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Experimental Study of the Influence of the Static Stiffness of Lathes on the Tool Wear Behavior

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Abstract: The aim of this study is the study of the influence of the machine tools rigidity on the tool wear when turning with carbide tools in an industrial environment. The tests were carried on three different lathes characterized by their static stiffness. On each lathe, the evolution of the carbide tool wear was studied according to a method based of the experimental design included the cutting time, the cutting speed and the feed rate. Significant differences clearly appeared between the three machine tools showing the necessity of integrating of a rigidity parameter on the tool life models. Thus, a modified Gilbert tool life model included the rigidity of the machine tool was proposed which can be easily used for industrial application.

Key words: Machine-tool rigidity, carbide tool wear, tool life time model, evolution, lathe, Gilbert tool life model

INTRODUCTION

For a cutting process, a wide range of factors such as the cutting conditions, the tool material or the lubrication can influence the technological parameters like the machining precision, the quality of the machined surface, the cutting power or the production cost. Among these factors, one was often neglected: the machine tool itself. Indeed, most of general results proposed in the machining study, generally consider that the machine tool is an invariable factor or has a neglected influence. In fact, the existence of a large diversity of machine tools implies that the technical characteristics such as the stiffness, the kinematics chain and the degree of automation differ from one machine tool to one other.

By consequence, it is important to wonder if the results obtained in different research laboratories, in particular in the tool wear domain, are reproducible and can be directly employed by other researchers or industrials. In this study, we try to answer to a part of this question. For that, a series of turning tests following an experimental design (Boulanouar, 1996; Yallese *et al.*, 2005) were carried out on three turning machine tools with variable static stiffness under different cutting conditions The parameters retained in the experimental design are: the cutting time t, the cutting speed V, the feed rate f and the width of cut d. For wear characterization, flank wear and crater wear were considered. The static stiffness of each lathe was determined for each considered parallel lathe. Thus, quantitative and qualitative relationship between the tool life time t, the cutting conditions V, f, d and the stiffness of the machine tool J_m were analyzed. Then a modified model for tool life time was proposed including the static stiffness of the considered parallel lathe.

Model for static stiffness of lathes: The different components of the mounting (lathe, workpiece, tool, tool holder) form an elastic system (machine-piece-tool system). During a machining operation, this system is subjected to the cutting forces which produce elastic deformations and displacements of the different components resulting from gaps at the articulations. The magnitude of the elastic deformations is defined on the one hand by the applied cutting forces and on the other hand by the stiffness of the elastic system. The variations of the cutting forces, which are controlled by the chip formation mechanism itself and by the interaction between the different components of the system, lead to irregular deformations and deflections affecting the shape and the dimensions of the finished workpiece. Thus, the machining accuracy may be influenced for a great part by the stiffness of the machine-piece-tool system.

The most important variations of the displacements results from the variation of cutting the normal component fy of the cutting load. Therefore, we consider principally the stiffness of by the quotient between this normal component fy and the resulting deflection y in the

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direction of this force (Kovan, 1970; Carrino *et al.*, 2002; Liu Zhan Cliang, 2000; Salgado *et al.*, 2005; Guo Jianliang and Han Rongdi, 2005; Rene Mayer *et al.*, 2000; Ratchev *et al.*, 2004; Philippe and Jean-Yves Hascoet, 2005). The stiffness is then given by the following general equation:

$$J = \frac{F_y}{y} \tag{1}$$

In the case of the machining of a cylindrical bar mounted between the research head and the tailstock, the stiffness of a lathe is obtained on the basis of the following considerations. The action of the normal force fy applied at a point located on the workpiece surface at the distance x (Fig. 1) between the tool nose and the research-head displaces:

- The research head from the point A to the point A' with a deflection y_{wh},
- The tailstock from the point B to the point B'' with a deflection y_t,
- The trolley from the point C to the point C' with a deflection y_{ch}
- The axis of rotation of the workpiece from AB to A'B.

