Real-time Prediction of the Cutting Tools Wear

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Abstract

In this paper, we present a nonlinear observer to predict on-line the wear of cutting tools during machining.

The observer provides the components of the flank wear and the crater wear as state variables. The cutting parameters: feed, cutting speed, depth-of-cut and rake angle are the input variables of the system; the process output is the measured machining force.

The simulation results are compared to those obtained by others researchers. The states of the wear estimated by the observer are in good agreement with those given by the mathematical model of the cutting process behaviour.
KEYWORDS: Wear, Cutting tools, Real-time prediction, Observer, Machining force.

1. Introduction

The productivity of a numerically controlled machine-tool is one of the major concerns of the industrialists. It is directly related to the cutting time. This last depends on several factors such as the machining process (turning, milling, drilling), the type of cut (roughing, finishing), the choice of the cutting conditions, and the cutting tools life.

The wear of the cutting tools is a destructive process of the superficial layers which leads to the progressive modification of the shape and surfaces of a tool. This modification affects the tool properties and decreases its machining capacity. The degree and the shape of wear influence directly many aspects of the machining process as cutting force, temperature, product quality, etc. The tool life is conditioned by its degree of wear; consequently, the time of machining and therefore the cost are related to wear.
Mainly, the types of the cutting tools wear are: flank wear due to the friction between the tool and the machined surface, and crater wear which occurs on the rake face. The prediction of the tool life or the wear of cutting tools, for a tool-work combination and a given cutting conditions, requires a good understanding of the mechanisms intervening in the tools damage. For this purpose, mathematical models were developed to make possible the prediction of the wear evolution according to the time, and this with a view to design an adaptive control of the machining process and to improve its performances. The wear of cutting tools can be estimated via indirect variables such as the change of the machined surface quality, the shape and the color of the chip, the cutting forces, the vibrations, the acoustic emissions, etc. The implementation of an adaptive control requires knowledge of the state or a part of this one at every time. The state variables can be compiled from the knowledge of the inputs and outputs during a fixed time interval. Thus, the observer goal is precisely to provide an estimation of the current value of the state-vector according to the inputs and outputs of the system. This estimation has to be made in real-time when the observer imitates the dynamic process.

For our contribution, we will to develop a nonlinear observer to predict in real-time the flank wear and crater wear used as criteria to end the use of tool.

2. Shapes and criteria of wear

The cut consists in separating a chip from the part using the cutting edge of a tool. During the passage in the primary shear zone Z_I (see fig. 1), the material undergoes in a very brief time a considerable plastic deformation and heating. Moreover, the friction of the chip on the rake face generates in the tool-chip interface at low cutting speed a built-up edge. At high speed, this built-up edge is replaced by a secondary shear zone Z_{II} which raises the tool temperature very strongly and leads its deterioration directly (by abrasion, plastic deformation, chemical reaction, diffusion, etc.).

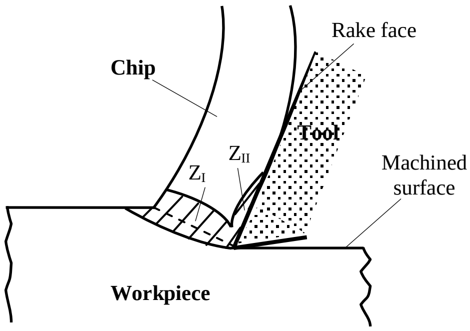

Fig. 1: Chip formation

The chip formation implies on one hand the rubbing of the tool on the machined surface, and, on the other hand, the friction of the chip on the rake face.

These contacts lead to macroscopic damage: flank wear noted V_B and crater wear named K_T. Flank wear is relative to the tool-work contact, and crater wear concerns the rubbing at the tool-chip interface. These shapes of wear are reported on the figures 2 and 3.

