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G. Methon, C. Courbon, R. M'Saoubi, M. Girinon, Joël Rech. Numerical modeling of wear in orthogonal cutting of multilayer coated tools. 18th CIRP Conference on Modeling of Machining Operations, CMMO 2021, Jun 2021, Ljubljana, Slovenia. pp.67-72, 10.1016/j.procir.2021.09.012 . hal-04092874

HAL Id: hal-04092874

<https://hal.science/hal-04092874>

Submitted on 22 Jul 2024

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18th CIRP Conference on Modeling of Machining Operations

Numerical modeling of wear in orthogonal cutting of multilayer coated tools

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Abstract

The present work aims at improving tool wear simulation in orthogonal turning operations by considering local wear properties at the scale of the coating. A multi-step procedure developed in previous studies is first employed to predict cutting tool wear by combining a pure thermal model to an Arbitrary-Lagrangian-Eulerian (ALE) thermomechanical sub-model in order to predict the thermomechanical loadings applied onto the tool. The tool geometry is updated by moving the tool nodes, taking into account the local contact pressure, sliding velocity and temperature. The key improvement of this paper is to implement a specific wear model for each of the coating layer and substrate depending on the current position of each node at the contact interface. A comparative study is performed between the homogenous wear equation and the improved multi-layer model. This work highlights that an adaptive wear rate calculation based on nodal position has to be considered to achieve an actual predictive model.

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Keywords: Turning; Wear; Coatings;

1. Introduction

Tool wear is one of the main physical phenomena determining production costs and thus its prediction remains a key issue. Nowadays, numerical simulations are widely used in order to simulate machining operations. Computation analyses offer the possibility to study the tool-material interactions at low costs compared to experimental campaigns. It allows to develop predictive models based on physical understanding of the severe thermo-mechanical loadings withstood by the cutting tools. The contribution of a large number of papers has been summarized in [1]. Most of the models are concerned with 2D orthogonal cutting operations [2–6]. For instance, Rech et al. [6] developed a numerical iterative procedure to simulate tool wear in orthogonal cutting. This work investigated crater and flank wear of a solid carbide

tool during the machining of a 304L steel. However, advanced carbide tools are now coated with single or multilayer coatings in order to increase their wear resistance. It is obvious that the wear resistance of the coatings differs from the substrate one. So this work aims at updating the previous numerical simulation of cutting tool wear by considering a coating, characterized by a specific wear model, on top of a carbide substrate. The case study of this paper concerns the orthogonal cutting of a 15-5PH martensitic stainless steel with a coated carbide tool.

At first, the numerical model is described. Then a sensitivity study is conducted for 3 different cutting speeds. A comparison is performed between two tool-system formulations. The first one is multilayer formulation with a bilayer coating. The second one is a homogeneous formulation in which the averaged wear properties of each layer plus the

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substrate is used. It is important to note that this paper will not present any comparison with some experimental results. It mainly aims at introducing a multilayer coating in a wear simulation, to propose a first theoretical sensitive investigation to coating's structure, and emphasize the need of considering the tool at this scale in a tool wear simulation

2. Numerical Model

2.1. Wear Simulation

A multi-step tool-wear modelling procedure was developed by [6]. The principle of this iterative method is illustrated in Fig. 1. This model enables to reach rapidly a mechanical steady state thanks to an Arbitrary Lagrangian Eulerian (ALE) model developed in Abaqus/Explicit©. Then, the thermal steady state is reached within a long thermal simulation in Abaqus/Implicit©. Based on these two models, the thermomechanical loadings at the tool-workmaterial interface can be estimated, i.e. the normal stress σ_n , the sliding velocity V_{sl} , and the temperature T . Then, based on a wear model considering the influence of (σ_n, V_{sl}, T) , tool geometry is updated by moving the tool edge nodes. In this paper, the effect of temperature is not considered in the wear model (Eq.1). This strong assumption is possible as temperature is strongly related to sliding velocity [6] that is already present in the wear model. Moreover there is a huge uncertainty on this parameter due to a great lack of scientific knowledge on thermal issues in this narrow tool-workmaterial interface [7]. So this enables to simplify the simulation by performing only the ALE explicit simulations.

