Estimating Machinability Factors in Turning of Inconel 625 under different lubricating conditions using 3D DEFORM FE Analysis

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Abstract: *This paper contributes to the investigation of machinability factors in turning the nickel-based Inconel 625 superalloy with PVD coated TiAlN tungsten carbide cutting insert. The machinability parameters – cutting force (Fc), tool wear rate* (dw/dt)*, and tool temperature (T) are visualized graphically using the FE model based Deform 3D software interface. The paper discusses the application of boundary conditions, and meshing used for simulating results. The results of the dry turning simulation showed a maximum level of cutting force, tool-tip temperature, and tool wear rate in comparison with conventional MQL and NMQL conditions. The NMQL conditions showed a reduction in cutting force with the use of h-BN NMQL environment compared with dry and conventional MQL machining by 41% and 27%, respectively. Further, the comparison of cutting tool temperature for three simulated conditions showed a clear-cut reduction of temperature in NMQL conditions in comparison with dry and conventional MQL, by 44% and 30%, respectively.*

Key Words: *Cutting force, Deform 3D, Inconel 625, Machinability, Tool temperature, Tool wear rate*

1. INTRODUCTION

In current manufacturing industries the superalloys of nickel and titanium are frequently used in aerospace, electronics, defense, medical and marine sectors as they have a distinct blend of characteristics like the ability to maintain good strength at elevated temperatures, corrosion and wear resistance (Lotfi et al., 2016, [9]).

In this regard, Inconel 625 is a nickel -based superalloy that is widely used in the aerospace and gas turbine engine manufacturing industries due to its superior properties such as high melting temperature, high corrosion and creep resistance and maintaining the required strength and hardness at high temperatures (Lotfi et al., 2016, [8]). But machining Inconel 625 and other similar materials presents major challenges, such as high heat generation and increased cutting force in the machining area, with an increased rate of tool wear, which eventually adds to the product cost. Therefore, by keeping that in mind the use of NCF (Nano-cutting fluids) with the MQL technique has emerged as an advantage in the manufacturing industry, as it improves the machinability with minimal use of cutting fluids, precisely considering the case of hard materials. (Li et al., 2002 [5]; Park et al., 2017, [11]).

The application of NCFs (Daugthongsuk et al., 2007, [3]) is due to the higher surface area to volume ratio, which improves the heat transfer state, good dispersion stability and wettability which is dependent on the concentration of nano additives.

For sustainable machining, the cost of production should be low without reducing the product quality. The higher cutting forces and machining temperature directly affect the production cost as it causes high friction and elevated rate of tool wear which reduces the tool life as well as the surface finish of the work material.

In this regard, hexagonal Boron Nitride (h-BN) nanoparticles are identified as one of the main additives in base conventional cutting fluids. These lamellar hexagonal structured, environmentally friendly solid lubricants are well-known for good thermal stability and high thermal conductivity that make them a valuable additive for conditions that require rapid removal of heat (Lipp et al., 1989, [6]). Hence, this paper focuses on investigating how the machinability of the Inconel-625 superalloy is affected with the use of nano-cutting fluids with the MQL technique during machining.

DEFORM-3D software is used for the preliminary study which analyzes the machinability of Inconel 625 with Dry, MQL, and NMQL conditions. The metal cutting model was developed using the Lagrangian formulation. The developed model is capable of simulating the cutting conditions based on frictional conditions and the mechanical properties of the tool and work material.

The performance factors such as cutting force (F_c), tool wear rate ($\frac{dw}{dt}$), and tool temperature (T) are visualized graphically using a software interface. The FE model geometry, the application of boundary conditions, and meshing used for this research are discussed here.

2. FINITE ELEMENT ANALYSIS USING DEFORM

DEFORM-3D 11.0 is a commercially available Finite Element tool that is used for the analysis of the machining process. The use of DEFORM 3D aids to obtain information that is tough to be iterated through experimental work, also helping to make problems of finite element less expensive and time-consuming.

The analysis of machining operation is done with the help of the Lagrangian method and the arbitrary Lagrangian-Eulerian method. This software produces a graphical as well as a pictorial representation of the simulation process.

The performance factors like cutting force/load (N), tool wear rate (mm/sec), and temperature (ºC) distributions are visualized graphically in the software interface. The finite element method in DEFORM-3D is solved by three step process e.g. pre-processing, simulation, and post-processing.

In the pre-processing segment, the work material properties (Inconel 625) and tool material (TiAlN, PVD coated tungsten carbide) properties are defined and the simulation is performed in steps based on the cutting conditions, and the model is stored in the database.

In the next segment of the computational analysis, the various inputs were assigned, such as the number of elements, the number of simulation steps required, process conditions, the orientation of the tool, and the workpiece etc.

Once initial conditions are assigned, the model simulation is done. Finally, the results can be viewed in the post processor.

Figure 1. shows the process flow of the Deform 3D computational system (Besha et al., 2021, [1]).