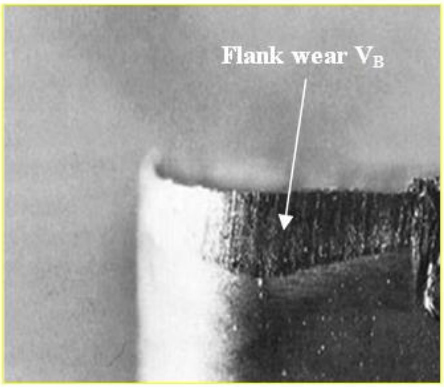

Fig. 2: Flank wear

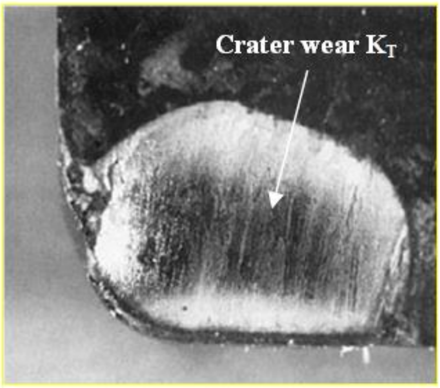

Fig. 3: Crater wear

Before the tool failure, it is possible to define an acceptable limit value of the cutting tool wear said wear criterion (norm ISO 3685); this criterion differs according to the type of cut: roughing or finishing.

In rough cut: the ideal wear criterion corresponds to the value of wear at the end of the stabilization phase. This value is very variable according to the cutting conditions, the work material and the cutting tools. We can indicate, for carbide tools, an acceptable limit of the average value of flank wear: V_B = 0.6 mm.

In finish cut: the state of the machined surface and its dimensional tolerances are the criterion wear; they correspond to a limit value of the flank wear equal to 0.3 mm for carbide tools.

Crater wear is related to the feed (f) by the relation:

$$K_T = (0.06 + 0.3\ f)\ \text{mm} \qquad (1)$$

3. Models of the cutting tools wear

In practice, two kinds of models are relative to the cutting tools wear: the first concerns the prediction of the tool life according to the cutting parameters; the second deals with the predictive models of the cutting tools wear. In the present study, we are interested to the second family of models [2], [3], [4], [5], [6], [7].

3.1. Model of Koren and Lenz

Koren and Lenz [2] proposed a model of the cutting process in turning where the flank wear is the superposition of two states variables. The equations that govern the model are:

$$\begin{cases} \dot{V}_{B1} = -\dfrac{V_c}{l_0}\left(V_{B1} - K_1 \dfrac{F_c}{f \times a_p}\cos\gamma\right) \\ \dot{V}_{B2} = K_2\sqrt{V_c}\,\exp\left[\dfrac{-K_3}{273+\theta_c}\right] \\ V_B = V_{B1} + V_{B2} \\ F_c = [K_4 f^{n_1}(1-K_5\gamma) - K_6 - K_7 V_c]\,a_p + K_8 a_p V_B \\ \theta_c = K_9 V_c^{n_2} f^{n_3} V_c^{n_4} F_c \end{cases} \qquad (2)$$

Where V_c is the cutting speed, f is the feed, and a_p is the depth-of-cut. V_{B1} and V_{B2} are the components of flank wear activated respectively by mechanical and thermal effects. F_c is the cutting force, θ_c is the average cutting temperature at the tool-chip interface, and γ is the rake angle. l_0, K_i (i=1, 9) and n_j (j=1, 4) are the model parameters determined from machining tests.