At the distance x from the research head, the axis of rotation is displaced to the deflection y_x.Thus the total deflection ym is given by the summation of y_{ch} and y_x:

$$y_m = y_{ch} + y_x \tag{2}$$

$$y_x = y_{wh} + K \tag{3}$$

$$y_{wh} = \frac{R_A}{J_{wh}} \tag{4}$$

$$y_{ch} = \frac{F_y}{J_{ch}} \tag{5}$$

The value of K is determined from the triangle A'B'B Fig. 1:

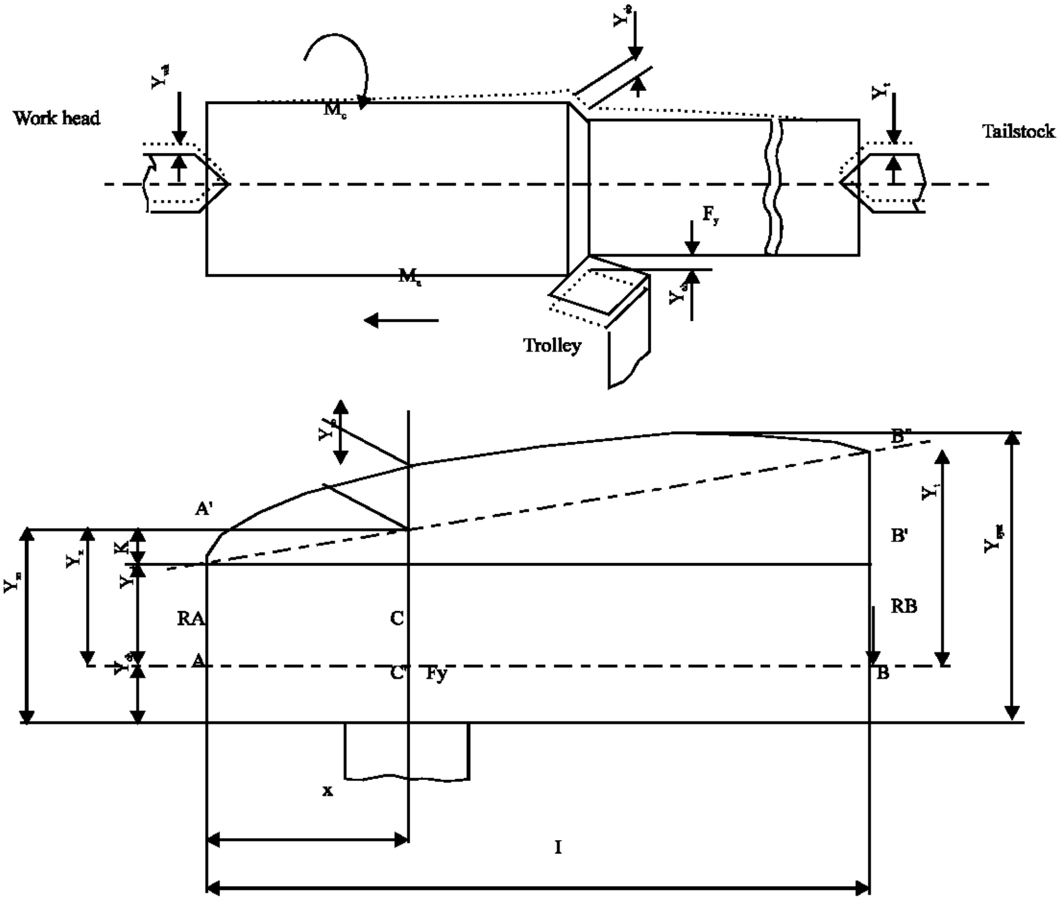

Fig. 1: Schema for calculation of the static stiffness of the machine-piece-tool system