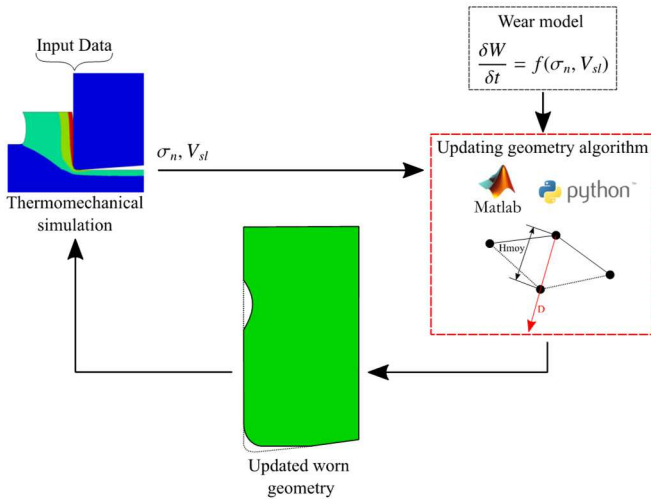


Fig. 1. Wear simulation iterative method

The wear model, used in this study, was developed by Archard et al. [8]. It considers abrasive wear by a simple combination of sliding velocity V_{sl} and contact pressure σ_n :

$$\frac{\partial W}{\partial t} = \frac{k}{H} \cdot V_{sl} \cdot \sigma_n \quad (1)$$

Where $\frac{\partial W}{\partial t}$ is the tool wear rate, k is a wear coefficient and H is the material hardness (N/mm^2).

The ALE simulated cutting time was set at 1ms which enables to reach a steady-state for the thermomechanical loadings due to the rapid chip stabilization. The corresponding thermomechanical loadings withstood by the tool are assumed to be constant during 5 seconds of continuous cutting. Then the geometry is updated based on the wear model included in the MATLAB routine. A new ALE simulation is run and so on for the next 5 seconds of cutting. In this work, 30 iterations have been simulated, which correspond to 150 seconds of cutting. The computation time lasted 20 hours on a standard computer.

2.2. ALE simulations

The basement of the wear simulation is a 2D ALE orthogonal cutting model developed in Abaqus/Explicit©. Such models are well known in the literature [9-11]. They have been successfully employed to predict: cuttings force, tool temperature, stresses in the workpiece and chip formation. The present model is composed of a deformable workpiece and a rigid cutting tool (Fig.2). The tool is fixed while there is a material flow through the workpiece. This material flow is defined through two Eulerian borders located at the top of the chip and at the right output of the modeled part. Heat exchange is allowed by thermal contact conductance between the tool and the workpiece. Value of the conductance was set at $10^4 \text{ W/m}^2\cdot\text{K}$ [7]. Regarding the mesh properties, both parts are meshed with 4-node coupled temperature-displacement elements (CPE4RT). The model is composed of 9,000 elements mostly located at the contact interface which is the region of interest in our case.

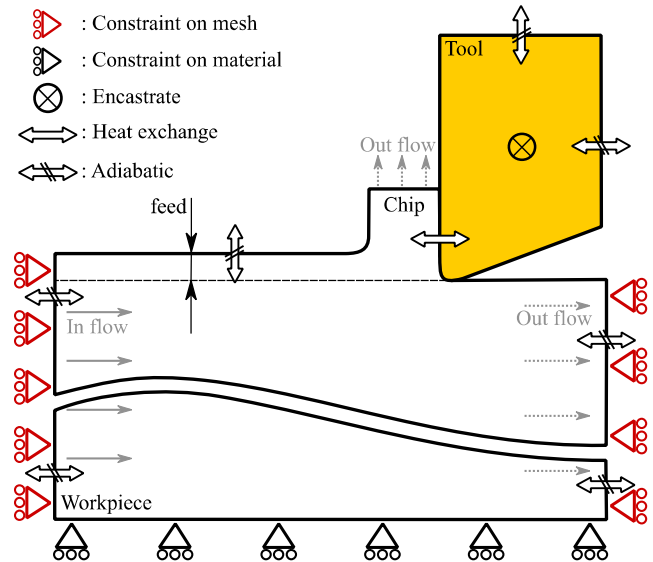


Fig. 2. 2D ALE model and boundary conditions

Regarding the flow-stress model, a Johnson-Cook (Eq.2) equation has been used.

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

Parameters of this model were determined by Mondelin et al. [12], they are listed in Table 1.