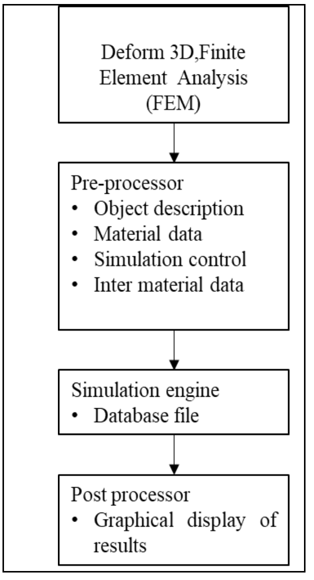


Figure 1: Process flow of Deform - 3D

3. EXPERIMENTAL DETAILS

3.1 Prediction of machinability parameters for machining under different lubricating conditions

For predicting the performance parameters (F_c, T, dw/dt) under different lubricating conditions, the simulation was performed with the optimized set of parameters attained from Taguchi grey analysis as - (v_c) as 60m/min, (f) as 0.3 mm/rev, and (d_c) as 0.25mm. Figure 2 depicts (a) the analysis domain during simulation (b)the pre-cut surface of the workpiece and (c) the .STL file which is used in DEFORM 3D v.11 software for modeling. The properties of Inconel 625 and tungsten carbide tool are defined in Table 1 and 2, respectively.

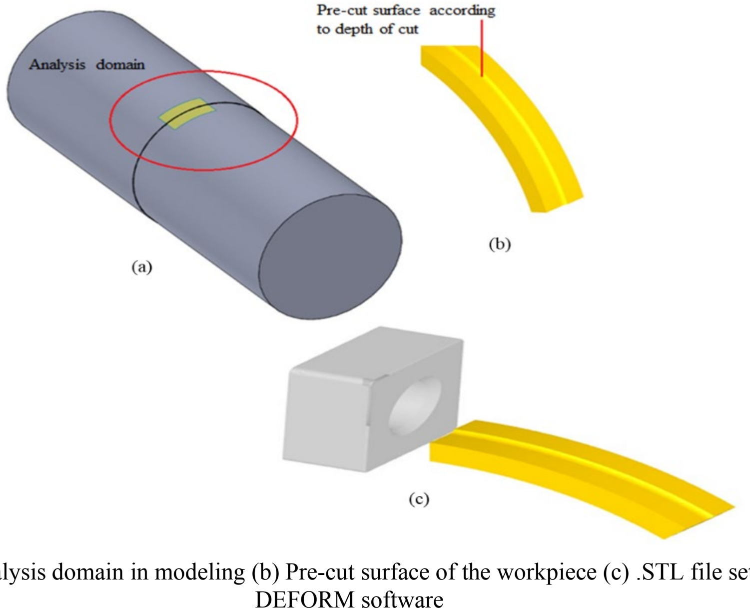


Figure 2: (a) Analysis domain in modeling (b) Pre-cut surface of the workpiece (c) .STL file setup used for DEFORM software

Table 1: Thermo-physical properties of Inconel 625 [Lotfi et al., 2016]

Property	Value
Specific heat (J/kg.ºC)	430
Thermal conductivity (W/m ºC)	9.8
Poisson's ratio	0.308
Elastic modulus (GPa)	209
Thermal expansion E-06 (m/mºC)	12.8
Yield strength (MPa)	558.8
Hardening modulus (MPa)	2201.3
Strain rate sensitivity coefficient	0.000209
Thermal softening coefficient	0.8
Hardening coefficient	1.146
Melting temperature of the work material (ºC)	1350
Plastic strain rate (ᵋ0)	1670 s-1
Material Emissivity	0.85

Table 2. Thermo-physical properties of tool material WC [Lotfi et al., 2016]

Property	Value
Density (ρ) kg/m^3	14.5×10^3
Ultimate tensile strength (MPa)	3,000
Modulus of elasticity (GPa)	650
Thermal conductivity (W/(m K))	58.9888
Poisson ratio	0.25
Heat capacity (J/kg ^{0}K)	15.0018

For simulation of turning Inconel 625 a sparse solver is used. 250 steps are used for the simulation process. Each time – step included 5.93876e-06 second which is proportional to 0.01232 mm of cutting length for each stroke step. Therefore, the total length of 3.08241mm of work material with 1.48e-03 seconds of time was spent simulating each of the considered lubricating environments. The tool and work material are defined as rigid and plastic objects.

The Johnson-Cook flow stress model (Lotfi et al., 2016, [8]) is used to define the workpiece material constitutive behavior, refer to equation 1,

$$\sigma = [A + B(\varepsilon^{-n})]\left[C\, ln\left(\frac{\acute{\varepsilon}}{\acute{\varepsilon}_0}\right)\right]\left[1 - \left[\frac{T - T_r}{T_m - T_r}\right]^m\right] \quad (1)$$

where σ is the equivalent flow stress, ε is the equivalent strain, έ is the plastic strain rate, ε_0 is the reference of plastic strain rate constants A, B, C, n, and m are the yield strength, hardening modulus, strain rate sensitivity coefficient, strain-hardening, and thermal softening exponent, respectively (refer to table 1).

Also, T is temperature, T_m is melting temperature, and T_r is reference temperature (20°C). The mesh of 171228 elements are defined for better distribution of output parameters. The simulation process was carried out with a feed rate of 0.3 mm/rev, cutting velocity 60 /min, and depth of cut 0.25 mm; these are optimal machining parameters achieved from Taguchi-Grey analysis from preliminary experiments and literature (C. Padhy et al., 2020, [10]). The simulation of the performance parameters such as F_c, T, and dw/dt were analyzed.

