NUMERICAL INVESTIGATION OF MACHINING CHARACTERISTICS OF HASTELLOY-X

Mehmet Alper Sofuoğlu[1*], Fatih Hayati Çakır[2], Selim Gürgen[2], Sezan Orak[1], Melih Cemal Kuşhan[1]

[1]Eskişehir Osmangazi University, Mechanical Engineering Department, 26480, Eskişehir, Turkey
[2]Vocational School of Transportation, Anadolu University, 26470, Eskişehir, Turkey
Corresponding author:[*]asofuoglu@ogu.edu.tr

Abstract: Nickel-based alloys provide high corrosion resistance and high-temperature strength but these alloys possess poor machinability. Hastelloy-X is one of the nickel-based alloys. There are many studies about finite element modeling of nickel-based alloys but studies of Hastelloy- X are limited. In the present work, machining characteristics of Hastelloy-X were investigated and a numerical model was developed for the turning operation of Hastelloy-X. Cutting speed of 40 m/min and feed rate 0.1 mm/rev were taken into consideration in the operations and the results were evaluated considering process outputs such as cutting forces, cutting temperature and effective stresses The proposed model is applicable for the turning operation of Hastelloy-X.
Keywords: Hastelloy-X, turning operation, DEFORM-2D

Introduction

Modern product designs and manufacturing technologies are changing day by day. In this context, there are many innovative methods used in manufacturing and many methods applied in improving manufacturing processes. Some of the developed methods (3d printing, etc.) work differently according to the traditional manufacturing methods. The use of nickel alloys is important with the development of aviation and the energy sector. For this reason, it's machining needs to be investigated thoroughly.

Nickel-based alloys are extensively used because of their advantages in the spacecraft engines and gas turbine components These alloys have some important benefits: being heat-resistant, retaining their high mechanical and chemical properties at elevated temperatures, having high melting temperatures, enhanced corrosion resistance as well as resistance to thermal fatigue, thermal shock, creep, and erosion (Akıncıoğlu et al., 2016; Ulutan and Özel, 2010). However, these alloys have some problems in machining because they have an austenitic matrix and similar with stainless steels, work hardening is rapidly seen during machining. Also, increase in tool flank wear, cratering and notching are observed at elevated temperatures. (Choudhury and El-Baradie, 1998).

According to literature studies, machining of Hastelloy was not sufficiently investigated. Furthermore, previous studies focus on the statistical models based on experimental results. Hastelloy is a candidate material to be investigated through numerical studies in order to improve the machining operations and reduce the experimental expenses. In the present work, a numerical model was developed for the turning operation of Hastelloy-X. The verification of the numerical model was performed comparing the maximum insert cutting temperatures with the experimental results. In addition to these outputs, effective stresses and cutting forces were discussed.

Materials and Methods

In this work, 2D finite element model for orthogonal cutting is developed in DEFORM-2D program. In this context, Langrange finite element formulation is used by continuous and adaptive meshing method. Dry cutting conditions are used in the tests. 2-dimensional simulation studies in machining are preferred because of their simplicity and solution time comparing to 3D simulation studies. Hastelloy-X is used as material. The workpiece is assumed as plastic. The tool is assumed rigid in developed model. In the simulations, ultrasonic vibration is applied at 20 kHz and 20 microns in the cutting direction. The feed rate is taken as 0.1 mm/rev. Cutting speed is selected as 40 m / min. Mesh convergence is obtained. 2500 elements for Hastelloy-X and 1500 elements for tungsten carbide tool are determined and results are not changed above the number of these elements. With the remeshing operation, the number of mesh is increased in the cutting region at the time of machining, thereby facilitating the convergence of the solution. In the simulations, X is the cutting direction and Y is the feed direction (Figure 1).