Regarding the coating thermal properties, their role is neglected due to their very thin thickness, based on Rech et al. works [13-14] but the tribological properties of the tool-system are taken into account via the friction model. Tool geometry is defined with a 2° rake angle and 5° clearance angle. The cutting conditions were set at a feed of 0.3 mm, whereas cutting speed varies in the range: 100-180-250 m/min.

2.3. Multilayer coating

The main aim of this paper is to introduce a coating on top of the carbide substrate so as to make wear simulation in accordance with modern cutting tools. As coatings are often composed of several layers, two formulations are considered. A first formulation considers a double layer coating with two coatings with specific wear properties in addition to the carbide characterized by its own ones. 3 wear models are thus necessary for each material as shown in Fig.3. A second formulation considers a homogenized tool system, with the same thickness, having wear properties corresponding to averaged properties of the two previous coatings and the substrate. In this second configuration, a single wear model is necessary as shown in Fig. 3. This second configuration corresponds to the state of art proposed by [6].

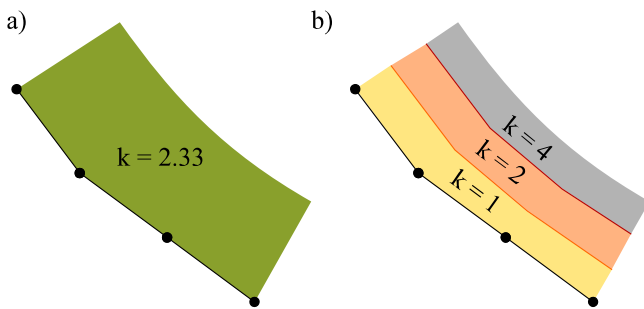


Fig. 3. Wear coefficients for a) the homogeneous coated tool and b) multilayered coated tool

The two coatings considered in this paper are the one observed on a cutting tool from SECOTOOLS having an Al₂O₃ layer (2 μm) deposited on top of a TiCN layer (5 μm) making the interface with the WC-Co substrate.

During wear simulation, nodes are moved after each iteration. For each node, the active wear model depends on their actual position within the tool system as shown in Fig. 4. At the beginning (Fig.4.a), the wear properties of the first layer is affected to all the nodes at the tool top surface. Then, after some iterations (Fig.4.b), the wear model of the second layer is activated for the nodes x and y as their updated coordinates (x' and y') are now located in the second layer. However nodes w and z remains with the same first wear equation because their coordinates (w' and z') stands in the first coating layer. Fig.4.c shows the worn tool geometry after several iterations. The nodal displacement of x is calculated using the third wear equation of the substrate as its position x' is located in the WC-Co. In this study, different wear coefficients were introduced in Archard wear model to simulate the different coating layers. In the current paper, the objective was not the identification of each actual wear model but rather to emphasize the importance of considering this

location variation of wear properties compared to an homogenized tool system. However a consistent order of magnitude for each wear coefficient has been extrapolated from [15] leading to k = 1 for Al₂O₃, k = 2 for TiCN and k = 4 for the substrate (Fig.3). So the TiCN coating wears twice faster than the Al₂O₃ coating. The WC-Co substrate wears four times faster than the Al₂O₃ coating.

Regarding the formulation considering a homogenous tool system, an averaged coefficient of k = 2.33 has been chosen (Fig. 3).

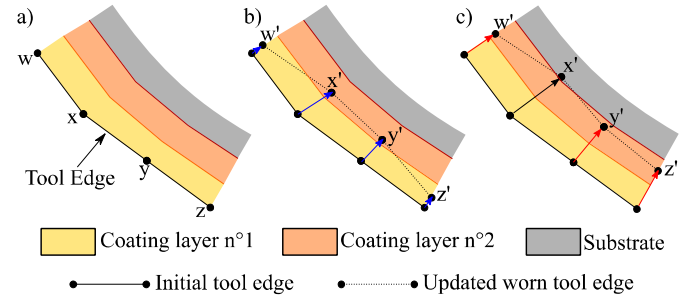


Fig. 4. Multilayer coating formulation (a) Initial tool; (b) Nodal displacement after first iterations; (c) Nodal displacement after several iterations.

