EFFECT OF TURNING PARAMETERS OF AISI 316 STAINLESS STEEL ON TEMPERATURE AND CUTTING FORCES WITH FINITE ELEMENT MODEL

by

Engin UNAL[*] and Faruk KARACA

Department of Mechanical Engineering, Technology Faculty, Fırat University, Elazig, Türkiye

Original scientific paper
https://doi.org/10.2298/TSCI22S1061U

Stainless steel materials are widely used in many industries today. Most of these materials are machined by turning. Modeling the temperature in the metal cutting process is a crucial step in understanding and analyzing the metal cutting process. However, when turning parameters are not chosen carefully, the integrity of the material deteriorates and the desired machining quality cannot be achieved. In this study, the effects of turning parameters on cutting temperature and force were investigated. Cutting speed, feed rate, and depth of cut were used as variable parameters for temperature and force analysis. Numerical analyzes were performed in ANSYS Workbench in accordance with the boundary conditions. Therefore, temperature distribution and cutting force were evaluated. As the control parameters increase, both the temperature and the cutting force increase. As a result, it can be considered that AISI 316 is the best choice for stainless steel alloy, since the minimum cutting speed, feed rate and minimum depth of cut conditions reduce the temperature formed in the cutting tool.

Key words: *AISI 316 stainless steel, cutting force, cutting temperature, finite element method, machining.*

Introduction

The most important and indispensable element of the machining industry is undoubtedly the cutting tools. Cutting tools used in all areas of the manufacturing sector directly affect the processing cost and production speed. The improvements in machining, the increase in cutting speed and feed rates day by day, the use of different materials in production and the development of machine tools have also led to the development of cutting tools. Today, the cutting properties of carbide tools have been significantly improved. Excellent combinations of alloying elements and heat treatments give this material excellent hardness and good toughness as well as wear resistance properties. As a result of technological developments, carbide tools that are coated and produced with powder metallurgy are used intensively today [1, 2]. Machinability has a very important place in the evaluation of the performance of cutting tools. Machinability parameters include the quality of the machined surface, the tempera-

[*]Corresponding author, e-mail: enginunal@firat.edu.tr

ture occurring during cutting, tool wear and force. The chip formation mechanism, in which machinability is mainly affected, is actually a very complex subject that brings together different branches of science (thermodynamics, plasticity, heat transfer). The heat generated during metal cutting is significant enough to affect the plastic deformation of the workpiece material as well as the cutting edge. Although softening and local ductility are required for machining hard materials, the heat generated has a negative effect on tool life and performance, and control of the cutting temperature is necessary to achieve optimum tool performance [2, 3]. For this reason, it is sometimes not possible to experimentally measure every parameter that occurs during cutting. Particularly, the finite element method is a widely used numerical analysis method for estimating some data (strain rate, tool stresses, tool-chip contact length and temperature distribution in the tool) during cutting. However, obtaining more realistic and experimental results from finite element solutions depends on the material model used and the friction conditions close to the friction conditions in real cutting conditions [4, 5]. When the studies on this subject are evaluated in general, it is seen that the Johnson-Cook material model is used more appropriately in the cutting process simulations [6-8].

In this study, the effects of depth of cut, feed rate and cutting speed parameters on the temperature and cutting forces at the tool-chip interface were investigated. In order to perform the turning operations in orthogonal conditions are modelled with the finite element method.

Material and method

In this study, the thermal variations and cutting forces at the tool-chip interface were investigated by simulating the turning process of AISI 316 steel in ANSYS Workbench. In order to analyze, a workpiece with a diameter of 40 mm and a height of 30 mm, whose material properties are given in fig. 1 due to temperature variation, was preferred.