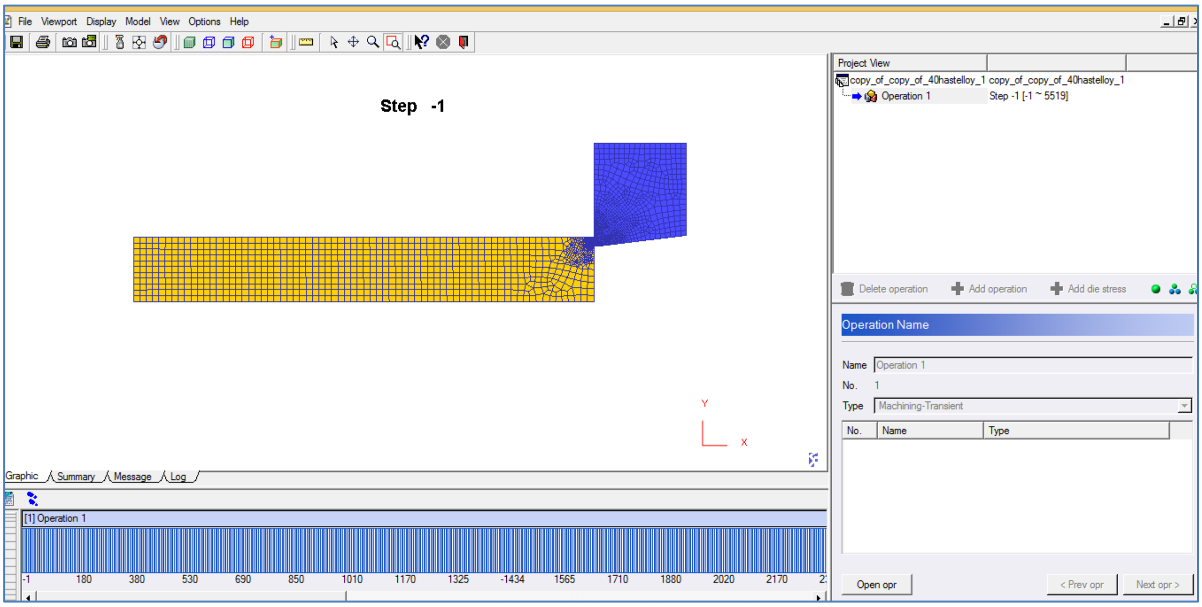

Figure 1. A snapshot from DEFORM-2D

The initial temperature of the workpiece is set as 20 ° C. The Johnson Cook (JC) material model is used to model the workpiece. In high strain situations, JC model produces reasonable results. This model shows the precision of the strain rate in the material. Equations for this model are given in Eq. 1-2. Table 1 shows the coefficients of this model.

$$\sigma = \left(A + B\varepsilon^{n}\right)\left(1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)\left(1 - T^{*}\right)^{m} \qquad (1)$$

$$T^{*} = \frac{\left(T - T_{room}\right)}{\left(T_{melt} - T_{room}\right)} \qquad (2)$$

$\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}$: strain rate / reference strain rate

n : strain rate sensitivity for the material

T_{room}: Room temperature

T_{melt}: Melting temperature of workpiece

A, B, C, m : Material constants

Table 1. Johnson Cook coefficients for materials used in simulations

	A(MPa)	B(MPa)	C	n	m	$\dot{\varepsilon}_0$
Hastelloy-X	380	1200	0.012	0.55	2.5	0.001

Johnson Cook material models are based on many tests and coefficients are determined by curve fitting techniques. Split Hopkinson compression tests are performed at different strain rates and temperatures in order to determine the model coefficients. The coefficients used in this study were given in Table 1. These values were reported in literature by Abotula et al. 2011.The material of the cutting tool is WC + TiAlN coating and cutting tool has a rake angle of 0° and a clearance angle of 7°. The tool tip hone radius is 0.02 mm.

Different damage models and fracture criteria have been defined in the literature in order to predict of chip shapes and cutting forces. Cockcroft & Latham fracture criterion is selected in this study. Thus, the morphology of serrated chips could be observed. Similar approach was used before the study performed in the literature (Çakır et al., 2015).

Friction model and coefficients are determined by using different studies in the literature (Özel and Ulutan, 2012). The friction zones determined during the machining of Hastelloy-X are given in Fig 2. The friction zone is divided into two sections. The part of the tool hone radius is taken as shear friction zone and the value is 0.9. The second region is defined on the top of this region to the portion where the chips are rubbing the cutting tool. This region is determined as coulomb friction and the value is taken as 0.7.