2.4. Friction at the interface

Several papers have shown that friction at the tool-workmaterial interface plays a major role on the thermomechanical loadings on the tool edge [1,7,16,17]. In this study, friction is set to be dependent of sliding speed (V_{sl}) at the interface following Equation 3:

$$\mu(V_s) = \mu_k + (\mu_s - \mu_k) \cdot e^{-d_c \cdot V_{sl}} \quad (3)$$

Where μ_k is the kinematic friction, μ_s is the static friction and d_c is the decay coefficient.

Mondelin et al. [12] performed friction tests with a pin-on-cylinder experimental set-up with an Al₂O₃ coated pin on a 15-5PH workpiece. Based on their results, μ_k was set at 0.8, μ_s at 0.15 and d_c at 1.0.

As this study is a preliminary work to develop a multilayer wear model and because of computation limitations, authors decided to apply the same friction formulation for the different coating layers. If the local friction variation is not indeed taken into account, the friction model still represents the tribological behaviour of the tool-system, which can be seen as a first assumption. This will also give the possibility to highlight the specific effect of the wear model without any interaction with the friction formulation. Introducing a specific friction model is a perspective of improvement.

3. Results

3.1. Wear indicators

Wear simulations have been performed for the two configurations (homogeneous material ⇔ double layer coated tool). The wear criteria illustrated in Fig. 5 have been quantified.

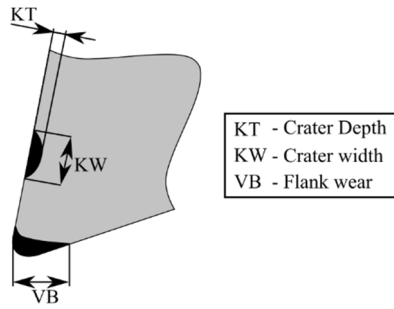


Fig. 5. Wear parameters of tool wear

Figure 6 shows an example of 2 wear formulations after 140 seconds of machining time. It highlights that these formulations result in different wear profiles. It can be noted that wear is different at both the crater and flank faces. Detailed results are presented in sections 3.2 and 3.3 below.

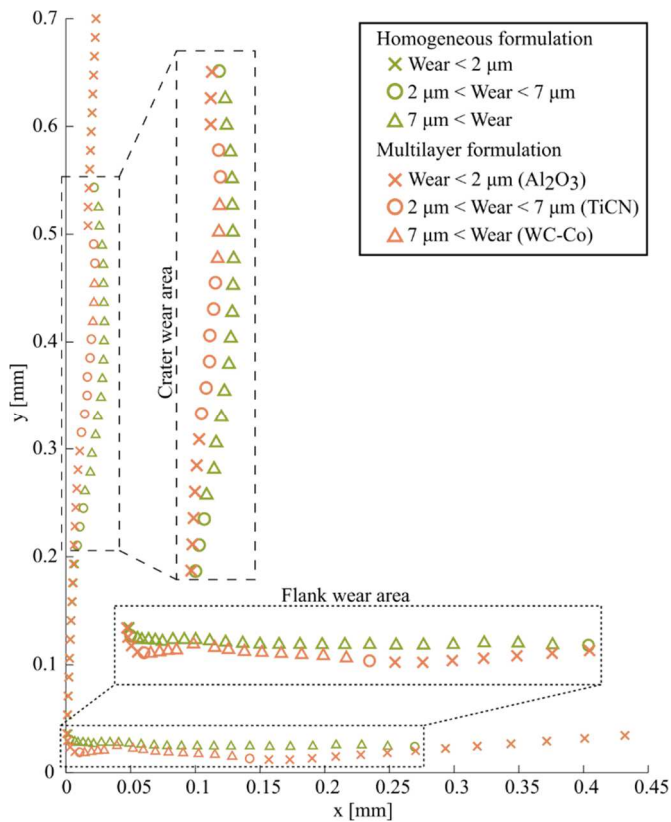


Fig. 6. Wear profiles for homogeneous and multilayer formulations after 140 seconds of machining time at 180 m.min⁻¹.

3.2. Crater Wear

The evolution of crater width (KW) has been plotted in Fig.7 for a cutting speed of 180 m.min⁻¹. The multilayer coated tool highlights that KW becomes almost stable after 70 seconds of machining while KW goes on increasing for a homogeneous coating formulation. It reveals that the Al₂O₃ and TiCN have an effective influence on wear progression on the rake face as illustrated in Fig.8. This is due to the much lower wear coefficient *k* for these layers.