3.2. Model of Danai and Ulsoy

The model of Danai and Ulsoy [3] completes the model of Koren and Lenz [2] by adding a state including the effect of crater wear. Also, the diffusive component of the flank wear is considered to be activated by thermal effect due to the temperature at the tool-work interface noted θ_f. The equations that govern the model of Danai and Ulsoy are expressed as follows:

$$\begin{cases} \dot{V}_{B1} = -\dfrac{V_c}{l_0}\left(V_{B1} - K_1 \dfrac{F_c}{f \times a_p}\cos\gamma\right) \\ \dot{V}_{B2} = K_2\sqrt{V_c}\,\exp\left[\dfrac{-K_3}{273+\theta_f}\right] \\ V_B = V_{B1} + V_{B2} \\ \dot{K}_T = K_{10} F_c V_c \exp\left[\dfrac{-K_{11}}{273+\theta_c}\right] \\ F_c = [K_4 f^{n_1}(1-K_5\gamma) - K_6 - K_7 V_c]\,a_p \\ \qquad + K_8 a_p V_B - K_{12} K_T \\ \theta_c = K_9 V_c^{n_2} f^{n_3} a_p^{n_4} F_c \\ \theta_f = K_{13} V_c^{n_5} f^{n_6} + K_{14} V_B^{n_7} \end{cases} \qquad (3)$$

Where K_i (i=1, 14) and n_j (j=1, 7) are the model parameters determined from machining tests.

4. Observer of Park and Ulsoy

J-J. Park and A. G. Ulsoy [4] proposed a nonlinear observer to predict on-line the flank wear using the cutting force measurement.

The scheme of the observer is illustrated by figure 4:

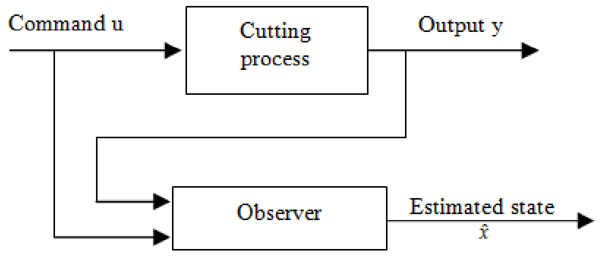

Fig. 4: Observer design

This observer uses the model of Danai and Ulsoy [3] without taking into account the crater wear. The equations that express the formulation of the flank wear observer are given as follows:

$$\begin{cases} \dot{\hat{V}}_{B1} = -\dfrac{V_c}{l_0}\left(\hat{V}_{B1} - K_1 \dfrac{F_c}{f \times a_p}\cos\gamma\right) + G_1(F_c - \hat{F}_c) \\ \dot{\hat{V}}_{B2} = K_2\sqrt{V_c}\exp\left[\dfrac{-K_3}{273+\hat{\theta}_f}\right] + G_2(F_c - \hat{F}_c) \\ \hat{V}_B = \hat{V}_{B1} + \hat{V}_{B2} \\ \hat{F}_c = [K_4 f^{n_1}(1-K_5\gamma) - K_6 - K_7 V_c]\, a_p + K_8 a_p \hat{V}_B \\ \hat{\theta}_f = K_{13} V_c^{n_5} f^{n_6} + K_{14}\hat{V}_B^{n_7} \end{cases} \qquad (4)$$

Notice that $F_c - \hat{F}_c$ is the error of observation between the measured and estimated cutting forces.

The observed states are the components $\hat{V}_{B1}$ and $\hat{V}_{B2}$ of the flank wear activated respectively by mechanical and thermal effects.

The gains of the observer G_1 and G_2 are determined by a poles placement corresponding to a second order system having a natural pulsation ω_n and a damping factor ζ that define the dynamics of the observer.

5. Simulation results

We report in the following table the cutting parameters and those of the models.