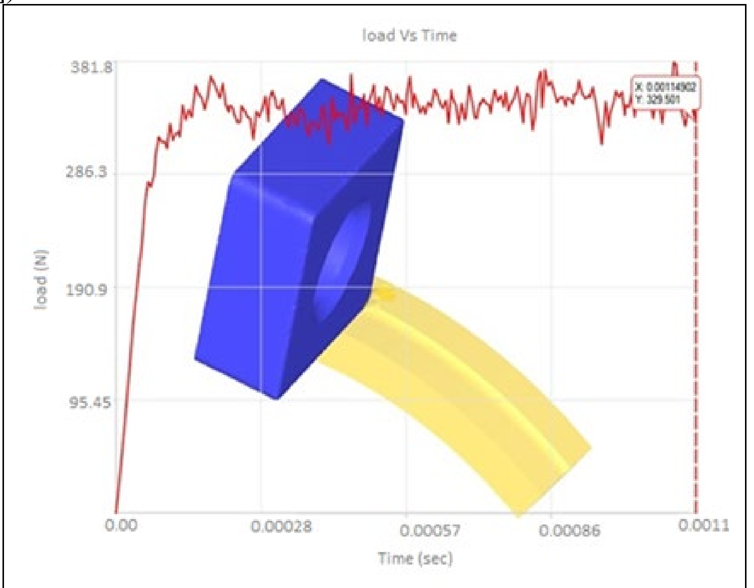
4. RESULTS AND DISCUSSIONS

4.1 Prediction of the cutting force under different lubricating conditions

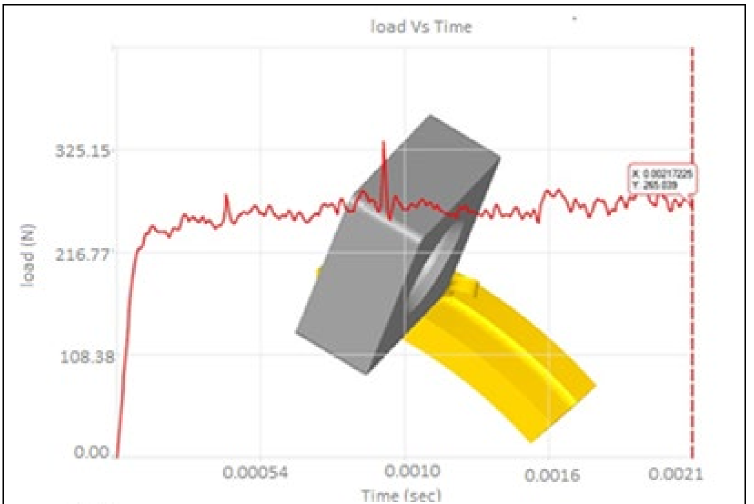
Figure 3 describes the cutting forces (load) generated by the FEM simulation for dry lubrication, conventional MQL, and h-BN NMQL, respectively. The simulated cutting force is highest for dry lubrication with the reduction in the case of MQL environment and further reduces for MQL nano lubrication with h-BN additives.

The highest cutting force is recorded in the case of dry machining because of the absence of lubrication which increases the friction at the machining zone. A clear reduction in cutting force in h-BN NMQL environment over dry by 41% approximately 27 % over conventional MQL machining is seen. The cutting forces are affected by the generated friction.

An increase in friction elevates the value of the cutting force. For simulation, the μ (coulomb friction constant) values are taken as 0.6, 0.3, and 0.2 for Dry, conventional MQL, and NMQL conditions, respectively (Filice et al., 2007, [4]; Celik et al., 2013, [2]; Loganathan et al., 2018, [7]).



(a)



(b)