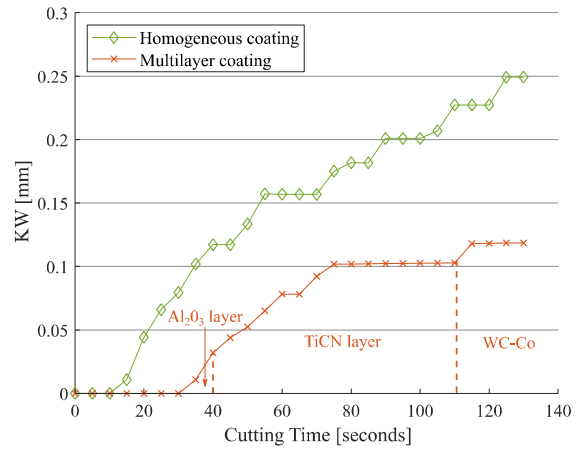


Fig. 7. Crater width (KW) value for the homogeneous tool and the multilayered coated tool at 180 m.min⁻¹

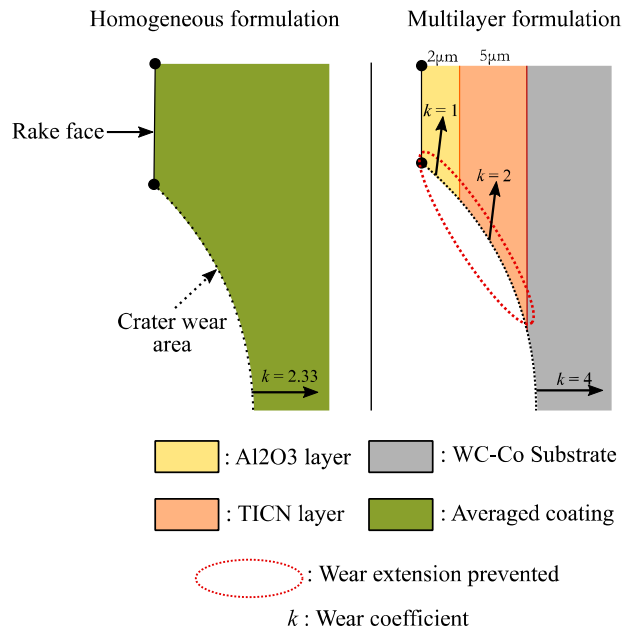


Fig. 8. Crater width (KW) extension limited for the multilayer formulation due to lower coating wear coefficients

Fig.9 shows the crater width after 140 seconds for three cutting speeds and both case studies. It shows that wear magnitude is 2 to 3 times higher for the homogeneous material than for the multilayer one. The evolution of KW is not monotonous between 100 & 250 m/min. This statement is the consequence of the friction and flow stress models. Friction coefficient depends on sliding velocity as shown by Mondelin et al. [12]. The higher is the friction coefficient, the higher is the shear strength and by the way, the lower is the sliding velocity. For a cutting speed of 100 m/min, local friction coefficient are in average higher than for 180 m/min. However there is a limit to the shear strength due to the constitutive equation of the work material. Below a critical level of friction coefficient (around 0.3), the friction model is disassociated from the sliding velocity. This explain why there is not a monotonous behavior of KW over cutting speed. Another analysis has been carried out for the crater depth (KT) in Fig.12. The multilayer coated tool shows significantly better wear resistance than the homogeneous one. Even if the depth of 7 μm (*k* = 4, substrate layer in the multilayer case) is reached after 110 seconds of machining, KT evolution

remains stable. This is due to lower sliding speed in the center of the crater wear area compared to the sides of the crater where sliding speed can be 10 times higher. Figure 10 shows the pressure and sliding speed on tool edge for both formulations. It can be seen that velocity profiles are very different for both formulations. It means that sliding speed is mainly affected by the crater profile as the friction and model properties are the same in both cases.

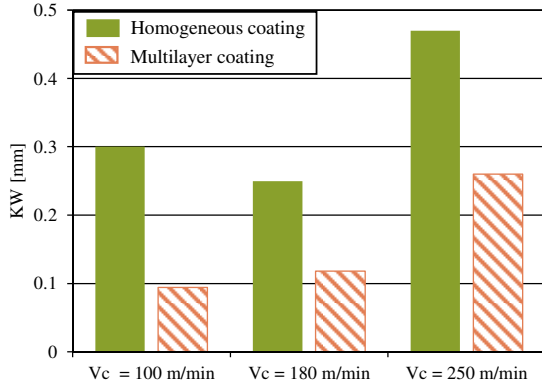


Fig. 9. Crater width (KW) value for homogeneous coated and multilayered carbide at three different cutting speeds after 140 seconds of machining

worn profile. Wear depth is measured orthogonally to the initial profile as shown in (Fig.14).