Cutting parameters	
V_c = 200 m/min ; f = 0.08 mm/tr ; a_p = 1.27 mm	
Parameters of models	Values for simulation
K_1	4.4 10^{-5}
K_2	20
K_3	8000
K_4	2531
K_5	0.57
K_6	86
K_7	0.1
K_8	504.65
K_9	0.056
K_{10}	8
K_{11}	22000
K_{12}	2000
K_{13}	72
K_{14}	2500
l_0	20
n_1	0.76
n_2	0.45
n_3	-0.55
n_4	-0.95
n_5	0.4
n_6	0.6
n_7	1.45
Tool geometry	
γ	10 °

Tableau 1: Parameters of models [2], [3], [4]

These parameters correspond to a turning operation of the work material AISI 4340 by a triangular carbide insert of “Valenite” manufacturer (VC55 TNMA432) [4].
At the beginning of the machining, we set the initial conditions to zero for the components of flank wear activated by mechanical and thermal effects (V_{B1} = 0 and V_{B2} = 0) for the mathematical model that imitates the cutting process. The initial conditions for the observer are: $(\hat{V}_{B1}, \hat{V}_{B2})_{t=0} = (0.05, 0.05)$.

The observer gains are taken equal to G_1 = -0.0095 and G_2 = 0.0014 (ω_n = 3 rd/s and ζ = 0.8).

Figures 5, 6 and 7 show respectively the evolutions of the flank wear components activated by mechanical and thermal effects and that of the flank wear.
These figures show the results obtained in simulation while considering the structure of the observer of Park and Ulsoy [4].

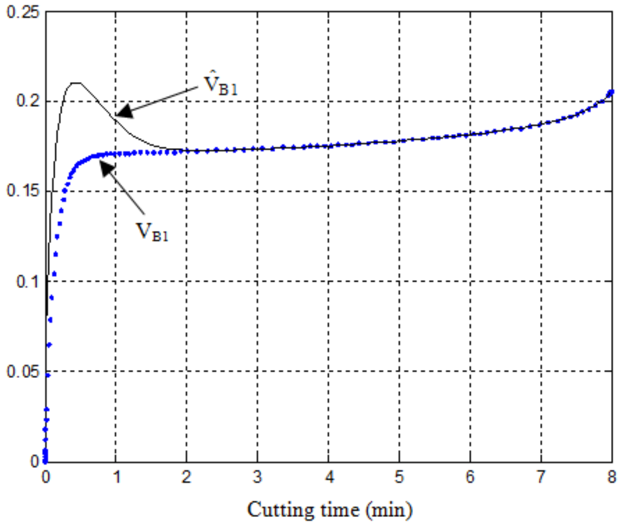

Fig. 5: Wear activated by mechanical effect

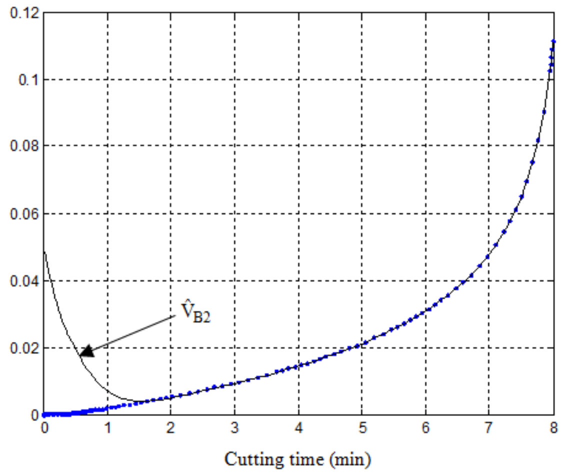

Fig. 6: Wear activated by thermal effect

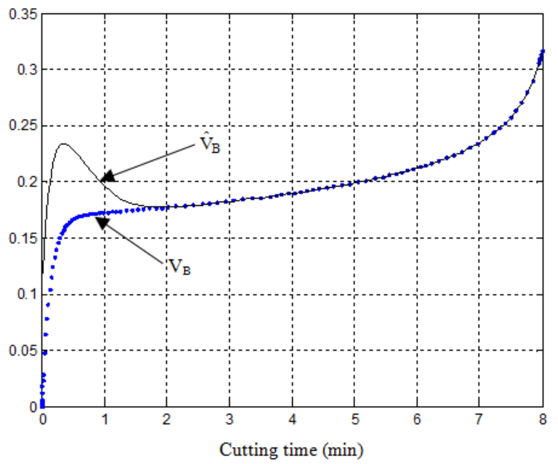

Fig. 7: Flank wear

The simulations have been done under the Matlab software. In order to coinciding our simulation results to those obtained experimentally in reference [4], we assigned to the parameter K_2 the value of 134.5.