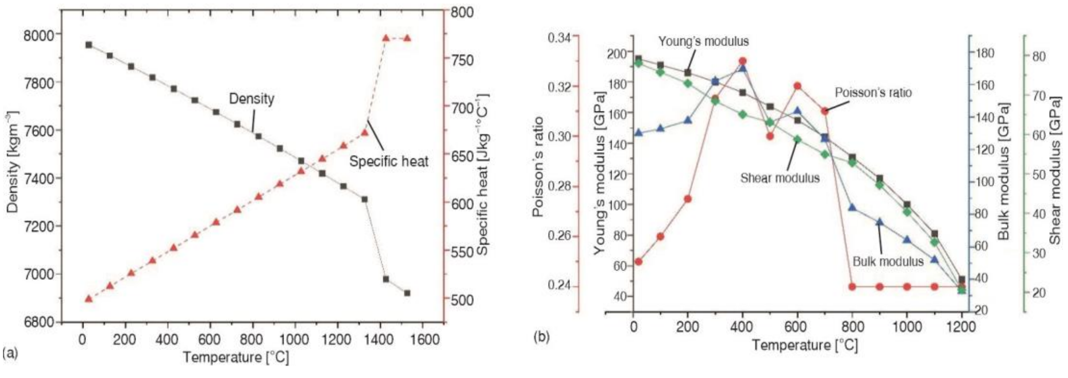

Figure 1. Mechanical properties of AISI 316 stainless steel; (a) density, specific heat via temperature and (b) poisson's ratio, Young's, bulk, shear modulus via temperature

The CCMT 09 T3 04-WM 4215 insert tool was used for turning. The explicit method is applied in finite element calculations. Time iterations are controlled by the ANSYS Workbench auto-increment technique. The cutting tool and workpiece model 102880 nod has element number 111927. The 0.1 mm tetrahedron element model was preferred for the cutting tool tip radius, and the Hexahedron element model was preferred for the workpiece, fig. 2. A 3-D unified thermomechanical model was created for the finite element analysis. In the transient thermal analysis, SOLID87 Tetrahedral Thermal

Solid structured elements containing 10 nodes used for 3-D heat transfer in the ANSYS program were used, fig. 2. This mesh structure has the ability to conduct heat in three dimensions and is preferred for both steady-state and transient analysis. It is very useful for transferring thermal calculations between nodes when it comes to structural analysis and is the most preferred type [9]. In the structural analysis of the temperature obtained from the thermal analysis using the mesh [10], these elements can be applied to the nodes as volumetric forces. According to the graph seen in fig. 3 previously reported in the literature, the number of mesh elements corresponding to the region after the intersection point of the temperature and solution time curves is reported as inefficient [11]. For this reason, the number of approximately 102880 elements before the intersection point was chosen as the optimum value for the analysis.

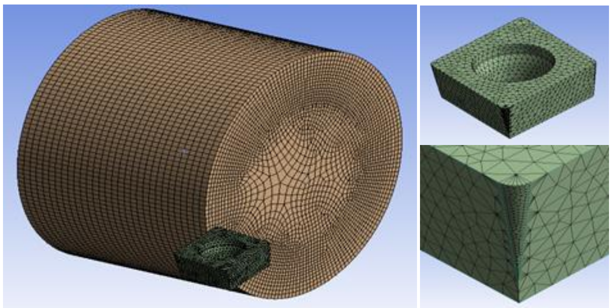

Figure 2. Mesh model of the cutting tool and workpiece

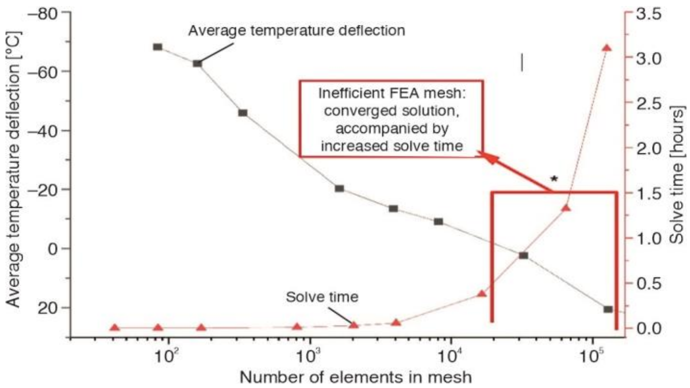

Figure 3. Confirmation study of the effect of mesh size on results

For the cutting speed parameter boundary condition, the rotational movement of the workpiece is applied at different cutting speeds, with the z-axis in fig.4 as the reference. The feed rate is modeled in the z-axis direction in fig. 4, with the machining parameters values given in tab. 1.

