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Wear estimation of coated tools using XFEM / level set function

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Abstract

In these last years, it has become common to improve the wear resistance of cutting tools, especially in high-speed machining by depositing single or multilayered coatings on their surface. During cutting process, high pressure (about 1 GPa) and temperature (about 1000 °C) generated at the tool-chip interface affect drastically the cutting zone inducing then damage and several wear modes as cracking, abrasion, and delamination of the coating. Studying the behavior of coatings and their various modes of degradation leads to a better understanding of their impact on the cutting tool life and the machining operation under optimal conditions. The main objective of this work is to perform an accurate model to predict the tool wear of coated inserts. The Usui wear law was used to simulate the tool wear process for the coating and the substrate. The coupled XFEM/Level Set Function was performed: (i) – to avoid distortion of the mesh when the worn tool profile is updated, (ii) - to facilitate the material interfaces representation of the substrate/coatings system implicitly via the level set function and finally (iii) to reduce the CPU calculation time. Indeed, the mesh size is not dependent on the coating thickness with this approach. Thanks to additional enrichment functions in the XFEM formulation, the continuity of the displacement and temperature fields at the substrate/coating interface is insured. Besides, several cutting tests have been performed to validate the proposed model.

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Keywords: Wear; Coatings; eXtended Finite Element Method

1. Introduction

Many investigations on the tool wear can be found in the literature [1–4] to analyze and show the influence of wear on the cutting process performances and costs. In fact, the tool life and the roughness quality of the final products are directly affected by the tool wear progression. The presence of wear in cutting tools influences significantly the thermomechanical loads at the tool/chip interface. Indeed, Kagnaya [5] showed through several experimental tests that the pressure and temperature increase with the wear rate. Examination of cutting tool wear by experimental approaches is too long and expensive. That is why, these last years the standard finite element method (FEM) remains the most numerical method used to simulate machining operations as well to estimate the cutting tool life through the integration of wear models.

According to this technique, the FE simulation provides the required inputs for empirical wear rate equations. Many analytical and empirical models have been developed in order to represent different wear mechanisms, starting with abrasion [6,7] and adhesion [8,9] modes to the chemical wear mode [10,11]. Recently, a novel model was proposed by Halila et al. [12] to estimate abrasive wear mechanism based on the consideration of the abrasive particles embedded into the interface between the tool and the chip. The Usui model [8] has been used successfully for the prediction of wear for coated or uncoated tools. This wear model is suitable to be implemented in FEM code since it is a function of the known process parameters along the cutting tool such as stress, sliding velocity and temperature at the tool/workpiece contact. Many authors [13,14] have adapted the constants of Usui model to improve the estimation of the cutting tool wear. Using a hybrid procedure consisting of numerical and experimental

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investigations, Zanger and Schulze [15] estimated the progression of flank wear for an uncoated tool when machining the titanium alloy Ti-6AL-4V. Filice et al. [16], Xie et al. [17] and Yen et al. [18] have developed 2D model of the orthogonal cutting to predict flank wear and crater wear for carbide tools with a different workpiece materials and for different cutting conditions. The getting results of wear are in good agreement with experiments. Malakizadi et al. [19] developed a novel approach coupling the concept of the Response Surface Methodology (RSM) with the 3D FE modelling of the cutting process to predict the rate of flank wear for uncoated tools. They concluded that the numerical and experimental results are close despite that the effects of the normal stress in the Usui's wear model used in this approach was neglected.

In the coated tool case, to ensure the continuity of the temperature field at the coating/substrate interface, a mesh refinement must be ensured, that causes a significant increase in CPU calculation time. Moreover, the nodal displacement at the tool boundaries with the FE-simulations may lead to numerical problems especially the distortion of the mesh when the tool profile is updated [14]. To overcome these limitations, the XFEM/Level set [20] coupling has been used in this work to reduce the CPU calculation time caused by the small coating thickness in its mesh. In fact, the calibration of the wear model requires a high number of simulations and hence the importance of the CPU calculation time. The coupled model has been used also to treat the weak discontinuity between the coating/substrate interface without the need of a specific mesh thanks to the additional enrichment functions in the XFEM formulation. The Usui model has been used to simulate the tool wear for orthogonal turning 42CrMo4 steel with CVD-TiN-coated and uncoated tools. In the following section, the different steps used to achieve the tool wear simulation are described.