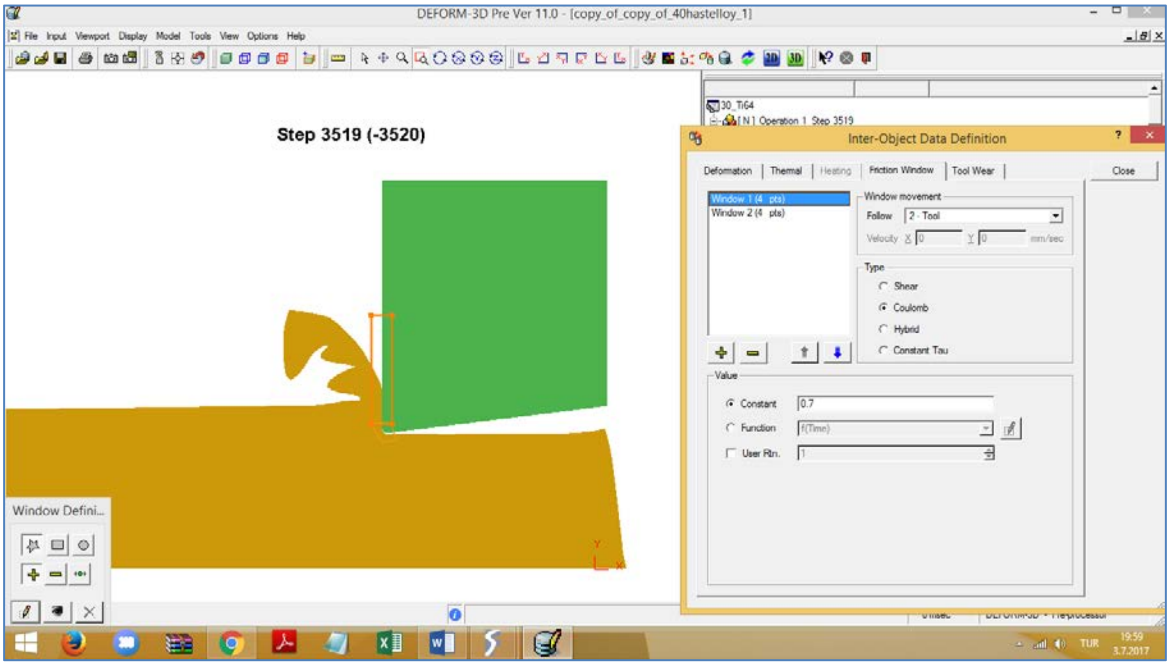

Figure 2. Friction zones determined during the machining of Hastelloy-X

Material properties for Hastelloy-X were given at Table 2. These properties have been determined with literature studies and in the producers catalogs as follows (Aghaie and Golaizi, 2008; Abotula et al., 2014).

Table 2. Mechanical and thermal properties of Hastelloy-X used in simulations

	Hastelloy-X
Modulus of Elasticity (MPa)	25^{0}C-205000 200^{0}C-198000 400^{0}C-187000 600^{0}C-173000 800^{0}C-157000
Thermal expansion (mm.mm^{-1}.°C^{-1})	20^{0}C-1.3e-5 200^{0}C-1.35e-5 400^{0}C-1.41e-5 500^{0}C-1.43e-5
Thermal conductivity (W.m^{-1}. °C $^{-1}$)	25^{0}C-9.2 200^{0}C-14.1 600^{0}C-21.9 800^{0}C-24.7
Emissivity coefficient	0.85
Poisson's ratio	0.32

Results and Discussion

Mean cutting forces, maximum cutting insert temperatures and maximum effective stress values are investigated in the numerical study.

Maximum cutting insert temperatures

Numerical results have been compared to experimental study to verify the developed numerical model. Maximum insert temperatures at the cutting edge measured during machining of Hastelloy-X alloy is given in Table 3. Results of experimental study and numerical results are compared. It can be said that the developed numerical model can predict cutting insert temperature within a range of 20% error. In this context, it is observed that the numerical model satisfies the experimental results.

Table 3. Maximum insert cutting temperatures

	Experimental (˚C)	Simulation (˚C)
Conventional turning	208.2	167.73

Mean cutting forces

Numerically determined mean cutting forces for Hastelloy-X are given in Figure 3. The force in the X direction is about 110 N and the force in the Y direction is about 30 N.

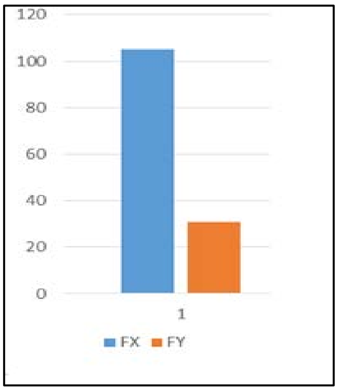

Figure 3. Cutting forces (N) for Hastelloy-X

Effective stresses

Effective stress distributions in turning of Hastelloy-X is shown in Figure 4. In conventional turning, the maximum effective stress is nearly 1600 MPa.

