Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Assessment of cutting tool wear using a numerical FEM simulation model

To cite this article: M Necpal and M Vozár 2024 *J. Phys.: Conf. Ser.* **2712** 012021

Assessment of cutting tool wear using a numerical FEM simulation model

M Necpal and M Vozár

Slovak University of Technology in Bratislava, Faculty of Materials Science and Technology in Trnava, Ulica Jana Bottu 2781/25, 917 24 Trnava, Slovak Republic

E-mail: martin.necpal@stuba.sk, marek.vozar@stuba.sk

Abstract. The advancement of computational modeling techniques, such as FEM, has allowed to simulate complex machining processes with improved accuracy. Wear prediction is a crucial aspect in understanding and optimizing machining processes, as it directly impacts tool life, surface quality and overall machining efficiency. This work focuses on the FEM simulation, specially utilizing the DEFORM software, in conjunction with the Usui wear model, for wear prediction in machining operations. The Usui wear model, a well-established and widely used wear prediction approach, accounts for multiple wear mechanisms that include adhesion, abrasion, and diffusion. By incorporating the Usui wear model into the FEM simulation framework within the DEFORM software, it is possible to understand wear phenomena in machining processes. The integration of Usui wear model algorithms into DEFORM enables the simulation to accurately predict wear rates, distribution patterns, and progression of tool deterioration. This predictive capability facilitates the identification of critical wear zones and guides proactive measures to improve tool life, reduce production costs, and optimize machining productivity. This work presents research focused on wear prediction in cutting processes, utilizing FEM simulation with DEFORM software and incorporating the Usui wear model. Through a comprehensive analysis of wear phenomena, this research aims to optimize cutting parameters, improve tool life, and contribute to the advancement of machining and manufacturing technologies.

1. Introduction

Although the development of special manufacturing technologies such as rapid prototyping, additive manufacturing, and 3D printing is enormous, conventional machining occupies a significant place in manufacturing technologies in economically developed countries. Research [1] shows that 15 % of total production is made by conventional machining.

A thorough understanding of the material removal process in metal cutting is essential in the design, selection of the tool material, as well as in the finalization of the cutting edge shape of the cutting edge. All of these parameters have an impact on ensuring the dimensional accuracy and surface integrity of the workpiece. The contact properties of the tool and the material to be cut affect the performance, quality, machining costs, and, most importantly, the life and durability of the cutting tool. If tool wear reaches a certain level, the cutting tool loses its ability to maintain the required machining requirements, and thus ends its service life. The cutting wedge must be replaced or its geometry modified, e.g. by grinding. Tool wear and associated tool life are of great importance in optimizing the cutting process.

Numerical simulation models contribute to the efficient and fast design of the production process. However, since the cutting process is non-linear and coupled by a thermo-mechanical process with rapid plastic change in the workpiece and friction at the tool-chip interface, the creation of a computer simulation model is one of the challenging tasks, especially on software and computer hardware performance. Numerical methods (FDM, FEM, AI, etc.) are used, among them FEM dominates in the simulation of the cutting process [2-4].

Since several wear mechanisms are encountered in the practice of cutting material, several wear models have also been developed. Basic wear models include the Tekeeyamas [5] wear model. Among the most well-known models of machining wear is the Usui [6] wear model. This model reliably defines the amount of tool wear in the case of conventional material machining with conventional sintered carbide-coated tools. In the case of special machining conditions or when using unconventional cutting tool materials, it is necessary to define a complex wear mechanism using several conditioning parameters. Attanasio [7] defines and uses a coupled abrasive-diffusive tool wear model due to simulating both tool wear phenomena. In this way, the accuracy of the tool crater wear prediction is increased.