2. Prediction of tool wear

To predict the cutting tool wear progression, a multi-steps modelling strategy was adopted. As a first step, orthogonal cutting simulation using the Arbitrary Lagrangian Eulerian (ALE) approach has been performed in Abaqus code, to simulate the chip formation process and to calculate the thermomechanical loading on the tool surface (pressure, velocity and temperature). In the second step, the cutting tool was isolated and a transient thermal analysis was carried out using the XFEM/Level-set coupling. Developed under the Matlab code, this step is applied to the thermomechanical loaded tool for long durations corresponding to the experimental machining time. This strategy was presented in a previous work [21]. In the last step, the wear model has been integrated.

Since the quality of the tool wear simulation strongly depends on the predicted thermomechanical loading and the tool wear model. For this reason, a validation of the ALE model was carried out based on the experimental results. A parametric study has been performed to determine the local friction coefficient μ_{loc}. In the same way, the heat transfer coefficient h for the tool-workpiece interface has been identified. The sequential step 1 of this approach is summarized in Fig. 1. In this work, Usui's wear rate model was used to calculate wear rate $\dot{w}$ on the tool surfaces. According to Eq.(1), Usui model is determined based on the normal stress σ_n, interface temperature T and the contact sliding velocity V_s. These quantities are obtained from the 2D-numerical simulations performed in step 1. A_U and B_U are the material constants to be determined.

$$\dot{w} = A_U.\sigma_n.V_s.e^{(-B_U/T)} \quad (1)$$

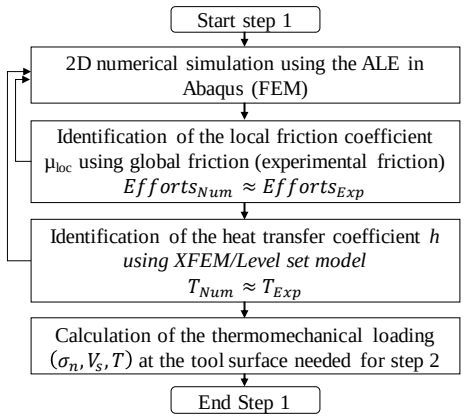

Fig. 1. Sequential step 1 of the proposed approach to identify the ALE model parameters and to calculate the thermomechanical loading required for step 2.

Information on the thermomechanical loading (pressure, velocity, temperature) recovered from the ALE simulation for each node of the tool profile has been applied to the coated tool as a boundary condition at the active zone of the tool (tool/workpiece contact zone). Indeed, it is difficult to perform this analysis directly with the ALE model because of the huge CPU calculation time (for only few milliseconds of machining) and the limited storage capacity, making cutting simulation very complicated. A subsequent nodal displacement of the mesh at the interface of the cutting tool in agreement with the calculated local wear rate is performed at each time increment in order to effectively adapt the geometry of the tool. The procedure for converting a wear rate to a displacement is detailed in [4].

During the wear process of the coated tool, the coating layer can be locally suppressed. Consequently, the coefficients of the wear model have to be changed. For this purpose, an identification algorithm based on the minimization (using the Genetic Algorithm [22]) of the error between the simulation and the experimental cutting process of the wear rate has been performed for the calibration of the coefficients A_U and B_U associated to each material (WC-Co (substrate) and TiN (coating)) (Fig. 2). During the wear process, when a mesh node at the contact interface of the coated tool exceeds the coating/substrate interface, the coefficients A_U and B_U automatically switch to the values associated with the substrate. Optimization has been done only for the last VB measurement. After each wear increment, the temperature field distribution is calculated according to the new mesh nodes position by a linear interpolation.