The observed variables are in good agreement with those of the process after 2 min. The tool life, for a wear criterion V_B = 0.3 mm, is about 8 min. The global error of prediction between the model and the observer of wear states tend toward zero when the time of machining is greater than 2 min.

In the simulation results presented above, we considered that the initial conditions were equal to zero for the model which corresponds physically to a new cutting tool; whereas the observer, for nonzero initial conditions i.e. different from those of the process, done a good prediction of the cutting tool wear after a machining time of 2 min. This time can be reduced while increasing the dynamics of the observer.

Now we can consider nonzero initial conditions for the cutting process model, which is the case of a used cutting tool. In this case, V_{B1}=0.175 and V_{B2}=0.0145 mm at the instant t=0; the observer uses zero conditions at the starting of the machining. The values of V_{B1}=0.175 and V_{B2}=0.0145 mm correspond to a machining time of 4 min that means that the tool has machined during 4 min.

In order to show the influence of the gains of the observer, we consider two values of the natural pulsation of the observer system; either ω_n=2.5 rd/s and ω_n=10 rd/s. Figures 8, 9 and 10 show respectively the evolutions of the flank wear components and the total flank wear.

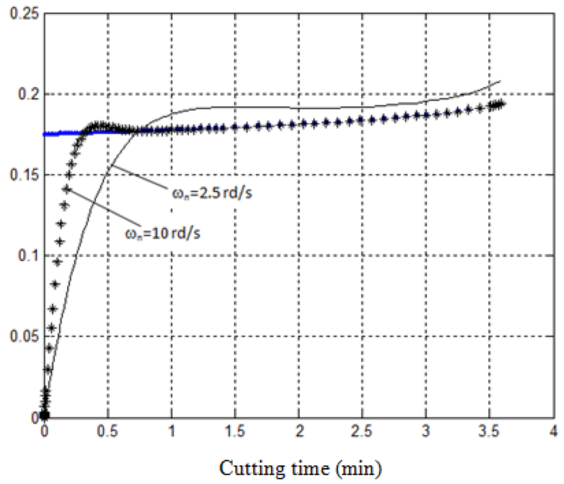

Fig. 8: Wears V_{B1} and $\hat{V}_{B1}$

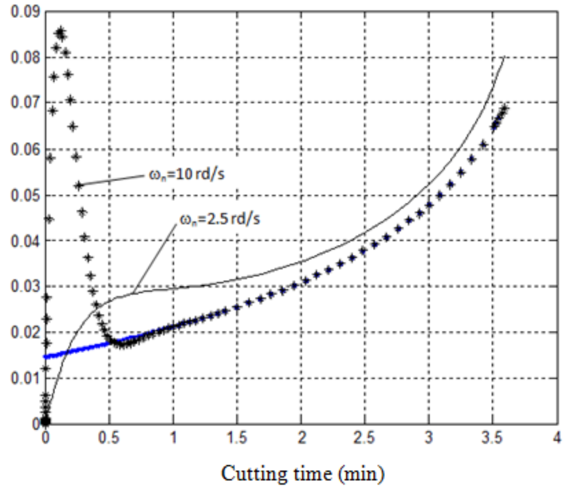

Fig. 9: Wears V_{B2} and $\hat{V}_{B2}$

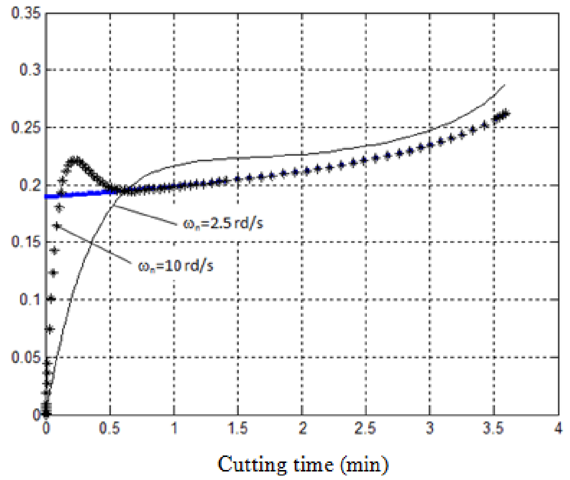

Fig. 10: Wears V_B and $\hat{V}_B$

