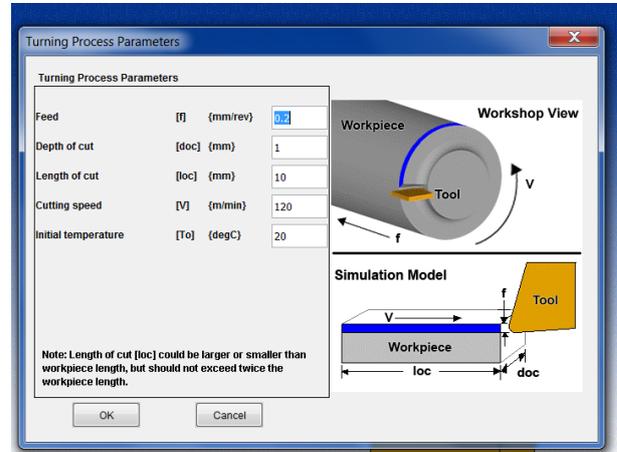


Figure 4. Defining of the process parameters

The workpiece and tool that are imported from existing databases have already defined mesh parameters and they can be changed. The Tecplot subroutine allows users to define the simulation output parameters to be displayed. After all preparations, a simulation is started. For the appropriate processing modes (Table 1), six simulations were created.

Table 1. Process parameters in simulations

Cutting parameters	Simulation name					
	TIO-1	TIO-2	TIO-3	TIO-4	TIO-5	TIO-6
Cutting speed, v [m/min]	120			110	130	150
Feed, f [mm/o]	0,2	0,7	1,2	0,3		
Depth of cut, a [mm]	1					

On the basis of these six simulations, the influence of the cutting speed and the feed on the temperature in the cutting zone and cutting forces was analyzed. The material of the workpiece was C45, Ø100 mm. The tool was a turning knife with a cutting plate made of P20 carbide. The rake angle of the knife is $\gamma = 10^\circ$ and the side clearance angle is $\alpha = 5^\circ$. The cutting length was 10 mm. The comparative views of the simulations are taken after 10 mm long cutting, (Fig. 5.) Fig. 5 shows the

differences in temperature distribution in the cutting zone for different parameters of cutting process. The option to display the mash in the simulations views is turned off, so the temperature fields can be noticeable. If necessary, individual parts of the image can be displayed enlarged, so the temperatures in the cutting zone can be seen more clearly.