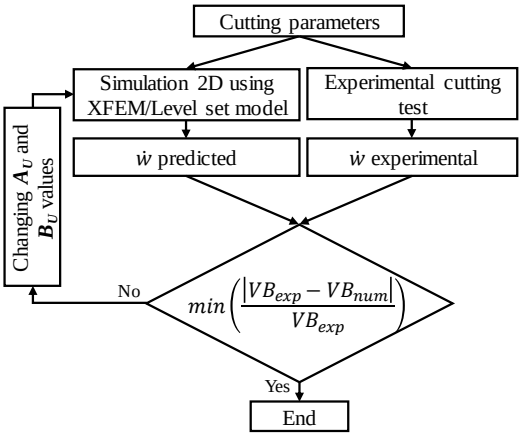

Fig. 2. Identification algorithm of the Usui wear parameters A_U and B_U.

2.1. ALE Simulation of the cutting process

In order to simulate the cutting process and getting the thermomechanical loads at the tool/chip interface, a 2D orthogonal cutting model has been developed under the Abaqus/Explicit FE code. Based on the ALE approach, a continuous remeshing method was adopted. Thus, intensive element distortions could be avoided. This approach is considered as the most appropriate to simulate continuous chips, it combines the feature of pure Lagrangian and Eulerian analysis. Friction at the tool/workpiece contact was considered using Coulomb's law. Thermomechanical elements have been used for the workpiece, while the cutting tool has been considered as a thermo-rigid body. A detailed description of the model is given in [23]. The Johnson-Cook model (Eq.(2)) parameters of the workpiece 42CrMo4 steel are reported in Table 1. The thermal and mechanical properties of the workpiece and the cutting tool are summarized in Table 2. The loads at the tool/chip interface and forces are stabilized after 0.04 s of the simulated machining operation which was proportional to 101 mm of the cutting length. The workpiece has been meshed with the CPE4RT mesh type and uniform mesh has been adopted (10 µm of size). The initial chip geometry has been defined based on the tool/chip contact length. This model was validated by comparing cutting forces and the temperature profile with the experimental results.

$$\sigma_{eq} = \left[A + B\bar{\varepsilon}^{n}\right]\left[1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^{m}\right] \quad (2)$$

In Equation (2), σ_{eq} is the flow stress of the work material, $\bar{\varepsilon}$ is the equivalent plastic strain, $\dot{\bar{\varepsilon}}$ and $\dot{\bar{\varepsilon}}_0$ represents, respectively, the equivalent plastic deformation rate and that of reference, T is the temperature and T_m and T_0 are, respectively, the melting and room temperatures. A, B, C, n and m are the material parameters.

Table 1. Johnson-Cook parameters [24] of the 42CrMo4 steel.

A (*MPa*)	B (*MPa*)	C	n	m	T_0 (°*C*)	T_f (°*C*)
600	643	0.0037	0.41	0.957	20	1460

Table 2. Material properties of the workpiece and the tool.

Physical parameters	Workpiece	Tool	
		Substrate	Coating
	42CrMo4 [25]	WC-Co [5]	TiN [26]
Density ρ (*Kg/m*^{3})	7.8e^3	14.8e^3	4.6e^3
Young's modulus E (*GPa*)	210	630	600
Poisson' ratio ν	0.3	0.23	0.2
Conductivity λ (*W/m/°C*)	46	55	22
Specific heat Cp (*J/Kg/°C*)	476	295	480
Expansion Coeff α (°*C*$^{-1}$)	1.2e^{-5}	-	-

2.2. Experimental Setup

In this study, turning experiments were performed on a MAZAK 200M high-speed machining center. A Kistler piezoelectric dynamometer and a thermocouple probe (type K) embedded through the cutting tool until 1.34mm from the rake face (see Fig. 5(a)) were used for the acquisition of the cutting force components and temperature successively. The experimental system and the workpiece dimension are shown in Fig. 4. The cutting tool was cut perpendicular to the center of the tool rake surface using the Electrical Discharge Machining (EDM) process to determine: (i) the coating thickness (Fig. 3), (ii) the tool geometry and (iii) the thermocouple hole dimension (see Fig. 5). The flank wear measurement was carried out using a high-magnification optical microscope.