For the correct use of simulation models concerning the machining process, the materials to be machined, and the tool materials used, it is necessary to calibrate the model. Hosseinkhani [8] defines the calibration work for wear models. The framework suggests the optimum number of experiments and simulations to be performed. This research methodology is based on a hybrid experimental/simulation approach with emphasis on the flank wear rate. Aiaro [9] develops an FE model to estimate tool wear, chip-tool contact length, and machining forces, under the combined effect, considering Nimonic 90 as workpiece material. Binder [10] simulated tool wear for turning of AISI 1045 with uncoated and PVD-TiAIN-coated cutting inserts. The calibration methodology for the tool wear simulation is presented, and the general approach of tool wear simulation and the extension for the consideration of coating and complex geometries are described.

The presented work is a demonstration of the use of the FEM milling model and its development in the DEFORM 3D software. The model includes a Usui wear model and the results are compared with an austenitic steel milling experiment under defined wear conditions.

2. Experiment set-up milling

The experiment was carried out in a CNC milling center with cutting parameters of radial depth 3 mm, feed per tooth 0.09 mm and cutting speed 190 $m.min^{-1}$. A monolithic milling tool was used.

2.1. Milling tool

The design of the tool was derived from the commercial SECO Tools JS754 100E2C.0Z4-HXT. Tools were manufactured from cemented carbide grade CTS20D which is equivalent to the ISO K20-K40 code. The basic parameters of the tool are summarized in table 1.

The geometry of the tool was designed using NUMROTOPLUS software. This tool was manufactured using a multi-axis tool grinder. The tool model can also be used to prepare the FEM simulation model. Figure 1 shows the use of cutter geometry to create a 3D FEM model of the milling operation.

2.2. Workpiece material

Austenitic stainless steel STN 17349/DIN X2CrNiMo17-12-2(AISI 316L) was used as experimental machined material. This type of steel contains austenitic structures, present as a result of alloying elements such as nickel, manganese, carbon, and nitrogen. It has a low yield strength of 230 to 300 MPa, but a high toughness of up to 240 $J.cm^2$. The thermal conductivity is relatively low with a value of 16.9 $Wm^{-1}K^{-1}$ but at a higher temperature, more than 500 °C, the thermal conductivity is higher, with a value of 21.9 $Wm^{-1}K^{-1}$. The thermal conductivity is temperature dependent, and this property must be included in the FEM material properties simulation.

Table 1. Milling tool parameter.

Tool parameters	Value
Cutting diameter	10 mm
Maximum shank diameter	10 mm
Count of cutting edges	4
Flute helix angle	48°
Main cutting edge setting angle κ_r	89°
Secondary cutting edge setting angle κ_r‘	4.15°
Corner chamber length/radius size	0.125×45° mm