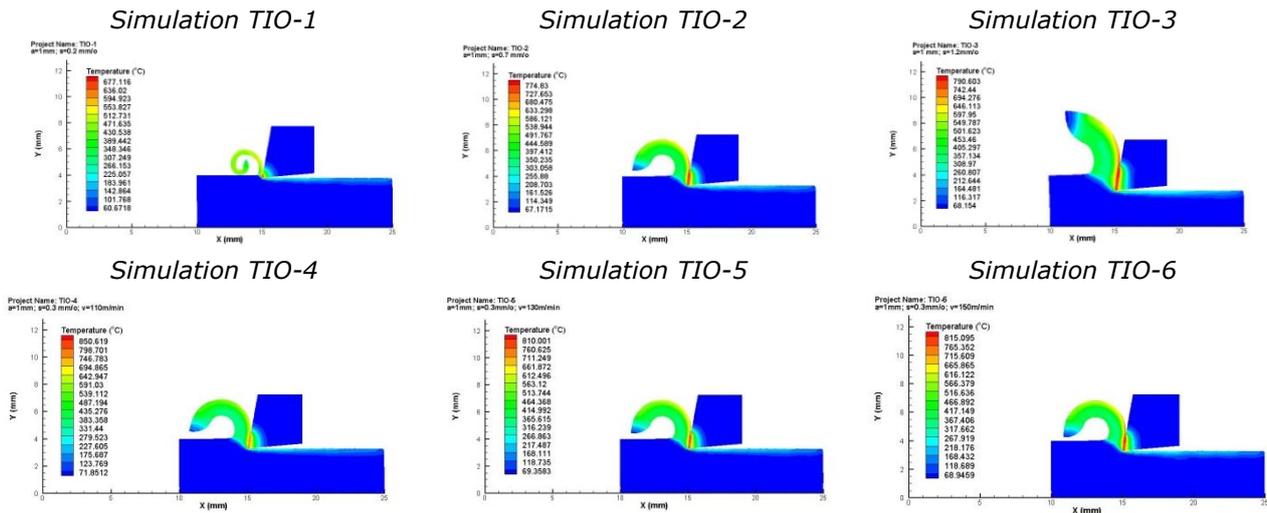


Figure 5. Comparative views of temperature in the cutting zone simulations, for different cutting parameters

Also, comparative diagrams of changes in cutting forces and temperatures in cutting zone for different cutting parameters were chosen as the output parameters of the simulations. Fig. 6 shows

comparative diagrams of the temperatures in cutting zone, and Fig.7.a and 7.b show comparative diagrams of the cutting forces for different cutting parameters.

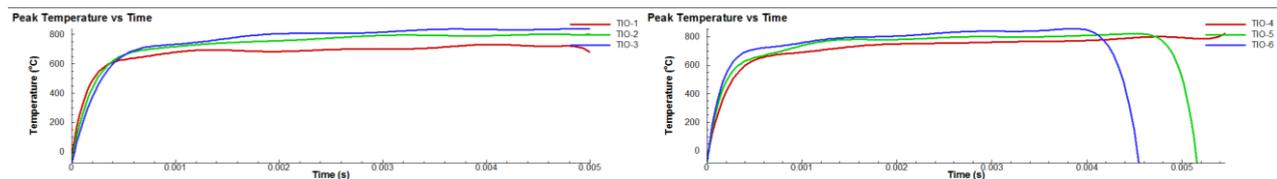
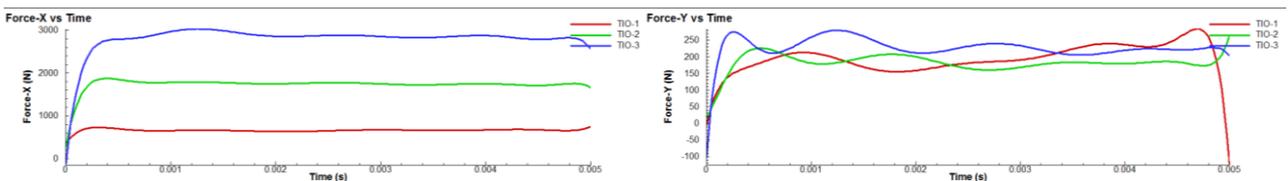
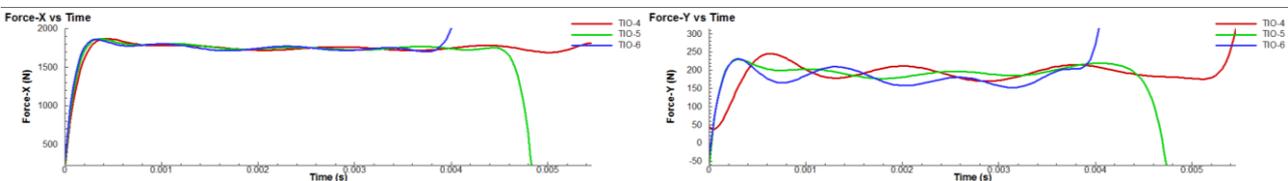