The cutting depth is provided by shifting the contact distance between the tool and the workpiece from the Geometry module. A total of 27 separate analyzes were performed for each cut-off level model. Thus, thermal variations and cutting forces occurring in the tool and workpiece were obtained.

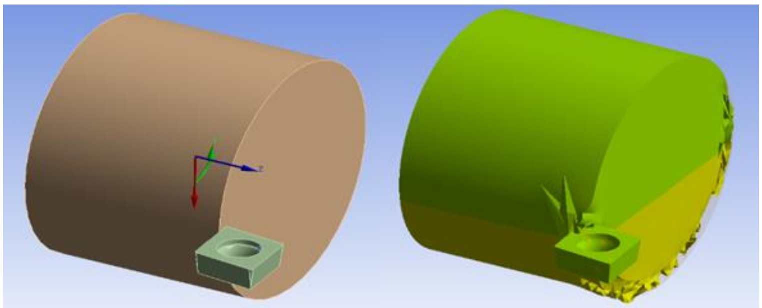

Figure 4. Orthogonal cutting model

Table 1. Experimental conditions of AISI 316

Factor	Level
Cutting speed, [m min^{-1}]	120 – 150 – 180
Feed rate, [mm rev^{-1}]	0.3 – 0.5 – 0.7
Depth of cut, [mm]	1 – 2 – 3

Results and discussion

During machining operations, thermal properties are important for tool life and deformation. High temperatures in the cutting process affect the tool and workpiece surface quality. The heat generated as a result of mechanical forces depends on the cutting conditions. Due to the friction in the chip slip zone and the tool rake surface, the temperature increase and as a result tool wear occur, and the tool life is also reduced [12]. One of the most important parameters affecting the temperature during cutting is the cutting speed.

In figs. 5(a)-5(c), changes in cutting tool temperatures and cutting forces depending on cutting speeds at 1 mm, 2 mm, and 3 mm depth of cut and 0.3, 0.5, and 0.7 [mm rev^{-1}] feed rate, respectively, are given. When fig.5 is examined, it is clearly observed that with the increase in cutting speed, the temperature at the tool tip and the cutting force increase. Here, the maximum temperature occurring in the tool at maximum cutting speed is 1147 °C, as shown in figure. The 180 [m min^{-1}] cutting speed at fig. 5(c), 0.7 [mm rev^{-1}] feed rate and 3 mm cutting depth parameter values were obtained. These values are the maximum parameter levels used in the model. On the other hand, the lowest tool temperature was obtained at 137.48 °C with 120 m min^{-1} cutting speed, 0.3 [mm rev^{-1}] feed rate and 1 mm cutting depth parameter values in fig. 5(a). Thus, in the finite element model presented, the maximum tool temperature at the maximum levels of the active parameters and the minimum tool temperature at the minimum levels have emerged. This result is similarly obtained in real experiments. As it is known, the cutting speed and the temperature change are directly proportional. In other words, with the increase of cutting speed, the temperature also increases [13]. Because, depending on the increasing cutting speed, the strain rate in the first deformation region also increases [14]. The high strain rate causes high heat generation during chip removal and thus the temperature increases [13, 15]. The tool temperature also increases with increasing depth of cut. This situation also agree with real experiments [16, 17].

In addition to the cutting temperature, the cutting force values increased with increasing feed rate and depth of cut. This is consistent with [18]. As can be mentioned from fig. 5, maximum numerical cutting force of 1288 N and 180 [m min^{-1}] cutting speed were obtained with 0.7 [mm rev^{-1}] feed rate and 3 mm pass amount parameter values. The lowest cutting force was obtained as 380.48 N with a feed rate of 0.3 [mm rev^{-1}], a depth of cut of 1 mm and a cutting speed of 120 [m min^{-1}].