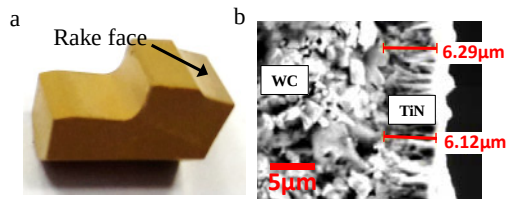

Fig. 3. (a) TiN-coated tool (made by EVATEC TOOLS); (b) Coating thickness.

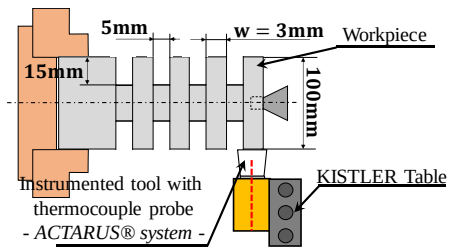

Fig. 4. Experimental setup.

The orthogonal turning experiments were carried out for the cutting speed Vc = 150 m/min and the feed rate

f = 0.18 mm/rev with coated and uncoated tool inserts. The results have been used to validate the simulation model as well as the tool wear characterization.

2.3. The XFEM/Level set model

Based on the partition of unity method "PUM". The XFEM method allows to model discontinuities within the domain of a mesh element. In this work, the XFEM method has been developed to perform a transient thermal analysis for the coated cutting tool. Contrary to the standard FE method, where the definition of the coating domain strongly depends on the mesh refinement, the XFEM/Level-set coupling makes possible to take into account the coatings presence without the need of a specific mesh. That is why, this technique allows reducing the CPU time calculation caused by the weak coatings thicknesses. The reproduction of the nodal thermal solution for the elements containing the fictitious positions of the coatings is given by the continuous finite element formulation of the thermal field according to the expression:

$$\mathbf{T}(x) = \sum_{i \in \Omega}^{n} \mathrm{N}_i(x)\mathbf{T}_i + \sum_{k \in \Omega^{enr}}^{n_{enr}} \mathrm{N}_k(x)\psi_k(x)\mathbf{b}_k \quad (3)$$

In the equation above, N_i and N_k represents the shape functions, $\mathbf{b_k}$ the nodal unknown and n_{enr} the total number of the enriched elements. The nodal set Ω^{enr} contains all the nodes of the element traversed by the material interface. The enrichment function $\psi_k(x)$ integrates the discontinuous thermal behavior at the interface. In this work, only interfaces involving weak discontinuities are considered. As proposed by Moës et al. in [20], $\psi_k(x)$ is chosen as follow:

$$\psi(x) = \sum_i |\xi_i| \mathrm{N}_i(x) - \left| \sum_i \xi_i \mathrm{N}_i(x) \right| \quad (4)$$

The enrichment function $\psi_k(x)$ is constructed by the level-set function $\xi(x)$ of the interface defined by the boundary Γ. The signed distance function can be expressed as:

$$\xi(\mathbf{x}) = \underbrace{\min \|\mathbf{x} - \mathbf{x}_\Gamma\|}_{x_\Gamma \in \Gamma} sign\left(\mathbf{n}.(\mathbf{x} - \mathbf{x}_\Gamma)\right) \quad (5)$$

where x and x_Γ indicate the respective coordinates of a current point and the point closest to the interface Γ. **n** is the normal unity at this interface oriented from the inside to the outside. The sign is then different from the two sides of the discontinuity. It is possible to affect the material properties associated to each domain (coatings, substrate), thanks to the signs of the values given by the level-set function ξ (Fig. 6).