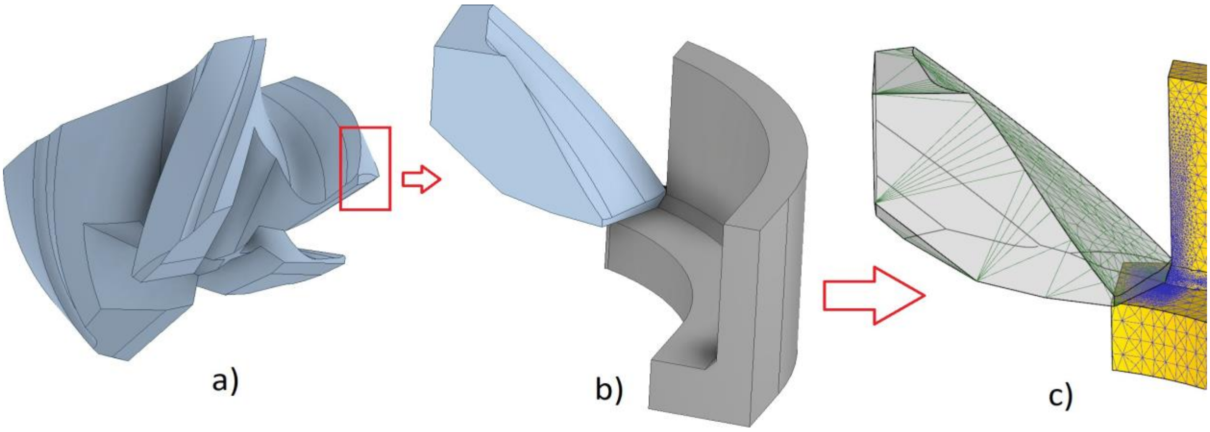

Figure 1. Geometry preparation for the 3D FEM model: a) complete 3D CAD model of the tool, b) simplified 3D model off the tool with the workpiece, c) cutting model in 3D DEFORM FEM software.

The machined material model for simulation is an ideal plastic thermodynamic model that describes the flow stress in physical quantities such as temperature, strain, and strain rate. The material model was selected for the given steel type from the standard DEFORM software database.

3. FEM setting and boundary conditions

The commercial DEFORM 3D in V12 was used for FEM simulation. The implicit solver uses Lagrangian formulation of the nonlinear time incremental problem, which allows the cutting process to be analyzed from the start of the cut, to the few µs when the chip begins to separate. Software DEFORM provides chip separation methods by re-mesh functionality which can be specified as increment depth between object, maximum stroke increment, maximum time increment, or maximum step increment. Remeshing also occurs automatically if the Jacobi determinant of any of the resulting elements is less than 0. In this case of milling operation, the remesh criterion was set as interference depth 0.01 mm. The parallel solver can use the Newton-Raphson or direct iteration method. Implicit setting of iteration is Newton-Raphson method, because provide low computation times, however, if the increment does not converge, the iteration method is switched automatically to direct method. This combination provides low computation times when providing an automatic solution. However, the calculation time is also influenced by other factors, such as the amount of elements, friction model, as well as the material model, etc.

Figure 1c shows the setting of the 3D cutting model. In the cutting zone, near the cutting edge of the tool side sizes, the elements are 0.018 mm. In the cutting zone, close to the cutting edge of the tool, the size of the elements faces is approximately 0.018 mm. If the feed per tooth is 0.09 mm, this element size results in 5 elements per chip thickness, which is satisfactory in this case. Since it is a step-by-step milling process, the thickness of the chip becomes thinner, causing complications in the simulation. The simulation had to be restarted several times during tool rotation, and in the end, when the cutting edge comes out of the material being machined, the simulation results can no longer be considered significant.

The tool model is defined as a rigid (nondeformable object), but since the thermo-mechanical properties of the machined material are used, it is necessary to define the thermal properties of the tool and consequently to mesh the geometry. The size of the mesh depends mainly on the geometric properties of the tool (radius of the cutting edge). The thermal conductivity of the tool has been set to 59 $Wm^{-1}K^{-1}$. The contact properties of the objects are: friction is set as a constant shear coefficient vale 0.25 and the heat transfer coefficient between objects is set to 5 $NS^{-1}mm^{-1}C$.

4. Result

The FEM cutting model provides a wide range of information on the mechanical, contact, and thermomechanical behavior of the material during chip formation. The quantities can be represented as arrays, or values, and vector quantities can be represented as lines (e.g. for velocity or force the direction of action is then known). It is also possible to mark points in space and then plot the waveforms of the quantities on a graph. Figure 2a) shows the result of the FEM 3D cutting model of the stress distribution field and the load in the tool feed direction Figure 2b).