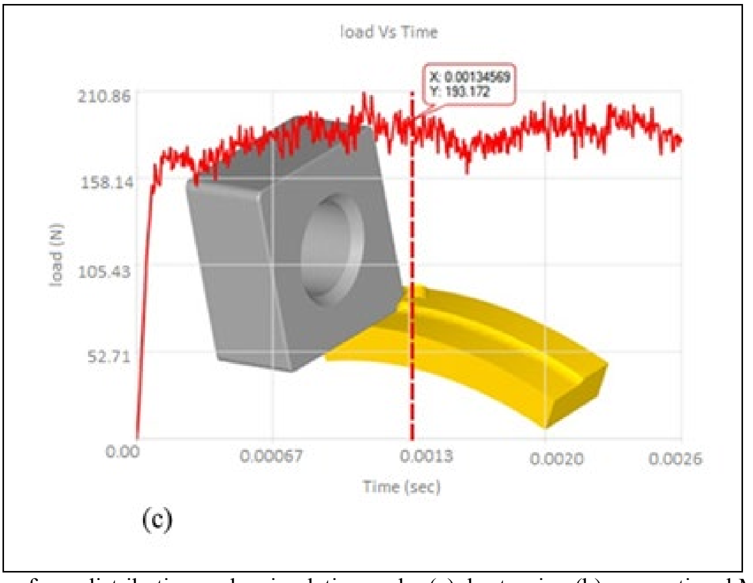
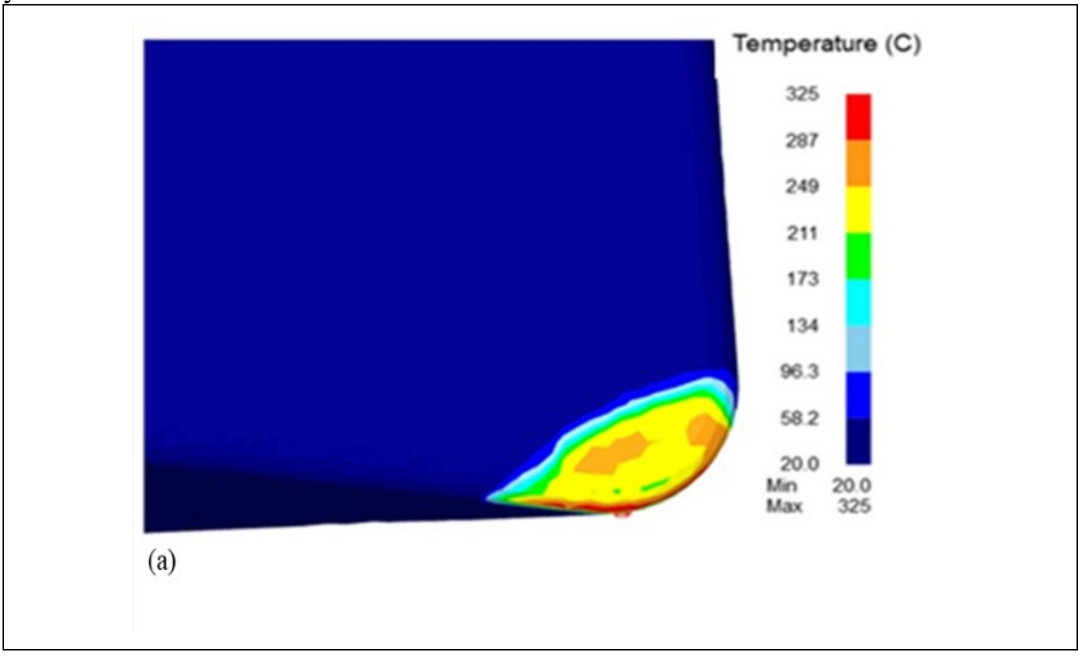
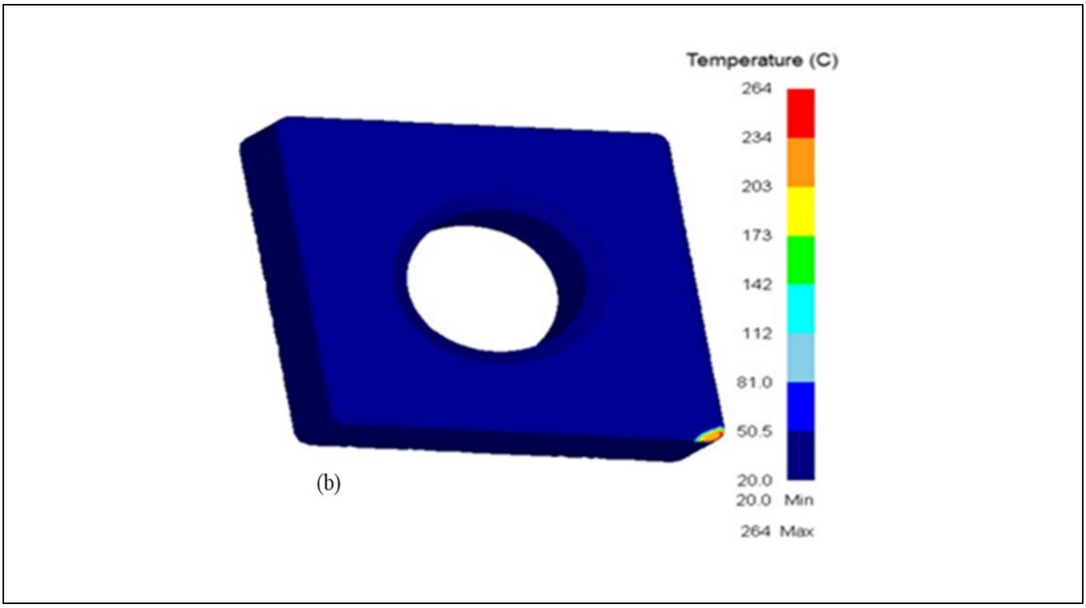


Figure 3: Cutting force distribution under simulation under (a) dry turning (b) conventional MQL (c) h- BN NMQL environment

4.2 Prediction of the tool temperature under different lubricating conditions

Figure 4 depicts the tool temperature during machining of Inconel, using different lubricating conditions. The cutting tool temperature was recorded for dry turning as 325ºC, for conventional MQL as 264ºC, and for NMQL with h-BN nano cutting fluid as 183ºC. The comparison of three simulated cutting tool temperatures showed a reduction of temperature for NMQL conditions in comparison with dry and Conventional MQL by 44% and 30% respectively. This shows clearly that the high rise of temperature in dry turning is due to higher plastic work and the absence of cooling fluid, which is lowest in turning with the NMQL system.