With this method, a sub-division of the enriched elements domains is necessary in order to structure the Gauss points in these elements. An algorithm has been implemented (not presented in this paper) for the cutting management of the enriched elements in agreement with the interfaces coatings/substrate thereby to the integration points positioning in each subdomain. According to the FE method, the mesh of the coated tool geometry should respect the boundaries imposed by the coating thickness. Consequently, the nodal displacement of the mesh can lead to numerical problems, in particular the mesh distortion when the tool profile is updated. On the other hand, within the XFEM/Level-set coupling, the implicit representation of the level-set function allows to define the material interface (coating/substrate) independently of the mesh, which enable to choose a larger element size than the thickness of the coating thus avoiding this numerical problem (see Fig. 7). The tool was meshed with 800 elements. A high number of integration points (np = 128 points) in the enriched elements only has been used in order to increase the solution accuracy.

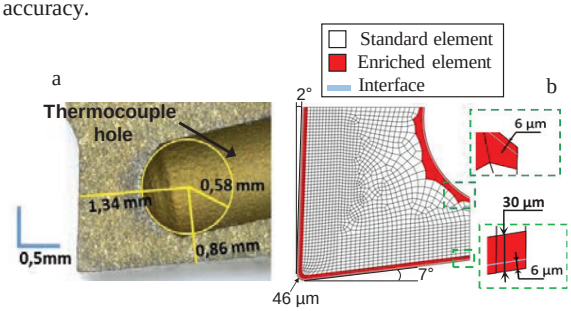

Fig. 5. (a) Cross section of the tool with the real dimensions of the thermocouple hole; (b) XFEM/Level-set mesh with the interface representation.

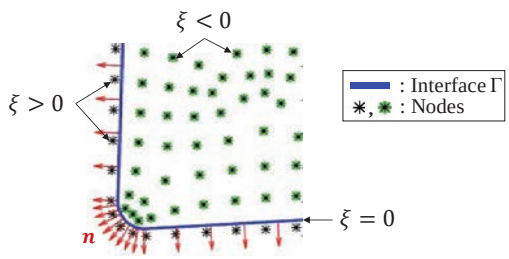

Fig. 6. Interface definition with a level set function for a coated structure.

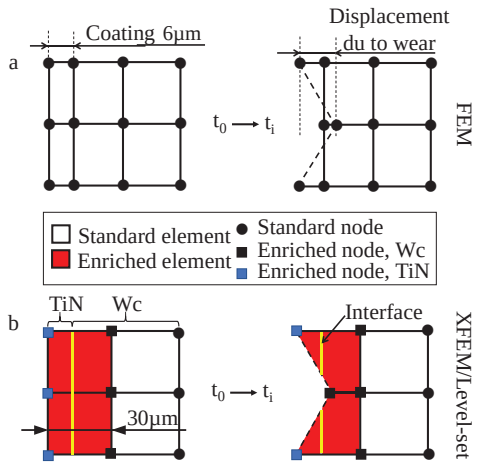

Fig. 7. Nodal displacement du to wear for: (a) FEM; (b) XFEM/Level set model.

Table 3. Usui tool wear model constants for the substrate and the coating.