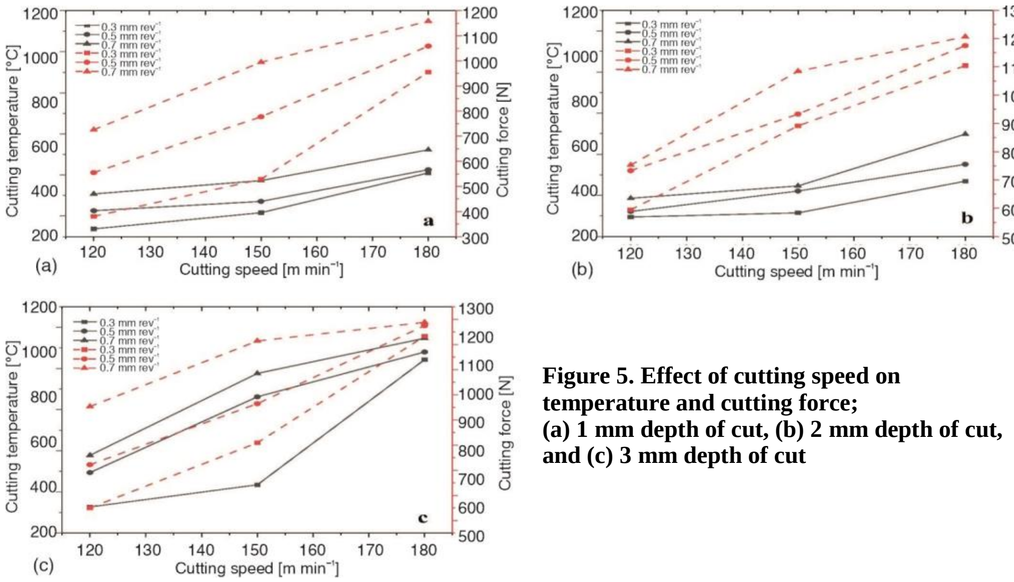

Figure 5. Effect of cutting speed on temperature and cutting force; (a) 1 mm depth of cut, (b) 2 mm depth of cut, and (c) 3 mm depth of cut

In addition, the temperature and cutting force variation depending on the feed rate are also given in figs. 5(a)-5(c). It is observed in all analysis results that the temperature formed with the increase of the feed rate increases. The effect of the feed rate on the tool temperature is more pronounced at high cutting speeds [3, 13, 19]. This increase in temperature with increasing feed rate is due to the increase in metal removal rate as the cutting energy increases with the metal removal rate. The increase in temperature promotes plastic deformation at the bottom of the cutting tool, which leads to further stretchable plastic deformation [20]. With increasing depth of cut and feed rate, the tool-chip contact area and the volume of material removed increase and therefore the main cutting force increases [21]. However, plastic deformation hardening occurs in austenitic stainless steels with increasing strength [22].

Conclusion

As a result, in this study, the turning process, which is one of the traditional machining methods today, can be modeled in the ANSYS finite element program and accordingly, the following conclusions can be drawn in the light of the information obtained within this modelling.

- The temperature and cutting forces increased with the increase in cutting speed.
- The temperature and cutting forces increased with the increase of feed rate.
- Temperature and cutting forces increased with increasing depth of cut.
- It has been observed that the most effective parameter in the temperature increase is the cutting speed.
- The FEM-based simulation models for commercially available software can be used for detailed estimates of temperature and cutting force distributions for these machining processes.

References

[1] Duan, C., *et al*., Finite Element Simulation and Experiment of Chip Formation Process During High Speed Machining of AISI 1045 Hardened Steel, *Int. J. Prod. Ind. Eng.*, *02* (2009), 01, pp. 28-32

[2] Petkovic, D., *et al*., Modeling of Cutting Temperature in the Biomedical Stainless Steel Turning Process, *Thermal Science, 20* (2016), Suppl. 5, pp. S1345-S1354

[3] Medina, N., *et al*., Influence of Turning Parameters on Cutting Temperature by Applying the Design of Experiments with the Definition of the Workpiece Material Behavior, *Thermal Science, 22* (2018), 6A, pp. 2539-2550

[4] Outeiro, J. C., *et al*., Modelling of Tool Wear and Residual Stress During Machining of AISI H13 Tool Steel, *AIP Conference Proceedings, 908* (2007), 1, pp. 1155-1160

[5] Nedić, B. P., Erić, M. D., Cutting Temperature Measurement and Material Machinability, *Thermal Science*, *18* (2014), Suppl. 1, pp. S259-S268