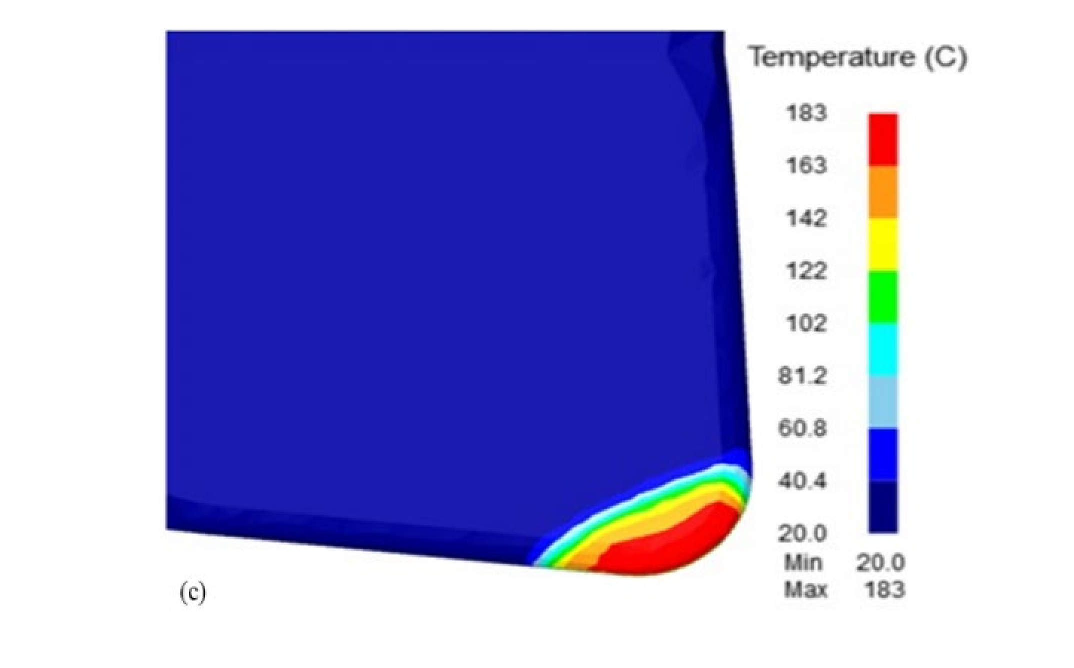


Figure 4: Cutting tool temperature distribution under simulation under (a) dry, (b) conventional MQL, (c) h- BN NMQL environment

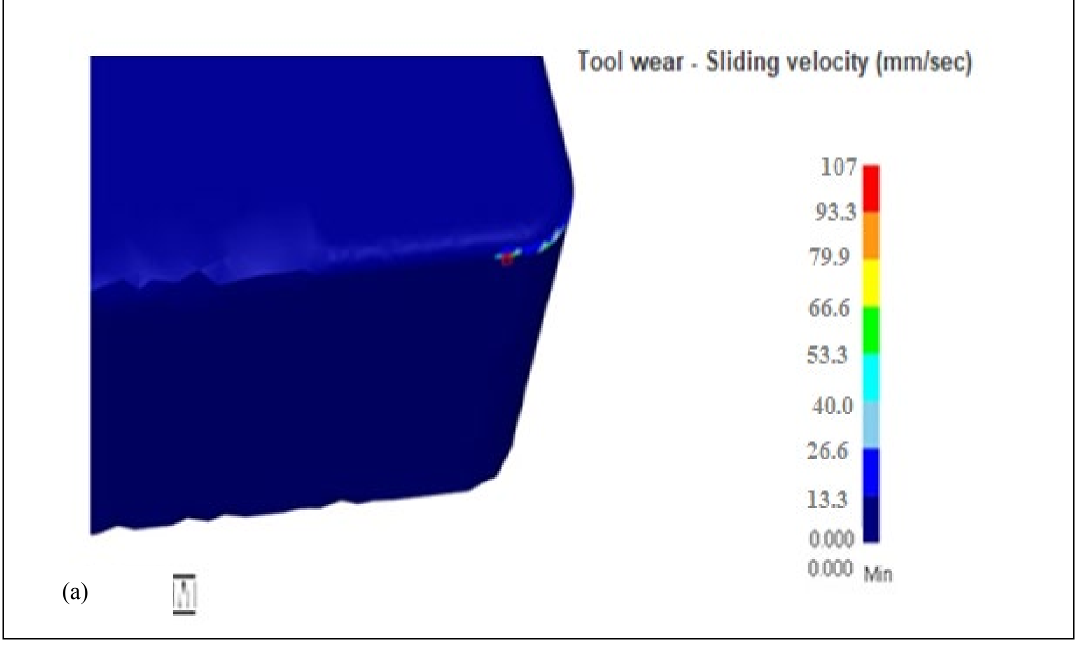
4.3 Prediction of the tool wear rate under different lubricating conditions