	WC-Co	TiN
A_U	$9.21e^{-9}$	$1.8e^{-9}$
B_U	2819	3402

3. Results

As described in Section 2, from each calculation step some pertinent results can be obtained. The cutting condition (Vc = 150 m/min and f = 0.18 mm/rev.) has been taken for the numerical analysis and validation. For the orthogonal cutting simulation using the ALE approach, the forces have been stabilized after some milliseconds (40ms) of the cutting process, allowing the parametric study on the local friction coefficient μ_{loc} directly with the model. As a result of this study, a local friction coefficient $\mu_{loc} = 0.6$ (for a minimal error between experimental and numerical cutting force components (F_c and F_f)) was obtained (Fig. 8). Whereas, in order to recover the temperature evolution at the thermocouple, the duration of the simulation should be in agreement with the experimental machining time, hence the interest of using the XFEM/Level-set coupling. Indeed, the transient thermal analysis performed on the tool requires only a few minutes of the CPU calculation time (about 5 minutes for a fixed step time $\Delta t = 8e^{-3}$s). Whereas, it takes about 5 hours when the FE method is used ($\Delta t = 2e^{-6}$s) (with a mesh conforming to the coating boundaries). Another parametric study has been done to define the thermal transfer coefficient *h*. The comparison between the measured and numerical temperature evolutions at the thermocouple position is given in Fig. 9 for the obtained value of the thermal transfer coefficient (h = 300kW/m^2/°C). Fig. 10 shows the temperature distribution in the coated tool at t = 9s as well as the position of the nodes (node1, node2 and node3) without the wear integration.

After the numerical model validation. The hybrid procedure was used to identify the coefficients (A_U and B_U) of the Usui model. The calibration has been performed only for the last experimental measurement (at t = 148s). The results of the calibration procedure are listed in Table 3. The calibration for the coated tool has been done for the flank face only, because no crater depth was observed during the experimental trials. The wear time increment was taken constant over the simulated cutting time. Fig. 11 shows the coated tool profile at different cutting times. The maximum crater depth is less than 3µm, which is close to the experimental results. Fig. 12 depicts the flank wear progress for the TiN-coated tool versus the cutting time. There is a good tendency between the simulated flank wear evolution and obtained results from machining tests. The numerical solution corresponds perfectly to the last experimental measurement, this shows that the wear model was well calibrated. However, an underestimation for the other experimental data can be noted. Several factors can be the cause of this gaps due to the numerical errors associated with the pressure, sliding velocity and temperature predictions. These thermo-mechanical loads applied to the flank face become non-uniform, and affect the individual nodal displacement process. As well as, the linear interpolation method used for the thermal field extrapolation at each new tool geometry adaptation generates numerical errors. These errors increase with the cutting time.

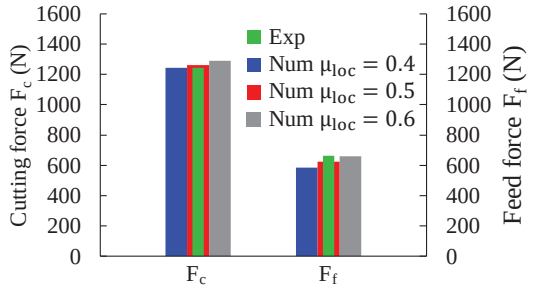

Fig. 8. Effect of the local friction coefficient on the forces.

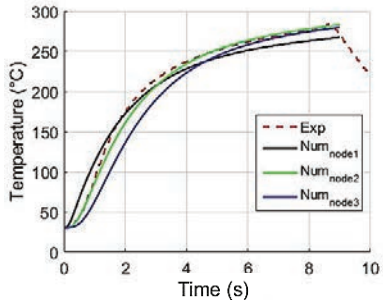

Fig. 9. Experimental temperature at the thermocouple versus numerical temperature evolution at nodes 1, 2 and 3 for h = 300kW/m^2/°C.

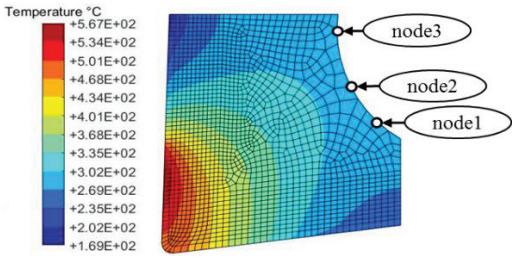

Fig. 10. Distribution of the temperature at t = 9s.