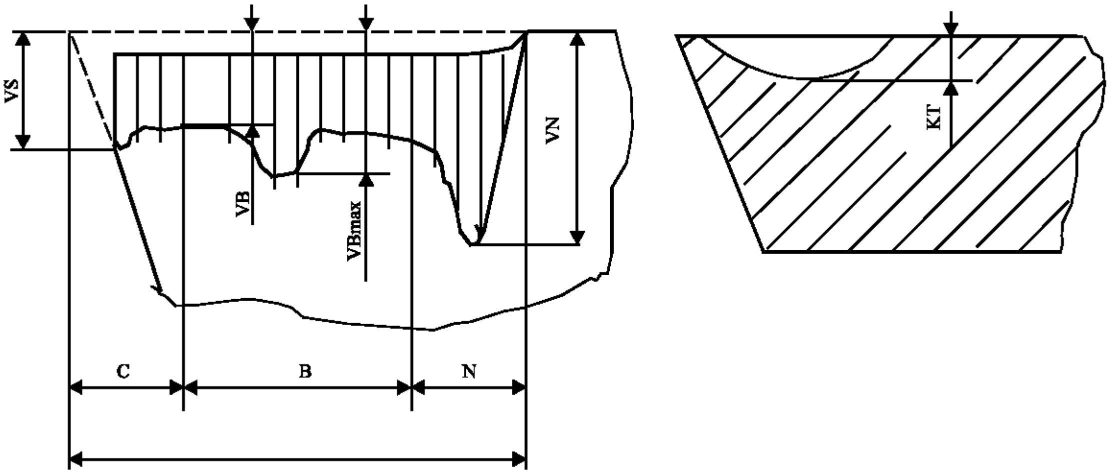

Fig. 2: Schematic representation of tool wear criteria (a) flank wear (b) crater wear

$$K = (y_t - y_{wh})\frac{x}{1} \tag{6}$$

$$\text{where } y_t = \frac{R_B}{J_t} \tag{7}$$

R_A and R_B are respectively the reactions of the research head and the tailstock, due to the application of the normal component force fy:

$$R_A = F_y.\frac{(1-x)}{1} \tag{8}$$

$$R_B = F_y.\frac{x}{1} \tag{9}$$

After substitutions and correspondent transformations, we obtain the following expression of the stiffness of the machine tool J_m:

$$J_m = \frac{F_y}{y_m} = \frac{1}{\frac{1}{J_{ch}} + \frac{1}{J_{wh}}\left(\frac{1-x}{1}\right)^2 + \frac{1}{J_t}\left(\frac{x}{1}\right)^2} \tag{10}$$

Wear of cutting tools: During the formation of the chip, several parts of the tool are in contact with the chip and the workpiece. The tribological conditions at the contact zones are very severe. Indeed, whereas the specific pressures in the contact surfaces of the machine elements do not exceed a few MPa and the temperatures are less than 100°C, the contact pressure at the tool chip interface is around in the contact surfaces of the active part of a tool is around the GPa and the temperature can be more than 1000°C, (Trent and Wright, 2000; Molinari and Nouari, 2002; Trent, 1988; List *et al.*, 2005; Poulachon and Moisen, 2003; Nabahani, 2001). The mechanisms of cutting tool wear are very complex implying mechanical and chemical phenomena. Some of the most important causes of tool wear are: plastic deformation, abrasion, adhesion and diffusion (Trent and Wright, 2000; Molinar and Novari, 2002; Trent, 1988; List *et al.*, 2005). The various kinds of tool wear mainly depend on the following parameters: the nature of the tool, the material of the parts, the tool geometry, the cutting conditions, the use of lubrication, the machining operation and the rigidity of the machine-piece-tool system. The consequence of the tool wear is a progressive modification of the tool geometry affecting the cutting temperature, the cutting forces, the accuracy and the surface roughness of the finished surface. At the flank face, sliding condition dominates and abrasion control the tool wear characterized by the measurement of VB, VS and VN (Fig. 2a). Analyses of wear have traditionally emphasized flank wear because of the direct influence of the tool flank face on the quality of the machined surface. At the same time, as said before the tool rake face is subjected to high pressure. At low cutting speed the built-up edge dominates, but by increasing the cutting speed, temperature increases too, then adhesion wear and diffusion wear take place (Trent and Wright, 2000;

Molinari and Nouari, 2002; Trent, 1988, List *et al.*, 2005; Poulachon, 2003; Nabahani, 2001). Adhesion wear is caused by the mechanical removal of the tool material when the adhesive junctions are broken. When the role of temperature becomes more important, diffusion between the elements of the tool and the chip are activated. In the case of the machining of steel with carbide tool, atoms diffused from the tool to the chip. Both adhesion and diffusion wears lead to a formation of a crater at the tool rake face characterised by the measurement of KT (Fig. 2b).