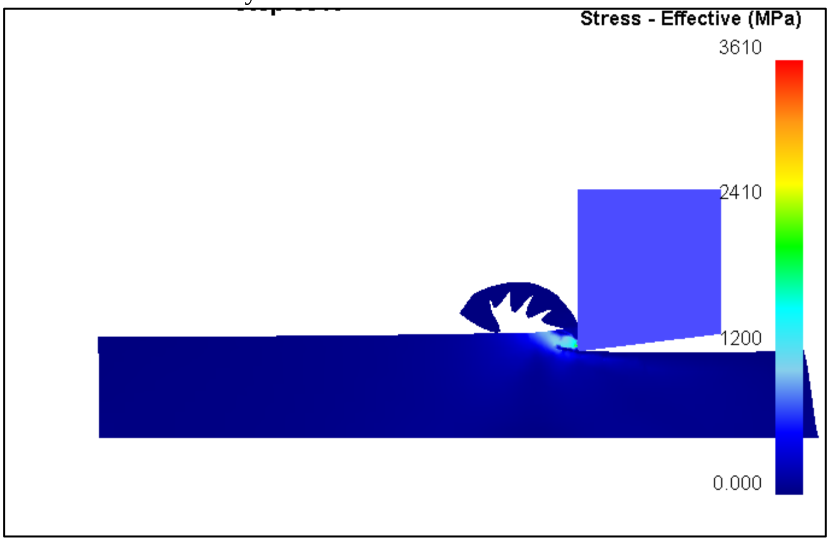

Figure 4. Effective stress distribution in turning of Hastelloy-X

Conclusion

In this study, machining of Hastelloy-X is modelled using finite element method. Mean resultant cutting force in the simulations is nearly 110 N. Maximum effective stress is approximately 1600 MPa. Maximum insert temperature is 167 ^{0}C which exhibits good agreements with the experimental results.

Acknowledgements

This work was financially supported by the Scientific and Technological Research Council of Turkey (TÜBİTAK Project #215M382) and the Research Fund of Eskişehir Osmangazi University (ESOGU BAP Project #2016-1086). The authors M.A.Sofuoğlu and S.Gürgen acknowledge the support of TÜBİTAK under programs 2228 and 2211 respectively.

References

Abotula, Sandeep, Shukla, Arun and Chona, Ravi. (2011). Dynamic Constitutive Behavior of Hastelloy X under Thermo-Mechanical Loads. *Journal of Materials Science* 46 (14): 4971–79.

Abotula, S., Heeder, N., Chona, R. and Shukla, A. (2014). Dynamic Thermo-Mechanical Response of Hastelloy X to Shock Wave Loading. *Experimental Mechanics* 54 (2): 279–91.

Aghaie-Khafri, M. and Golarzi, N.,(2008). Forming Behavior and Workability of Hastelloy X Superalloy during Hot Deformation. *Materials Science and Engineering*: A 486 (1–2): 641–47.

Akıncıoğlu, S, Gökkaya, H and Uygur, İ., (2016) The effects of cryogenic-treated carbide tools on tool wear and surface roughness of turning of Hastelloy C22 based on Taguchi method", *Int. J. Adv. Manuf. Technol.*, vol. 82, no. 1–4, pp. 303–314.

Çakır, Fatih Hayati, Gurgen, Selim, Sofuoglu, M.A. Celik, O.N. and Kushan, M.C., (2015). Finite Element Modeling of Ultrasonic Assisted Turning of Ti6Al4V Alloy. *Procedia - Social and Behavioral Sciences* 195 (Temmuz): 2839–48. doi:10.1016/j.sbspro.2015.06.404.

Choudhury, I., and El-Baradie, M., (1998) Machinability of nickel-base super alloys: a general review, *J. Mater. Process. Technol.*, vol. 77, no 1–3, pp. 278–284

Özel, Tuğrul, Sima, M. and Srivastava, A.K., (2010). Finite element simulation of high speed machining Ti-6Al-4V alloy using modified material models. *Transactions of the NAMRI/SME* 38: 49–56.

Özel, T., and Ulutan, D., (2012). Prediction of Machining Induced Residual Stresses in Turning of Titanium and Nickel Based Alloys with Experiments and Finite Element Simulations. *CIRP Annals - Manufacturing Technology* 61 (1): 547–50.

Ulutan, D. and Ozel, T., (2011) Machining induced surface integrity in titanium and nickel alloys: A review, *Int. J. Mach. Tools Manuf.*, vol. 51, no 3, pp. 250–280