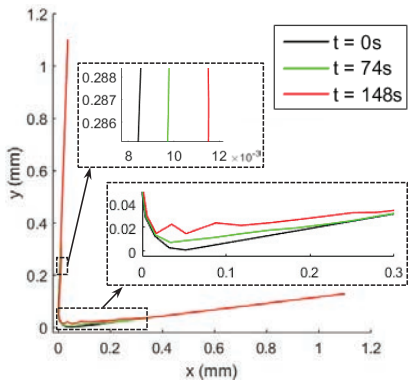

Fig. 11. Tool wear profile progress.

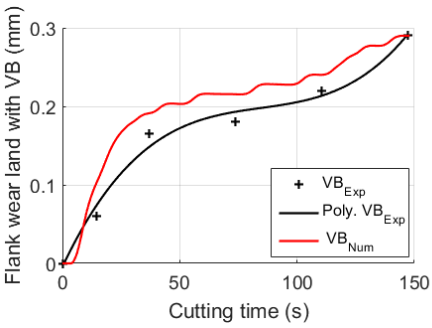

Fig. 12. Comparison between simulated and experimental wear for Vc = 150 m/min and f = 0.18 mm/rev.

4. Conclusion

A multi-steps modeling strategy was developed in this work to predict the coated tool wear progression. A 2D FE orthogonal cutting simulation using the ALE approach was developed to characterise and identify the thermo-mechanical loads at the tool/workpiece interface. A XFEM/Level-set coupling was developed to model the transient thermal behavior of the coated-tool. This model was used to ensure the continuity of the thermal field at the coating/substrate interface without the need for mesh refinement. The CPU calculation time gain allowed to perform a high number of simulations for the Usui model calibration and real machining time. Moreover, it allows to follow the wear progression at each time increment without numerical problems. An identification algorithm based on the experimental trials and simulation has been proposed to find the parameters for the Usui's wear model. At each step of this strategy, a validation with experiments was done.

The proposed strategy will allow in forthcoming work, a wear study of different coated tools (such as multi-layer coatings and complexes geometries). An additional wear model can be tested for other wear mechanisms (such as the diffusion wear) for wide cutting velocities range.