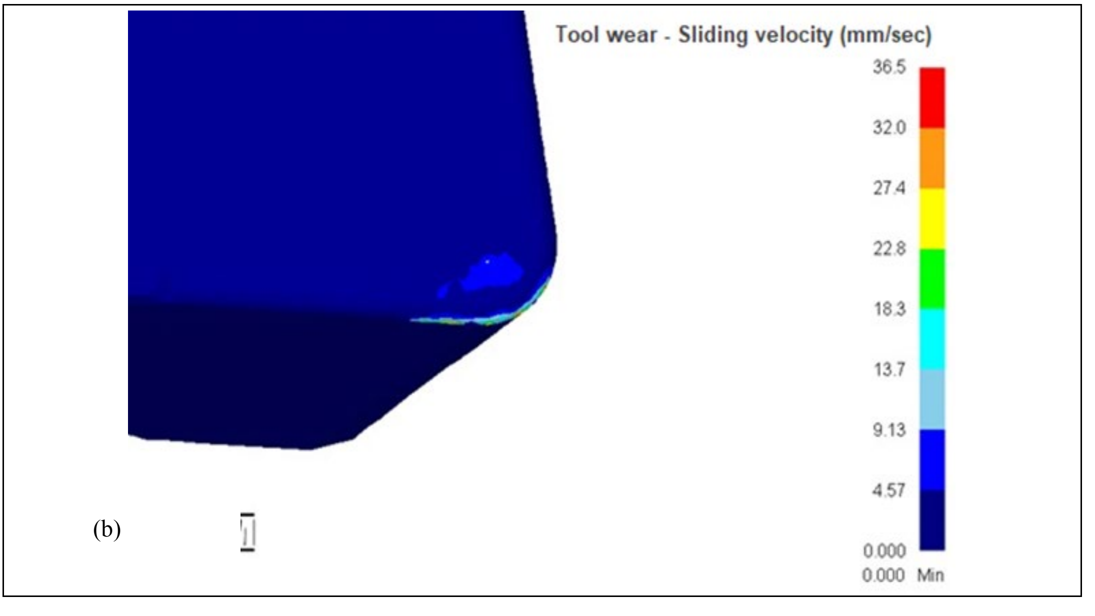
The tool wear under Dry, conventional MQL, and h-BN MQL is investigated and analyzed. A higher range of tool wear rate is observed for dry turning in comparison to conventional MQL and NMQL. The large coefficient of friction in dry machining which attributes to higher sliding velocity causes an increase in machining temperature. The tool wear rate (dw/dt) is a function of sliding velocity (ϑ), pressure generated (p) and temperature(T) as explained by

Usui model (with A, B as constants, A = $3.6e^{-9}$ and B = 1200 for TiAlN-coated carbide tools), refer to equation 2 (Usui et al., 1984, [12]).

$$\frac{dw}{dt} = A \times \mathrm{p} \times \vartheta \times e^{\frac{-B}{T}} \tag{2}$$

Figure 5 shows the sliding velocities at the cutting edge of the tool for (a) dry, (b) conventional MQL, and (c) NMQL conditions. Refer to figure 6, 7 and 8 for tool wear rate versus sliding velocity achieved for different lubricating conditions. The graphs show that as the sliding velocity decreases with conventional MQL and NMQL machining, the rate of the tool wear also decreases significantly in comparison to dry machining.





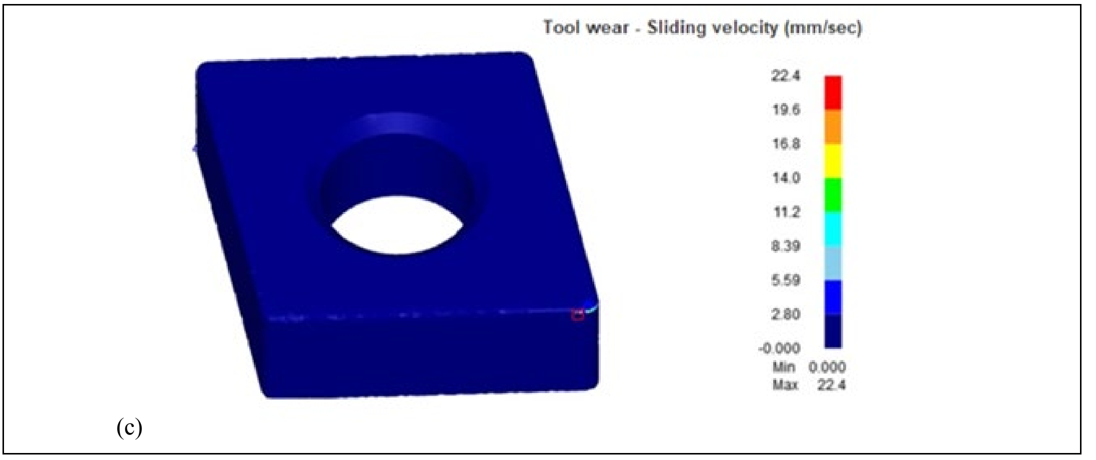


Figure 5: Sliding velocity on the cutting edge under (a) dry, (b) conventional MQL, (c) h- BN NMQL environment