[6] Yuan, Y. F., *et al.*, Determination of Flow Stress Based on Cutting Simulation and Optimization, Advanced Materials Research, 189 (2011), Feb., pp. 2274-2279

[7] Arrazola, P. J., *et al*., A New Approach for the Friction Identification During Machining through the Use of Finite Element Modeling, *Int. J. Mach. Tools Manuf.*, *48* (2008), 2, pp. 173-183

[8] Vaxevanidis, N. M., *et al*., Surface Roughness Analysis in High Speed-Dry Turning of a Tool Steel, *Proceedings*, 10th Biennial Conf. Engineering Systems Design and Analysis, 2010, Istanbul, Turkey, Vol. 49156, pp. 551-557

[9] Buhr, C., *et al*., A Computationally Efficient Thermal Modelling Approach of the Linear Friction Welding Process, *J. Mater. Process. Technol.*, *252* (2018), Sept., pp. 849-858

[10] Jiang, H.-J., Dai, H.-L., Analytical Solutions for Three-Dimensional Steady and Transient Heat Conduction Problems of a Double-Layer Plate with a Local Heat Source, *Int. J. Heat Mass Transf., 89* (2015), Oct., pp. 652-666

[11] Gardiner, J., Finite Element Analysis Convergence and Mesh Independence, https://www.xceed-eng.com/finite-element-analysis-convergence-and-mesh-independence/

[12] Di, C., *et al*., An Investigation of Temperature and Heat Partition on Tool-Chip Interface in Milling of Difficult-to-Machine Materials, *Procedia CIRP*, *58* (2017), Dec., pp. 49-54

[13] Davim, J. P., Figueira, L., Comparative Evaluation of Conventional and Wiper Ceramic Tools on Cutting Forces, Surface Roughness, and Tool Wear in Hard Turning AISI D2 Steel, *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, *221* (2007), 4, pp. 625-633

[14] Stevenson, M. G., Oxley, P. L. B., An Experimental Investigation of the Influence of Speed and Scale on the Strain-Rate in a Zone of Intense Plastic Deformation, *Proc. Inst. Mech. Eng.*, *184* (1969), 1, pp. 561-576

[15] Sun, X., *et al*., Material Properties and Machining Characteristics Under High Strain Rate in Ultra-Precision and Ultra-High-Speed Machining Process: A Review, *Int. J. Adv. Manuf. Technol.*, *120* (2022), Apr., pp. 7011-7042

[16] Ciftci, I., Machining of Austenitic Stainless Steels Using CVD Multi-Layer Coated Cemented Carbide Tools, *Tribol. Int.*, *39* (2006), 6, pp. 565-569

[17] He, H. B., *et al.*, A Study on Major Factors Influencing Dry Cutting Temperature of AISI 304 Stainless Steel, *Int. J. Precis. Eng. Manuf.*, *18* (2017), 10, pp. 1387-1392

[18] Korkmaz, M. E., Gunay, M., Finite Element Modelling of Cutting Forces and Power Consumption in Turning of AISI 420 Martensitic Stainless Steel, *Arab. J. Sci. Eng.*, *43* (2018), 9, pp. 4863-4870

[19] Bono, M., Ni, J., The Effects of Thermal Distortions on the Diameter and Cylindricity of Dry Drilled Holes, *Int. J. Mach. Tools Manuf.*, *41* (2001), 15, pp. 2261-2270

[20] Hua, J., *et al*., Effect of Feed Rate, Workpiece Hardness and Cutting Edge on Subsurface Residual Stress in the Hard Turning of Bearing Steel Using Chamfer+hone Cutting Edge Geometry, *Mater. Sci. Eng. A*, *394* (2005), 1-2, pp. 238-248

[21] Korkmaz, M. E., *et al*., Numerical and Experimental Investigation of Cutting Forces in Turning of Nimonic 80A Superalloy, *Eng. Sci. Technol. an Int. J.*, *23* (2020), 3, pp. 664-673

[22] Byun, T., *et al*., Temperature Dependence of Strain Hardening and Plastic Instability Behaviors in Austenitic Stainless Steels, *Acta Mater.*, *52* (2004), 13, pp. 3889-3899

Paper submitted: August 15, 2022
Paper revised: September 17, 2022
Paper accepted: October 10, 2022