MATERIALS AND METHODS

The static stiffness J_m of each tool machine was experimentally determined following the schema described in the paragraph 2 and Fig. 1. For the characterisation, a standard bar with a length of 300 mm and a diameter of 70 mm was used. The normal force fy was applied at the middle of the bar and measured using a dynamometric ring. The repulsions y of the different elements were measured thanks to a dial micrometer. The technical characteristics of the three parallel lathes and their static stiffness are reported in Table 1. The three lathes were also previously subjected to different controls of geometrical precision in both horizontal and vertical plans in order to verify that the lathes were in conformity according the norms. For wear investigation, dry turning tests were carried out on cylindrical bars made in steel C22 with a diameter of 70 mm. and having a usable length of 450 mm. The tool consists of a reversible carbide insert (type SNMN1204MO) with a carbide nuance of P25 mounted on a tool holder (type CSBNR322512) having the following geometrical parameters: $\Re r = 75°$, $\Re r_1 = 0°$ (over a length of 1.4 mm), ã = -6°, á = 6° and ë = - 6°. The overhang of the tool was 25 mm. The workpiece is mounted between a mandrel and a tailstock. The cutting conditions are the following: 100 m min^{-1} - 200 m min^{-1} for the cutting speed V, 0.11mm rev^{-1} - 0.22 mm rev^{-1} for the feed rate f and 1 mm-2 mm for the width of cut d. To estimate the tool life time t, we retained the admissible wear criteria: [VBmax] = 0.5 mm and [KT] = 0.15 mm were retained referring to the norm. VBmax was measured by optical with a precision of 0.005 mm. The crater wear KT was measured by a device including a dial micrometer.

Table 1: Stiffness of the machine tool and their technical characteristics

Machine tool	Stiffness J_m (daN mm^{-1})	Machine model	Engine power (kW)	Maximal distance between the centres (mm)	Weight (daN)
Lathe n°1	3046.55	1A616	4.4	700	---
Lathe n°2	1848.68	SN40C	6.6	1500	1720
Lathe n°3	1514.32	SN40C	6.6	1000	1620

Table 2: Mathematical model for the tool life time for each machine tool

Machine tool	Mathematical model of the tool life time T	Correlation coefficient R^2
Lathe n°1	$T = \frac{e^{16.617}}{V^{3.104} f^{1.012} d^{0.537}}$	0.87
Lathe n°2	$T = \frac{e.^{17,158}}{V^{3.219} f^{0.883} d^{0.723}}$	0.95
Lathe n°3 (series n°1)	$T = \frac{e^{16.190}}{V^{3.128} f^{1.126} d^{1.045}}$	0.89
Lathe n°3' (series n°2)	$T = \frac{e^{16.283}}{V^{3.165} f^{1.165} d^{0.956}}$	0.89

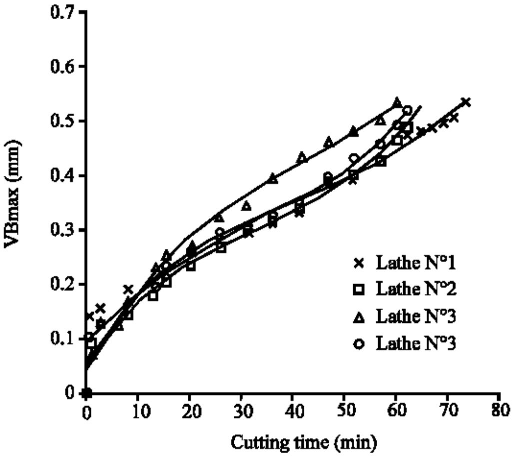

Fig. 3: Flank wear vs. cutting time for V = 100 m min^{-1}, f = 0.11 mm rev^{-1}, d = 1 mm

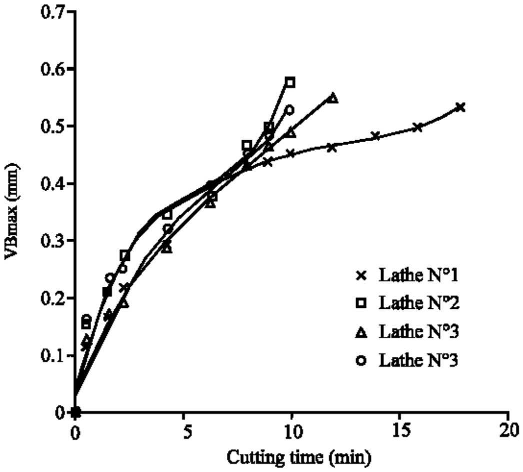

Fig. 4: Flank wear vs. cutting time for V = 200 m min^{-1}, f = 0.11 mm rev^{-1}, d = 1 mm