We notice that in spite of a different choice of the initial conditions, the observer ensures the prediction of flank wear of the cutting tool. The faster dynamics of the observer permits a faster estimation of wear. The tool life does not exceed 4 min for a wear criterion V_B=0.3 mm; therefore, the total tool life is in the neighbourhoods of 8 min if we add the machining time of 4 min already carried out.

We consider now the model of Danai and Ulsoy [3] that takes into account crater wear in order to design an observer which permits to estimate simultaneously the flank wear and crater wear of a cutting tool. The equations that govern the observer are expressed as follows:

$$\begin{cases} \dot{\hat{V}}_{B1} = -\dfrac{V_c}{l_0}\left(\hat{V}_{B1} - K_1 \dfrac{F_c}{f \times a_p}\cos\gamma\right) + G_1(F_c - \hat{F}_c) \\ \dot{\hat{V}}_{B2} = K_2\sqrt{V_c}\exp\left[\dfrac{-K_3}{273+\hat{\theta}_f}\right] + G_2(F_c - \hat{F}_c) \\ \hat{V}_B = \hat{V}_{B1} + \hat{V}_{B2} \\ \dot{\hat{K}}_T = K_{10}F_cV_c\exp\left[\dfrac{-K_{11}}{273+\hat{\theta}_c}\right] + G_3(F_c - \hat{F}_c) \\ \hat{F}_c = [K_4 f^{n_1}(1-K_5\gamma) - K_6 - K_7V_c]a_p \\ \qquad + K_8 a_p \hat{V}_B - K_{12}\hat{K}_T \\ \hat{\theta}_c = K_9 V_c^{n_2} f^{n_3} a_p^{n_4} F_c \\ \hat{\theta}_f = K_{13} V_c^{n_5} f^{n_6} + K_{14}\hat{V}_B^{n_7} \end{cases} \tag{5}$$

The gains of the observer G_1, G_2 and G_3 will be determined by a poles placement corresponding to a system of the third order: $(s^3 + 2\zeta\omega_n s^2 + \omega_n^2 s)$.

Figures 11, 12, 13 and 14 show respectively the evolutions of the flank wear components, the total flank wear and the crater wear.