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References

[1] B. Haddag et M. Nouari, « Tool wear and heat transfer analyses in dry machining based on multi-steps numerical modelling and experimental validation », *Wear*, vol. 302, nº 1, p. 1158- 1170, 2013.
[2] B. Haddag, H. Makich, M. Nouari, et J. Dhers, « Tribological behaviour and tool wear analyses in rough turning of large-scale parts of nuclear power plants using grooved coated insert », *Tribol. Int.*, vol. 80, p. 58- 70, 2014.
[3] E. Posti et I. Nieminen, « Influence of coating thickness on the life of TiN-coated high speed steel cutting tools », *Wear*, vol. 129, nº 2, p. 273- 283, 1989.
[4] Y.-C. Yen, J. Söhner, B. Lilly, et T. Altan, « Estimation of tool wear in orthogonal cutting using the finite element analysis », *J. Mater. Process. Technol.*, vol. 146, nº 1, p. 82- 91, 2004.
[5] T. Kagnaya, « Contribution à l'identification des mécanismes d'usure d'un WC-6% Co en usinage et par une approche tribologique et thermique », *MINES Paris Tech*, 2009.
[6] J. F. Archard et W. Hirst, « The wear of metals under unlubricated conditions », in *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 1956, vol. 236, p. 397- 410.
[7] E. Rabinowicz, L. A. Dunn, et P. G. Russell, « A study of abrasive wear under three-body conditions », *Wear*, vol. 4, nº 5, p. 345- 355, 1961.
[8] E. Usui, T. Shirakashi, et T. Kitagawa, « Analytical prediction of cutting tool wear », *Wear*, vol. 100, nº 1- 3, p. 129- 151, 1984.
[9] E. Usui, A. Hirota, et M. Masuko, « Analytical prediction of three dimensional cutting process—Part 1: basic cutting model and energy approach », *J. Eng. Ind.*, vol. 100, nº 2, p. 222- 228, 1978.
[10] T. N. Loladze, « Of the theory of diffusion wear », *CIRP Ann.-Manuf. Technol.*, vol. 30, nº 1, p. 71- 76, 1981.
[11] M. Nouari et A. Molinari, « Experimental verification of a diffusion tool wear model using a 42CrMo4 steel with an uncoated cemented tungsten carbide at various cutting speeds », *Wear*, vol. 259, nº 7, p. 1151- 1159, 2005.
[12] F. Halila, C. Czarnota, et M. Nouari, « Analytical stochastic modeling and experimental investigation on abrasive wear when turning difficult to cut materials », *Wear*, vol. 302, nº 1, p. 1145- 1157, 2013.
[13] M. Lotfi, M. Jahanbakhsh, et A. A. Farid, « Wear estimation of ceramic and coated carbide tools in turning of Inconel 625: 3D FE analysis », *Tribol. Int.*, vol. 99, p. 107- 116, 2016.
[14] M. Binder, F. Klocke, et D. Lung, « Tool wear simulation of complex shaped coated cutting tools », *Wear*, vol. 330, p. 600- 607, 2015.
[15] F. Zanger et V. Schulze, « Investigations on mechanisms of tool wear in machining of Ti-6Al-4V using FEM simulation », *Procedia CIRP*, vol. 8, p. 158- 163, 2013.
[16] L. Filice, F. Micari, L. Settineri, et D. Umbrello, « Wear modelling in mild steel orthogonal cutting when using uncoated carbide tools », *Wear*, vol. 262, nº 5, p. 545- 554, 2007.
[17] L.-J. Xie, J. Schmidt, C. Schmidt, et F. Biesinger, « 2D FEM estimate of tool wear in turning operation », *Wear*, vol. 258, nº 10, p. 1479- 1490, 2005.
[18] Y.-C. Yen, A. Jain, et T. Altan, « A finite element analysis of orthogonal machining using different tool edge geometries », *J. Mater. Process. Technol.*, vol. 146, nº 1, p. 72- 81, 2004.
[19] A. Malakizadi, H. Gruber, I. Sadik, et L. Nyborg, « An FEM-based approach for tool wear estimation in machining », *Wear*, vol. 368, p. 10- 24, 2016.
[20] N. Moës, M. Cloirec, P. Cartraud, et J.-F. Remacle, « A computational approach to handle complex microstructure geometries », *Comput. Methods Appl. Mech. Eng.*, vol. 192, nº 28, p. 3163- 3177, 2003.
[21] I. Bencheikh, F. Bilteryst, et M. Nouari, « Development of a hybrid modeling for the analysis of the coating influence on machining process », *Adv. Mater. Process. Technol.*, vol. 3, nº 1, p. 1- 11, 2017.
[22] A. Konak, D. W. Coit, et A. E. Smith, « Multi-objective optimization using genetic algorithms: A tutorial », *Reliab. Eng. Syst. Saf.*, vol. 91, nº 9, p. 992- 1007, 2006.
[23] S. Atlati, B. Haddag, M. Nouari, et A. Moufki, « Effect of the local friction and contact nature on the Built-Up Edge formation process in machining ductile metals », *Tribol. Int.*, vol. 90, p. 217- 227, 2015.
[24] J. Pujana, P. J. Arrazola, R. M'saoubi, et H. Chandrasekaran, « Analysis of the inverse identification of constitutive equations applied in orthogonal cutting process », *Int. J. Mach. Tools Manuf.*, vol. 47, nº 14, p. 2153- 2161, 2007.
[25] G. Germain, « Contribution à l'optimisation du procédé d'usinage assisté laser », Arts et Métiers ParisTech, 2006.
[26] T. M. Deform et U. Manual, « SFTC-Deform V9. 0.1 », *Sci. Form. Technol. Corp. Ed Columb. OH USA*, 2006.