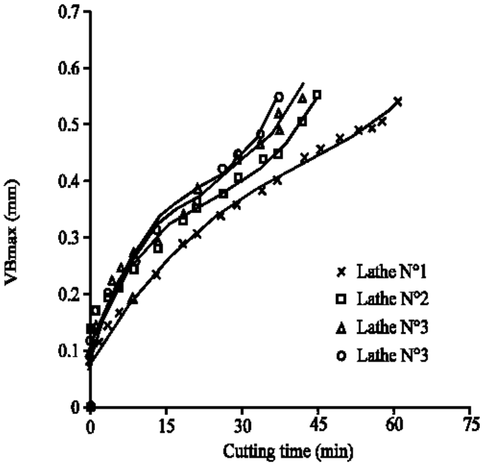

Fig. 5 : Flank wear vs. cutting time for V = 100 m min^{-1}, f = 0.22 mm rev^{-1}, d = 1 mm

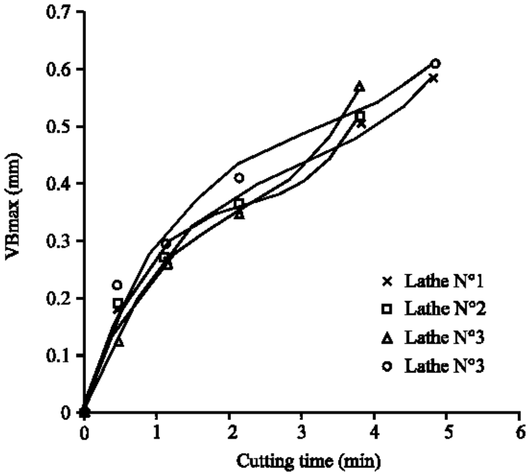

Fig. 6: Flank wear vs. cutting time for V = 200 m min^{-1}, f = 0.22 mm rev^{-1}, d = 1 mm

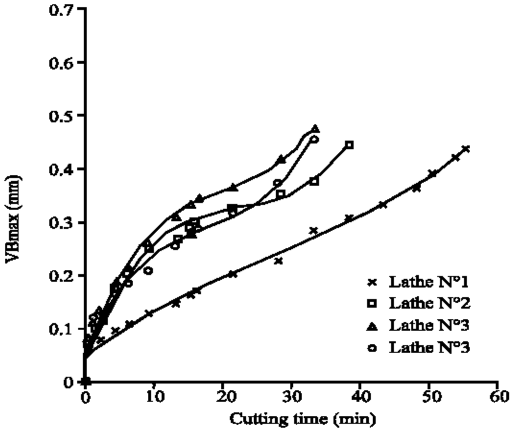

Fig. 7: Flank wear vs. cutting time for V = 100 m min^{-1}, f = 0.11 mm rev^{-1}, d = 2 mm

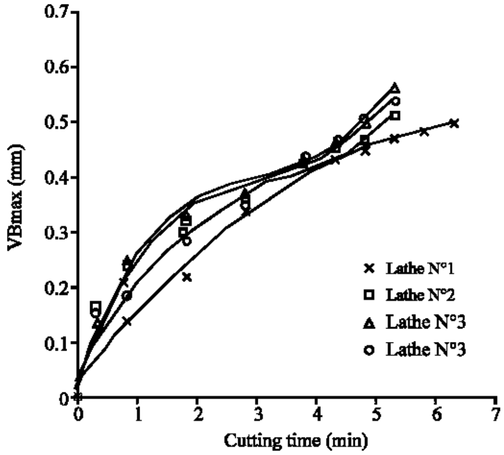

Fig. 8: Flank wear vs. cutting time for V = 200 m min^{-1}, f = 0.11 mm rev^{-1}, d = 2 mm

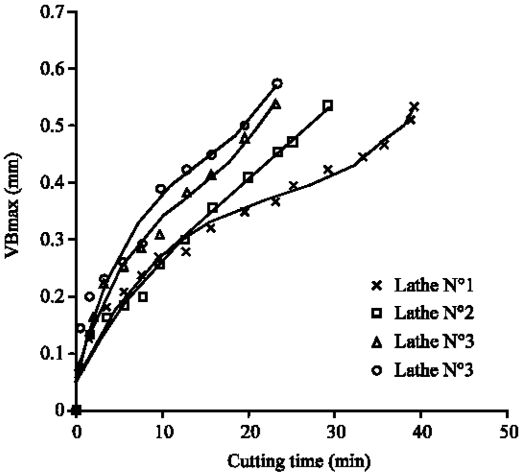

Fig. 9: Flank wear vs. cutting time for V = 100 m min^{-1}, f = 0.22 mm rev^{-1}, d = 2 mm