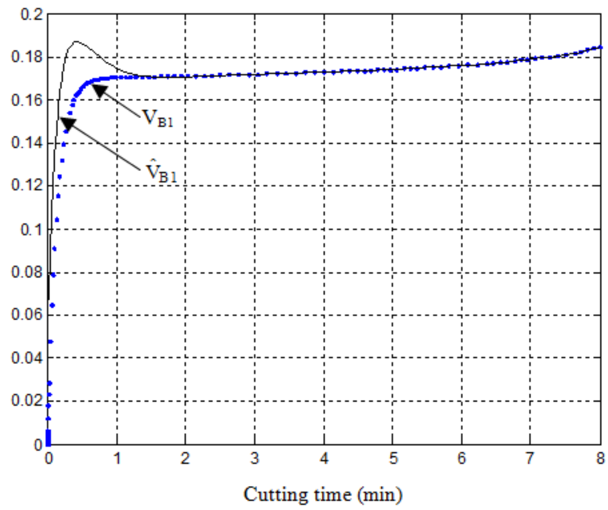

Fig. 11: Wears V_{B1} and $\hat{V}_{B1}$

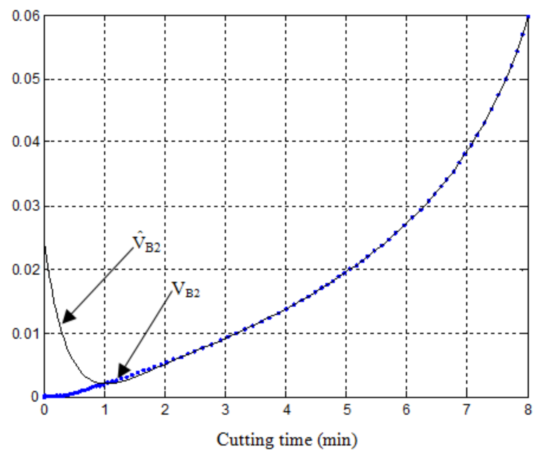

Fig. 12: Wears V_{B2} and $\hat{V}_{B2}$

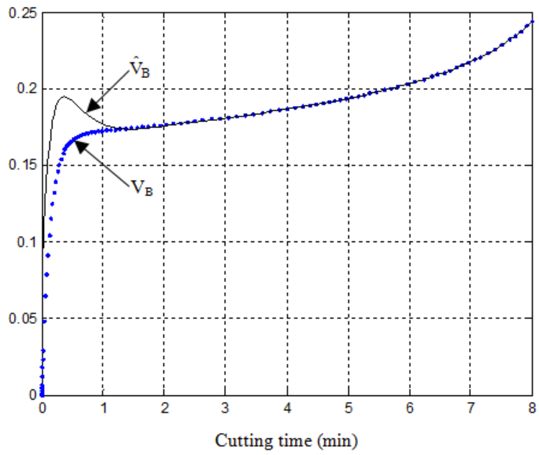

Fig. 13: Wears V_B and $\hat{V}_B$

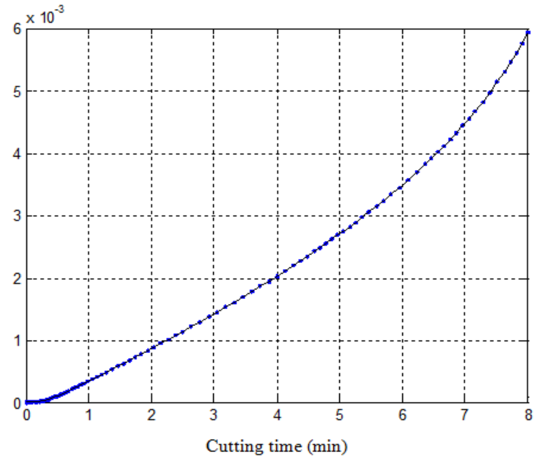

Fig. 14: Wears K_T and $\hat{K}_T$

These last figures correspond to a choice of ω_n equal to 3 rd/s and the initial conditions of the cutting tool wears are: $(\hat{V}_{B1}, \hat{V}_{B2}, \hat{K}_T)_{t=0} = (0.05, 0.025, 0)$. This choice of initial conditions is done in order to differentiate the estimated variables from those of the mathematical model. The crater wear is expressed according to the temperature at tool-chip interface which is formulated according to the cutting force; therefore, the crater wear may be determined directly from the cutting force measurement. We notice that the level of total flank value decreases relatively; this is caused by the reduction of the cutting force due to crater wear. This reduction allows a light gain in tool life.

We can at this stage consider that the model of Danai and Ulsoy is more complete owing to the fact that it integrates the flank and crater wear. This model will be useful to imitate the behavior of the cutting process, and we will choose the observer which uses the model of Park and Ulsoy. The gains of the observer will be determined like previously by a poles placement of the desired dynamics.

Figures 15, 16 and 17 show respectively the evolutions of the flank wear components and the total flank wear.