Figure 6.Comparative diagrams of temperatures in the cutting zone(TIO-1: $s=0,2\text{mm/o}$; TIO-2: $s=0,7\text{mm/o}$; TIO-3: $s=1,2\text{mm/o}$; TIO-4: $v=110\text{m/min}$; TIO-5: $v=130\text{m/min}$; TIO-6: $v=150\text{m/min}$)



a) $F_x = F_1$;

b) $F_y = F_2$



a) $F_x = F_1$;

b) $F_y = F_2$

Figure 7. Comparative diagrams of cutting forces(TIO-1: $s=0,2\text{mm/o}$; TIO-2: $s=0,7\text{mm/o}$; TIO-3: $s=1,2\text{mm/o}$; TIO-4: $v=110\text{m/min}$;TIO-5: $v=130\text{m/min}$; TIO-6: $v=150\text{m/min}$)

5. CONCLUSION

Based on the diagrams obtained by simulating the turning process, it can be seen that machining with increasing the feed leads to an increase in temperature. Machining with higher cutting speeds also results in an increase in temperatures in the

cutting zone. On the diagrams of the temperature distribution in the cutting zone, the difference in temperatures and their distribution, depending on the cutting parameters can be noticed. The paper also presents diagrams of changes in cutting forces F_1 (F_x on diagrams) and F_2 (F_y on diagrams) depending on the cutting parameters. From the

diagrams, it can be seen that the feed has a significant impact on main cutting force F_1 . Because the increase of the feed, the cross section of the chip also increases, which leads to an increase in the main cutting force F_1 . The cutting force F_2 does not change significantly with the feed change. The influence of the cutting speed on the cutting forces F_1 and F_2 is not significant as the influence of the feed. In the images obtained on the basis of simulations, a difference in the shape of the chip can be noticed, depending on the cutting parameters. The influence of the process parameters on the temperatures in the cutting zone and the cutting forces is a rather abstract concept for students. Due to the results of simulations, images and diagrams, these phenomena become visible, and thus more understandable to students. The simulations presented in the paper were taken out in demonstration mode, which takes less time, but the results are less accurate. Such simulations give a satisfactory concept of the temperatures in the cutting zone and cutting forces. They also give an idea of the influence of the cutting parameters on the temperatures in the cutting zone and cutting forces. In the case of more precise research, simulations should be done in simulation mode.

ACKNOWLEDGEMENTS

This study was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia, and these results are parts of the Grant No. 451-03-68/2020-14/200132 with University of Kragujevac - Faculty of Technical Sciences Čačak.

REFERENCES

- [1] Eckhardt, R. (1987). Stan Ulam, John von Neumann and the Monte Carlo Method., *Los Alamos Science*, 15, 131-136
- [2] Dali, M.N.A.M., Ghani, J.A. & CheHaron, C.H., (2017). Comparison between Dynamic and Non-Dynamic Cutting Tool Option in FEM Simulation for Producing Dimple structure, *Procedia CIRP*, 58, 613-616
- [3] Mitrović, A., (2016). Modeling of cutting process, *Ph. D. thesis*, Faculty of Technical Sciences, Novi Sad, Serbia, in Serbian
- [4] Nedić, B. & Lazić, M., (2007). Production technologies, Mechanical Faculty Kragujevac, Serbia, in Serbian
- [5] Kovač, P. & Milikić, D. (1998). Metal Cutting, Faculty of Technical Sciences, Novi Sad, Serbia, in Serbian
- [6] Third Wave Systems AdvantEdge 7.1, User's manual, 2015
- [7] Kincaid, J. P., Hamilton, R., Tarr, R., W. & Sangani, H., (2003). Simulation in Education and Training, *Applied System simulation*, pp 437-456
- [8] Movahhedy M. R., Gadala M. S. & Altintas Y., (2000). Simulation of chip formation in orthogonal metal cutting process: An ALE finite element approach, *Machining Science and Technology*, 4(1), 15-42
- [9] Zhang C., Mu A., Shen Q. & Zhang H., (2019). Simulation on Cutting Forces and Cutting Temperature in Broaching of 300M Steel, *THERMAL SCIENCE*, 23(5A), 2585-2594.