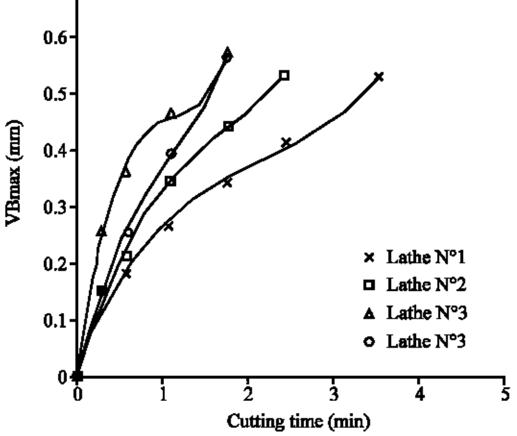

Fig. 10: Flank wear vs. cutting time for V = 200 m min^{-1}, f = 0.22 mm rev^{-1}, d = 2 mm

RESULTS

The flank wear VBmax increases more rapidly important than the crater wear KT. That is why; only the results of the admissible criterion of wear VBmax are presented and retained for the determination of the tool life time t. The evolutions of the tool wear according to the cutting time t, are illustrated in Fig. 3 to 10. By a statistical treatment, mathematical relationship (Gilbert model) of the tool life time t was determined as a function of the cutting speed V, the feed rate f and the width of cut d (Table 2).

DISCUSSION

The wear curves are classically subdivided in three distinct zones (Fig. 3-10). The first zone is characterized by a short fast increase; followed by a second zone which presents a stable evolution with a nearly linear tendency. The third zone is distinguished by a remarkable intensification of the wear, which will lead later to the collapse of the tool nose. The results show that the increase of the cutting speed V, feed rate f and the width of cut d cause a decrease of the tool life time. But, that is the cutting speed which has the greatest degree of influence, followed by the feed rate and finally the width of cut. However, the influence of V, f and d on the tool life time decrease when the stiffness of the machine tool increases. The results also show that on the machine tool which has the weakest stiffness (lathe n°3), the tool wear intensifies in the neighbourhood of the admissible value of flank wear. In other terms, the tool life time increases with the increase of stiffness of the machine tool. To evaluate the influence of the stiffness J_m on the tool life time t, we can analyse the relationship between the ratio of stiffness $Rr = J_{m1}/J_{m2}$ for two machine tools having respectively a stiffness J_{m1} and J_{m2} and its impact on the tool life time representing by the percentage$\Delta = T_1/T_2$ where T_1 and T_2 are the respective tool life time for a cutting condition:

- If the tests are repeated on the same machine (Rr = 1), the average relative difference in percentage for the Tool life time Δis in the order of = 1.50 %.
- If the tests were carried out two different machines having a Rr = 1.22, then the average relative difference in % of the tool life is respectively equal to Δ14.33 %.
- If the tests were carried out two different machines having a Rr = 2.01, then the average relative difference in % of the tool life is respectively equal to Δ = 35.50 %.

Based on these analyses, we can affirm that with the the stiffness of the machine tool has a large influence on the tool wear and tool life time.

Model of tool life time including the stiffness parameter: Because of the non neglected influence of the stiffness, we suggest to modify the mathematical model of the tool life time, by taking into account not only the influence of the cutting conditions but also the static stiffness of the machine tool. Hence, another analysis allowed us the deduction of another mathematical model; expressing for each cutting condition the relationship between the tool life time t and the static stiffness of the machine tool J_m (Table 3):

$$T = C\,J_m^{\,b} \tag{11}$$

The analysis of this model reveals that the values of C and the exponent b are not constant, but they are in function of the cutting conditions. This observation incited us to look for a mathematical expression linking these parameters. The statistical treatment of the values C and b function of V, f and d (Table 3) leads to the following model:

$$C = e^{9.392}\,V^{-3.169}\,d^{-2.867}f^{-3.805} \tag{12}$$

Table 3: Mathematical models of the tool life time including the static stiffness