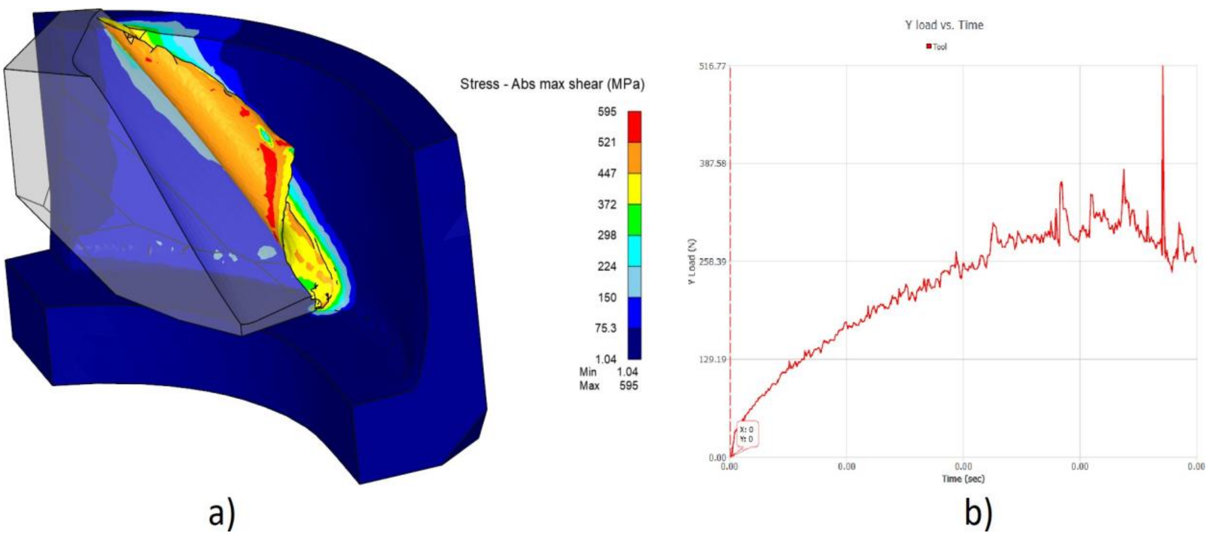

Figure 2. FEM simulation otput a) array of stress distribution, b) load in the direction of the feed.

Regarding the cutting wear mode, the following variables can be displayed: interface temperature, sliding velocity, interface pressure, wear rate, wear depth, and wear geometry. In the case of Worn geometry, this can be displayed as Isosurface. Figure 3a) compares the wear performance obtained by the experiment and 3b) the simulation software.

For a more thorough verification and calibration of the Usui simulation model, it would be necessary to measure the amount of material loss from the cutting tool. A significant inaccuracy of the measurement experiment occurs when adhesive wear enters the wear process.

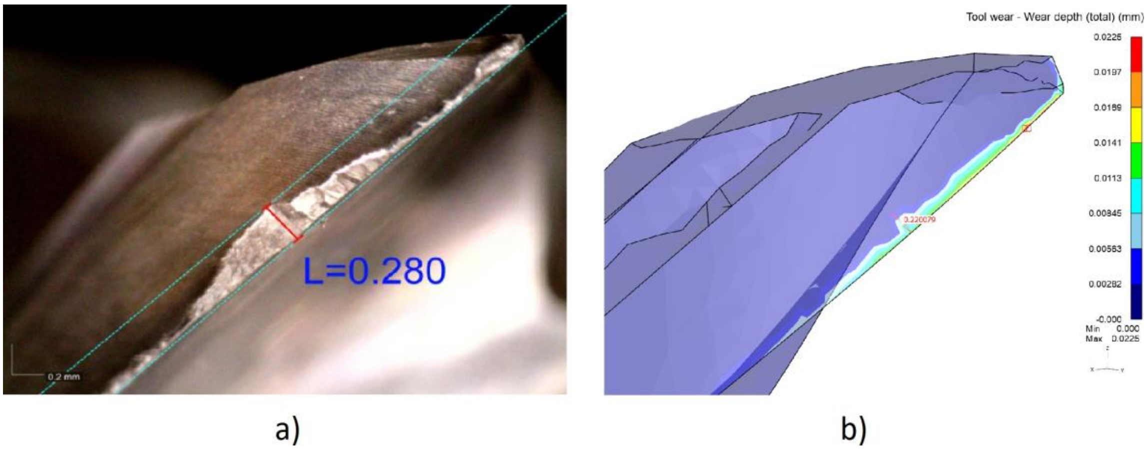

Figure 3. Flank wear a) measurement in Dino-Lite software, b) results of a measurement and visualisation shown in FEM postprocessing.