Even if the substrate is reached after 40 seconds (Fig.13), such as in the KW study, the bilayer coating prevents the wear extension along the flank face. Flank wear is also twice more severe for a homogeneous formulation, as shown in Fig.15.

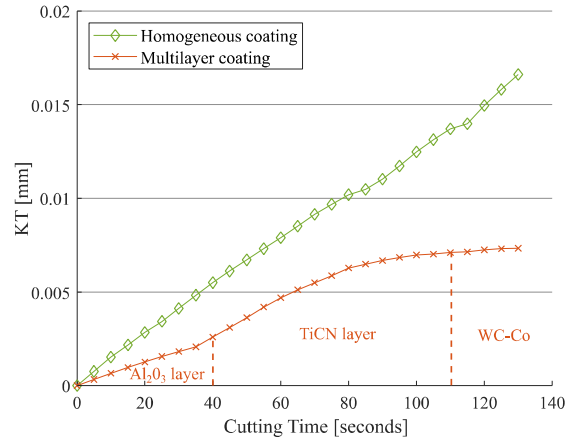


Fig. 11. Crater depth (KT) value for homogeneous coated and multilayered carbide at 180 m.min⁻¹

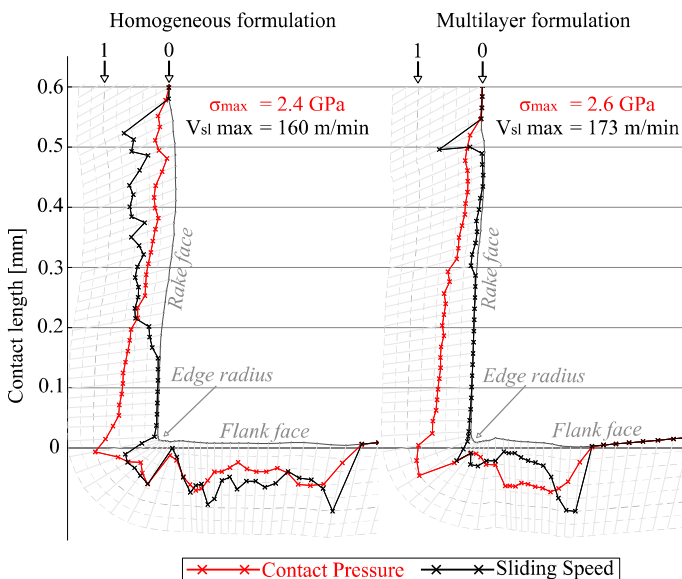


Fig. 10. Mechanical loadings on tool edge for both formulations at Vc = 180 m.min⁻¹ after 140 seconds of machining

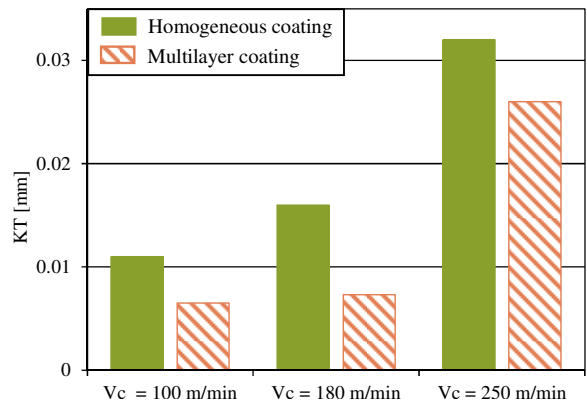


Fig. 12. Crater depth (KT) value for homogeneous coated and multilayered carbide at three different cutting speeds after 140 seconds of machining

Regarding the homogeneous coating, it can be observed that crater depth increases linearly (Fig.11). Unlike the multilayer formulation, as the crater width (KW) increases linearly, there is no sliding speed difference between the crater borders and its center. It results in a linear increase of crater depth.

Fig.12 highlights the crater depth after 140 seconds for three cutting speeds and both case studies. Homogeneous coating shows significantly larger crater depth.