Test	Cutting conditions			Model	Correlation coefficient	Constants of the model	
No	V(m min^{-1})	f (mm rev^{-1})	d (mm)	$T = C\,J_m^{\,b}$	R^2	C	b
1	100	0.11	1	$T = 13.479\,J_m^{0.206}$	0.998	13.479	0.206
2	200	0.11	1	$T = 0.017\,J_m^{0.851}$	0.923	0.017	0.851
3	100	0.22	1	$T = 0.171\,J_m^{0.727}$	0.99	0.171	0.727
4	200	0.22	1	$T = 0.536\,J_m^{0.246}$	0.755	0.536	0.246
5	100	0.11	2	$T = 0.130\,J_m^{0.750}$	0.998	0.13	0.75
6	200	0.11	2	$T = 0.192\,J_m^{0.434}$	0.992	0.192	0.434
7	100	0.22	2	$T = 0.029\,J_m^{0.895}$	0.952	0.029	0.895
8	200	0.22	2	$T = 7.590\,J_m^{1.045}$	0.962	7.59	1.045

$$b = e^{-0.042}\ V^{-0.021}\ f^{-0.388} d^{0.82} \qquad (13)$$

While substituting Eq. 12 and 13 in 11, we obtain the researched model (14) which expresses a qualitative and a quantitative relation between the tool life time t in one side, the cutting conditions (V, f, d) and the static stiffness J_m of the machine tool in the other side:

$$T = e^{9.392}\ V^{-3.169}\ d^{-2.867} f^{-3.805} J_m^{(e^{-0.042}\ V^{-0.021}\ f^{-0.388} d^{0.82})} \qquad (14)$$

The integration of the machine tool stiffness in an usual model of the tool life time has a great technical and economical importance. Indeed manufacturing costs, the macro and micro geometric accuracies of the mechanical pieces and the management of the production fluxes are in close relationship with the wear and life time of the cutting tools. This model may presents a precious information, in particular for the integrated systems of production.

CONCLUSION

Based on the previous analyses we can deduce the following principal conclusions:

- The values of the wear (Tool life) measured on the same machine reproduce with a relative average difference around±1,50 %.
- The static stiffness of the machine tools has a non neglected influence on the increase of the wear and consequently on the tool life time. When the stiffness changes from 1.0 to 2.0, the tool life time increase from 0 to 35.5 %.
- While machining on machine tools (parallel lathes), having a static stiffness varying between 1514.32 and 3046.55 daN/mm, we found mathematical models allowing to calculate:
- The tool life time as a function of the cutting conditions. Obviously, the results are specific to the tested machines but they are also acceptable for all other machine having an equivalent static stiffness (Table 2).
- The tool life time is not only a function of the elements of the cutting conditions but also of the static stiffness of the machine tool. In this case, the proposed model (Eq. 14) is acceptable for all other machine with the same characteristics type and having stiffness between 1514.32 and 3046.55 daN/mm and working within the range of the studied cutting conditions.
- The deduced mathematical model express a qualitative and a quantitative relation between the life time time, the cutting conditions and the static stiffness of the machine-tool. The model may be then used for optimizing a cutting process in an industrial context where different machines tools with various characteristics are used.

NOMENCLATURE

J : stiffness [daN/mm]
J_m : stiffness of the machine tool [daN/mm]
J_{ch} : stiffness of the trolley [daN/mm]
J_{wh} : stiffness of the research head [daN/mm]
J_t : stiffness of the tailstock [daN/mm]
f_y : normal component of the cutting effort [daN]
R_A : reaction of the research head [daN]
R_B : reaction of the tailstock [daN]
y : deflection of the system elements produced by the force fy [mm]
y_m : total deflection of the machine [mm]
x : distance between the tool nose and the research head [mm]
l : length of the workpiece [mm]
T : tool life time [min]
t : cutting time[min]*VBmax :* maximum flank wear [mm]
[Vbmax] : admissible flank wear [mm]
KT : crater wear [mm]
[KT] : admissible crater wear [mm]
V : cutting speed [m min^{-1}]
f : feed rate [mm rev^{-1}]
d : width of cut [mm]
γ : rake angle [°]
λ : inclination angle [°]
α : clearance angle [°]
ℜr : principal direction angle [°]
ℜr1 : auxiliary direction angle [°]

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