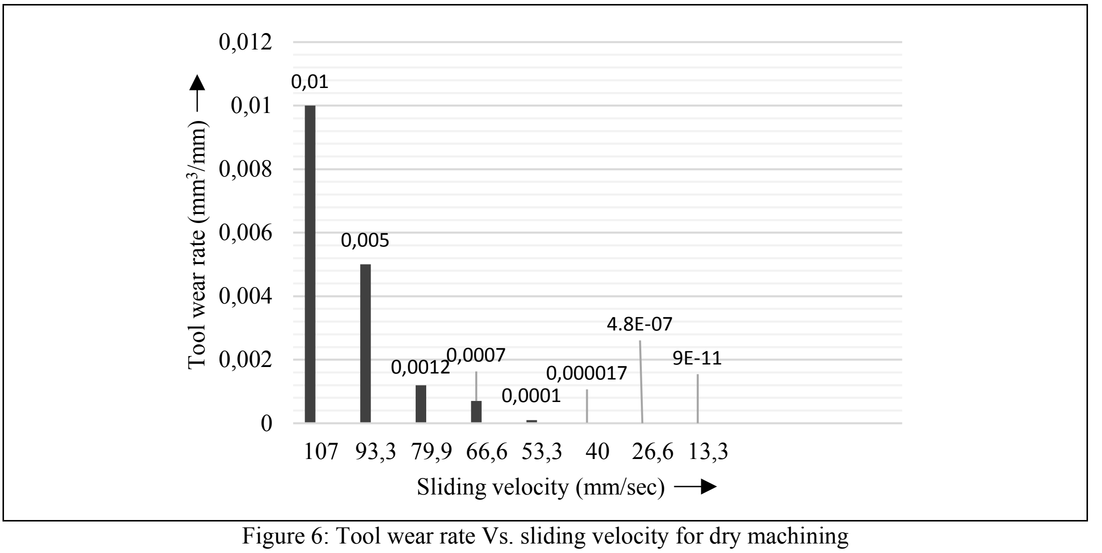


Figure 6: Tool wear rate Vs. sliding velocity for dry machining

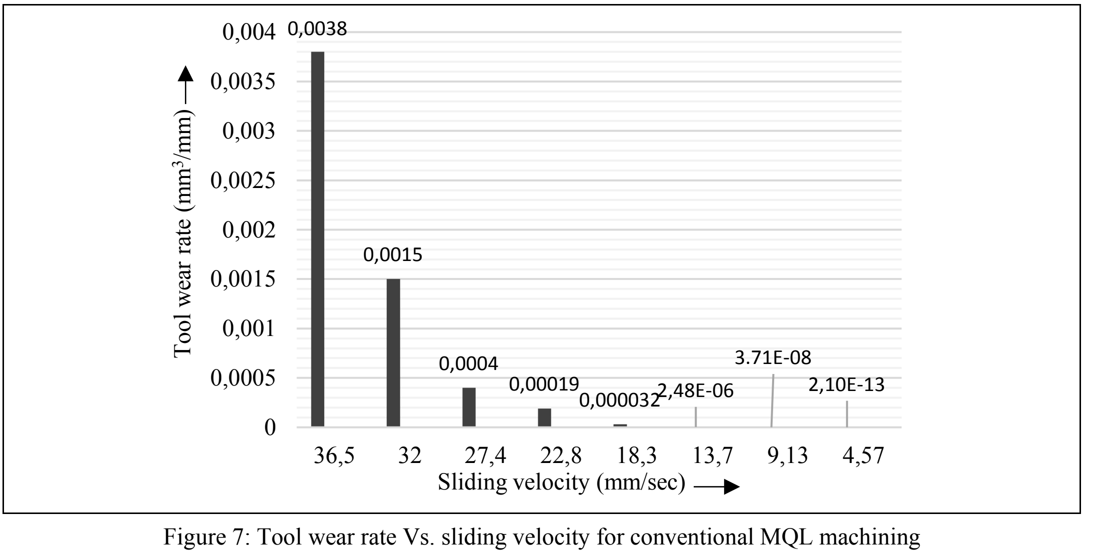


Figure 7: Tool wear rate Vs. sliding velocity for conventional MQL machining

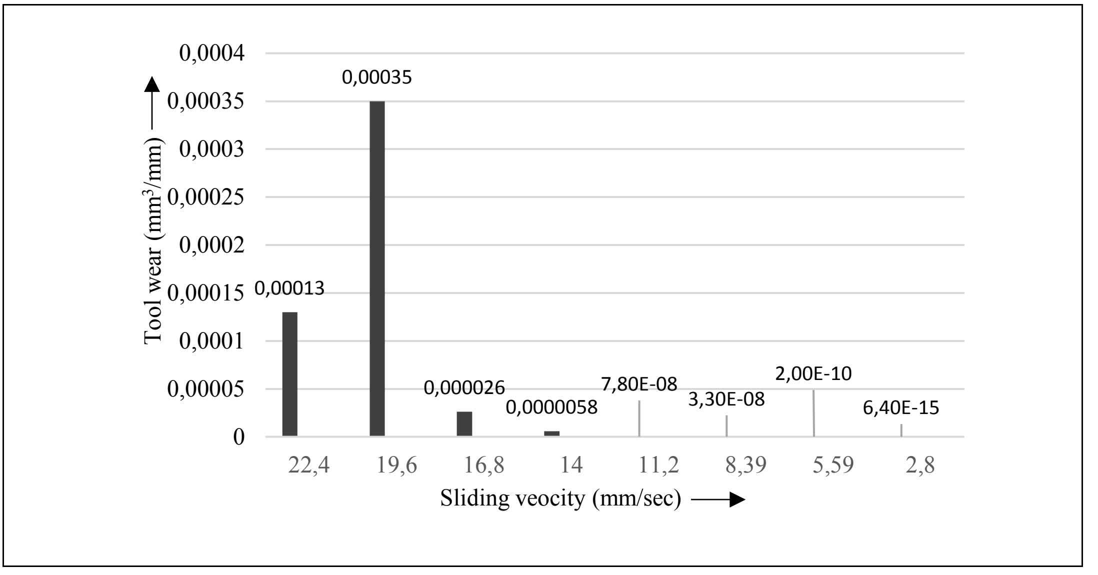


Figure 8: Tool wear rate Vs. sliding velocity for NMQL machining

5. CONCLUSIONS

The turning of Inconel 625 alloy was simulated using the DEFORM-3D software. The machining force, tool temperature, and tool wear rate were analyzed under the Dry, Conventional MQL and NMQL system. According to the results obtained from the simulation study, the dry turning showed a maximum level of cutting force, tool-tip temperature, and tool wear rate in comparison with conventional MQL and NMQL conditions. NMQL conditions showed a reduction in cutting force with the use of h-BN NMQL environment compared with dry and conventional MQL machining by 41% and 27%, respectively. Further, the comparison of the cutting tool temperature for three simulated conditions showed a clear-cut reduction of temperature in NMQL conditions in comparison with dry and conventional MQL, by 44% and 30% respectively. Results also displayed a decline in the values of the tool wear rate for NMQL technique in comparing with dry and conventional MQL system. These preliminary results indicate that MQL with h-BN nano-additive has a substantial advantage over the dry cutting and MQL with conventional cutting fluid machining conditions.

REFERENCES

[1] M. H. Besha, S. C. Devendra, S. S. G. Venkatesh, Analysis of effective stresses for titanium alloys in continuous forming process, *Materials Today Proceedings,* 10.1016/j.matpr.2021.02.289, 2021.

[2] O. N. Çelik, N. Ay, Y. Göncü, Effect of Nano Hexagonal Boron Nitride Lubricant Additives on the Friction and Wear Properties of AISI 4140 Steel, *Particulate Science and Technology*, Vol.**31**, no 5, pp. 501–506, 2013.