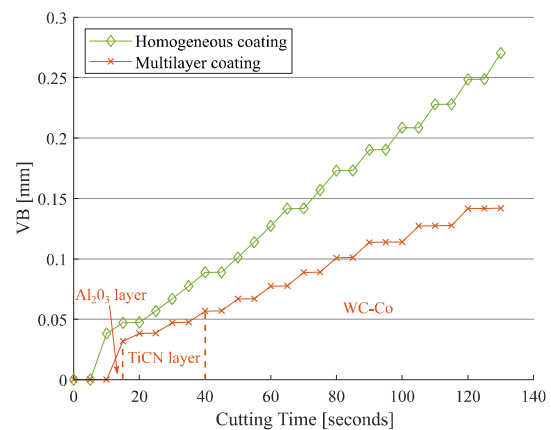


Fig. 13. Flank Wear (VB) value for homogeneous coated and multilayered carbide at 180 m.min⁻¹

3.3. Flank Wear

Flank wear evolution is shown in Fig.13 for both formulations at a cutting speed of 180 m.min⁻¹. In the case of flank wear, a depth of 7 μm is reached after the same time (±10%) in both study cases. Fig. 14 shows wear depth measurement between an initial (new) tool and its updated

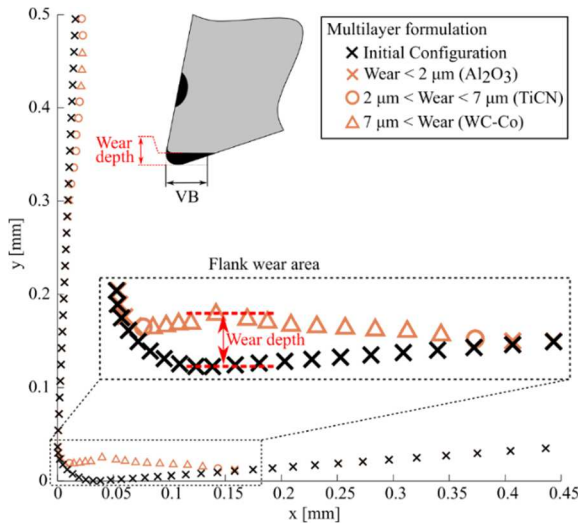


Fig. 14. Wear depth measured orthogonally to flank wear, example of wear the multilayered formulation at 180 m.min⁻¹ after 140 seconds of machining

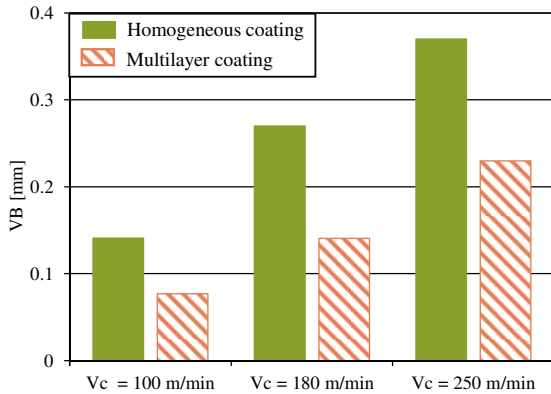


Fig. 15. Flank wear (VB) value for homogeneous coated and multilayered carbide at three different cutting speeds after 140 seconds of machining

4. Conclusion

The present work proposed to study wear in orthogonal cutting of multilayered coated tools. The iterative wear simulation enables to perform wear simulation using an ALE model and a wear algorithm updating the tool geometry. It has been shown that coating formulation plays a major role on the simulated wear results. The multilayer formulation has an impact on all three wear parameters considered in this study. Considering the assumptions made in this paper, such as the friction not depending of the coating layer and the temperature not taken into account, the bilayer coating plays a major role by limiting the wear extension on both rake and flank faces. Further works will be performed to understand the impact of coating thickness and friction properties on the simulated wear profiles. The bilayer coating also limits the wear depth as it reduces indirectly the sliding speed in the crater center. It is shown that wear rates of coating layers and the substrate should be carefully determined. Authors advises to implement a multilayer coating in order to achieve more accurate wear simulation. They are aware that keeping the same friction formulation for the different coating layers is a strong assumption that needs to be investigated. In the future,

experimental tests will be performed in order to assess the presented results.

Acknowledgements

Authors would like to express their gratitude to SECO Tools AB and CETIM for their financial support.

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