5. Conclusion

This research underscores the pivotal role of computational modeling, specifically Finite Element Simulation (FEM) using DEFORM software, in conjunction with the established Usui wear model, for wear prediction in machining operations. The ability to simulate complex machining processes with greater accuracy has opened up new avenues for understanding and optimizing these processes.

By incorporating the Usui wear model into the FEM simulation framework, this study provides a comprehensive understanding of the wear mechanisms that include abrasion mechanism. Through this integration, the research offers a powerful tool to accurately predict wear rates, distribution patterns, and the progression of tool deterioration.

The integration of advanced computational techniques, such as FEM and the Usui wear model, underscores the potential for continued innovation in the field of machining processes.

Acknowledgments

This work was supported by the Slovak Research and Development Agency of the Slovak Republic under Contract no. APVV-21-0071 and VEGA grant agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic and the Slovak Academy of Sciences, no. 1/0266/23 and project: Development of new progressive cutting tools for machining parts produced by WAAM additive manufacturing technology to reduce the number of cutting tools when machining parts from different types of materials, (ITMS2014+: 313011BWQ8) supported by the Operational Programme Integrated Infrastructure funded by the European Regional Development Fund.“

References

[1] Merchant M E 1998 An interpretive look at 20 th century research on modeling of machining *Mach. Sci. Technol.* **2**2 157–163. doi: 10 . 1080 / 10940349808945666

[2] Jawahir, I S, Stephenson, D A and Wang B 2022 A Review of Advances in Modeling of Conventional Machining Processes: From Merchant to the Present *J. Manuf. Sci. Eng.* **144** doi: 10.1115/1.4053522

[3] Sumesh C and Ramesh A 2023 Optimization and finite element modeling of orthogonal turning of Ti6Al4V alloys: A comparative study of different optimization techniques *Eng. Solid Mech.* **11** 11–22 doi: 10.5267/j.esm.2022. 11.002

[4] Kyratsis P, Tzotzis A and Davim J P 2023 FEM-Based Study of AISI52100 Steel Machining: A Combined 2D and 3D Approach *3D FEA Simulations in Machining* (Cham: Springer International Publishing) 47–62. doi: 10.1007/978- 3- 031-24038-6 3

[5] Takeyama H and Murata R 1963 Basic Investigation of Tool Wear *J. eng. ind.* **85** 33–37. doi: 10.1115/1.3667575
[6] Usui E, Shirakashi T and Kitagawa T 1984 Analytical prediction of cutting tool wear *Wear* **100** 129–151 doi: 10.1016/0043-1648(84)90010-3
[7] Attanasio A, Ceretti E, Fiorentino A, Cappellini C and Giardini C 2010 Investigation and FEM-based simulation of tool wear in turning operations with uncoated carbide tools *Wear* **269** 344–350. doi: 10.1016/j.wear.2010.04.013
[8] Hosseinkhani K and Ng E 2018 A hybrid experimental and simulation approach to evaluate the calibration of tool wear rate models in machining *Int. J. Adv. Manuf. Technol.* **96** 2709–2724. doi: 10.1007/s00170-018- 1687-5
[9] Airao J and Nirala C K 2022 Finite Element Modeling and Experimental Validation of Tool Wear in Hot Ultrasonic Assisted Turning of Nimonic 90 *J. Vib. Eng. Technol.* doi: 10.1007/s42417-022-00776-6
[10] Binder M, Klocke F and Lung D 2015 Tool wear simulation of complex shaped coated cutting tools *Wear* **330** 600–607 doi: 10.1016/j.wear.2015.01.015