[3] W. Daungthongsuk, S. Wongwises, A critical review of convective heat transfer of nanofluids, *Renewable and Sustainable Energy Reviews*, Vol **11**, no 5, pp. 797-817, 2007.

[4] L. Filice, F. Micari, S. Rizzuti, D. Umbrello, A critical analysis on the friction modelling in orthogonal machining. *Int. J. Mach. Tools Manuf.*, Vol. **47**, no 3–4, pp. 709–714, 2007.

[5] Q. Li, X.Yimin, Convective heat transfer and flow characteristics of Cu–water nano-fluid, *Science in China (Series E).*, Vol **45**, no 4, pp. 408–416, 2002.

[6] A. Lipp, K. A. Schwetz, K. Hunold, Hexagonal Boron Nitride: Fabrication, Properties and Applications*, J Eur Ceram Soc.*, Vol. **5**, no 1, pp. 3-9, 1989.

[7] P. Loganathan, N. Saravanakumar, G. Rajaram, Influence of Ag Nanoparticles for the Anti-wear and Extreme Pressure Properties of the Mineral Oil Based Nano-cutting Fluid, *Tribology in Industry,* Vol. **40**, pp. 440-447, 2018.

[8] M. Lotfi, M. Ashrafi, H. Amini, S. Akhavan, A. Farid, M. Jahanbakhsh, Characterization of various coatings on wear suppression in turning of Inconel 625: A three-dimensional numerical simulation, Proceedings of the Institution of Mechanical Engineers, *Part J: Journal of Engineering Tribology*, Vol. **23**, no. 6, pp. 734–744, 2016.

[9] M. Lotfi, M. Jahanbakhsh, A. Farid, Wear estimation of ceramic and coated carbide tools in turning of Inconel 625:3D FE analysis, *Tribol Int*., Vol. **99**, pp. 107–16, 2016.

[10] C. Padhy, P. Singh, Use of Multi-Objective Optimization Technique (Taguchi GRA Approach) in Dry Hard Turning of Inconel 625, *INCAS BULLETIN*, Vol. **12**, no 2, pp. 133-142, https://doi.org/10.13111/2066-8201.2020.12.2.11, 2020.

[11] K. H. Park, M. A. Suhaimi, G. D. Yang, D. Y. Lee, S. W. Lee, P. Kwon, Milling of titanium alloy with cryogenic cooling and minimum quantity lubrication (MQL), *Int. J. Precis. Eng. Manuf.,* Vol. **18**, pp. 5–14, 2017.

[12] E. Usui, T. Shirakashi, T. Kitagawa, Analytical prediction of cutting tool wear, *Wear*, Vol. **100**, no. 1, pp. 129–51, 1984.