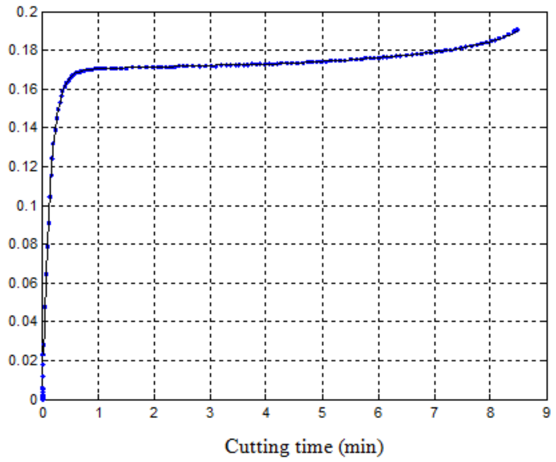

Fig. 15: Wears V_{B1} and $\hat{V}_{B1}$

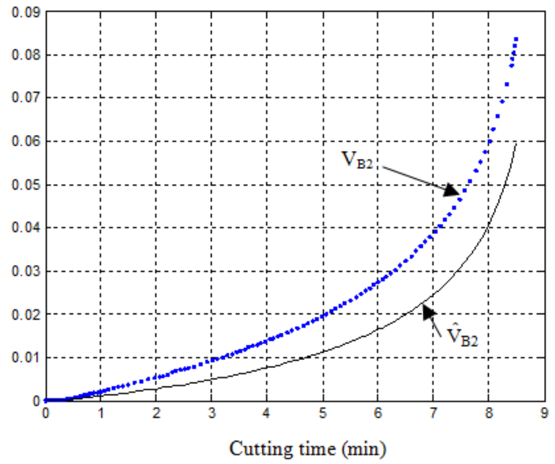

Fig. 16: Wears V_{B2} and $\hat{V}_{B2}$

Notice through figures 15 and 16 that the wear component activated by thermal effect and total flank wear differ from the estimated ones. This estimation error is obtained by neglecting the effect of crater wear in the formulation of the estimated cutting force; that is to say the term: $-K_{12} \cdot \hat{K}_T$. For this last simulation, we chose the value of the pulsation ω_n equal to 10 rd/s.

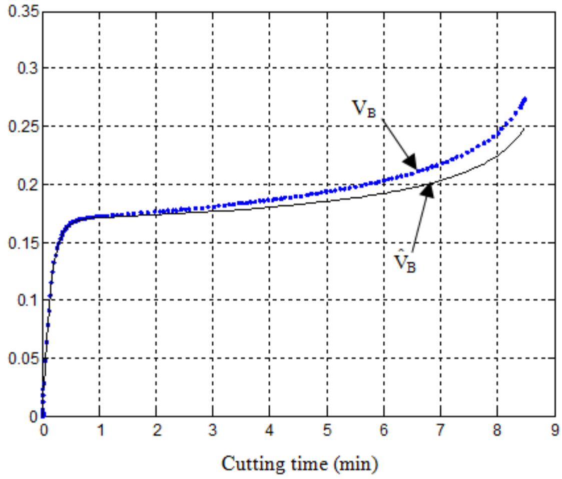

Fig. 17: Wears V_B and $\hat{V}_B$

6. Conclusion

In this work, we presented mainly two nonlinear observers allowing real-time prediction of the cutting tools wear. The observers use the measurement of the machining force. The temperatures, used for the estimation of the diffusive component of the flank wear and crater wear, are also estimated from the cutting force measurement.

The simulation for the observer of Park and Ulsoy give results of prediction which coincide with those obtained in experiment and reported in the reference [4]. The addition of crater wear in the model of Danai and Ulsoy deserves to be re-examined and confronted with experimental results.

Also, this work relatively to the observer of Park and Ulsoy will be supplemented by a formulation of the numerical version.

7. References

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