AN ANALYTICAL MODEL FOR TOOL WEAR USING THE SLIP-LINE FIELD APPROACH

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Abstract. *The construction of an analytical model for wearing of tools under conditions of orthogonal cut is basic for the agreement of the complex mechanisms that involve workpiece, tool and chip during the machining processes. The attainment of an analytical model that can represent the evolution of the flank wearing in the tool to the long one of the time extremely is complicated by the extreme number of involved variable in the process. The objective of this work is through the use of first model of slip-lines, of the basic law of the adhesion and the geometry of the worn tool, to propose an analytical model for evolution of the wearing flank (hf) to the long one of the time, in hard metal tools with positive rake angle. The calculation of the total forces of thrust and cutting depends on an incremental parcel that varies directly with the evolution of the flank wear. For analysis effect, only the second stage of flank wearing was considered, which presents soft and linear growth with the time, beyond do fact being the biggest region of work of the tool during the several machining processes. For validation of the model, some published experimental data had been used, which had presented good convergence with the model proposed under several times and cutting speeds. The percentile variations between the analytical and experimental flank wearing had not exceeded the 2.5% in all analyzed situations.*

Keywords: *Machining, wear, slip-lines.*

1. INTRODUCTION

The cutting tools have limited useful life due to the inevitable process of wearing and consequently they fail. Many efforts have been made with the intention of modeling theoretically the progression of the wearing and the thrust and cutting forces operating in several processes of machining, of form that the biggest number of combinations tool-workpiece is contemplated in the lesser possible number of expressions. However, the complex mechanisms related with the attrition between the tool and the chip, ally to the high number of variable that can influence in the process, make it difficult this type of analysis excessively.

Ral and Lal (1977) had considered an experimental model to analyze the life of a hard metal tool for machining under high speed established in Taylor's equation, where the product of the cutting speed for the time of cutting high a constant n is equal to one another constant C ($V_c.T^n = C$). A series of wearing curves was gotten, however, the model was created only for a specific situation e, therefore necessary to the exhausting accomplishment of experiments for attainment of a more accuracy equationing.

An analytical modeling, that possess the lesser possible number of experimentally getting constants, can serve to predict the evolution of the wearing in a bigger number of combinations tool-workpiece, under diverse conditions and speeds of cut. In this work, one searches to find an analytical expression for the evolution of the flank wearing with the time. Choudhury and Rao (1999) through a mechanistic analysis had found some expressions for cut forces, thrust forces and wear of flank. However, these relations well specific for one are given to combination tool-workpiece.

An adaptation of the first model of Lee and Shaffer (1951) for machining under conditions of orthogonal cut was made, which, through the theory of slip-lines, had gotten analytical relations for the cutting and thrust forces operating in a generic process of machining, however, without considering the occurrence of wearing in the tool.

With this, forces of cut and thrust are defined that appear in the tool as the flank wear progresses. These two forces you add beyond those predicts ones initially for Lee and Shaffer (1951), is called in this study of cut forces and thrust due to the flank wear, respectively Fc* and Fa*. Its equationing was based on the geometry of the tool and the assumption that the adhesive mechanism of wearing is the predominant one in the flank of the tool. These forces add the forces of initial cut and advance with the absence of wearing, Fco and Fao, respectively, and supply to the total value of the cutting forces and thrust, Fct and Fat, respectively, operating in the tool to the long one of the time.

After that, the validation of the model considered with data published for Ral and Lal (1977). The cutting speeds had varied of 5.57 the 7.93 m/s during steel carbon turning, under conditions of orthogonal cut. For analysis effect, the attrition coefficient μ_1 in the surface of exit of the tool was considered constant, however as comments made for Grzesik (1999), have a reduction in the coefficient of attrition to the measure that if increases the used speed of cut.

Then, based in these comments, the coefficient of operating attrition μ_2 in the flank of the tool was considered changeable and determined through experimental curves for evolution of the wearing with the time (Ral and Lal, 1977).

2. SLIP-LINE MODEL FOR ORTHOGONAL CUTTING WITH WEARING

The first model of slip-lines of Lee and Shaffer (1951), incorporating the wearing of flank in the orthogonal cutting, is shown in Fig. 1. The following assumptions will be assumed:

a) Deformation takes place under plane strain condition;
b) Deformation occurs in a thin zone (shear plane);
c) The workpiece material is rigid, perfectly plastic and its behaviour is independent of temperature and strain rate;
d) Continuous chip is formed;
e) Tool tip is sharp (zero nose radius), independently of the increasing of flank wear hf;
f) Stresses are uniform on the rake face (constant coefficient of attrition), however, in the face of propagation of the flank wear, the attrition coefficient is changeable with the cut speed;
g) Inertia effects are negligible.

The plane of shear AB (Fig. 1) makes an angle Φ with the direction of the cut speed. The initial forces of cut are transmitted through the triangular zone ABC where no deformation occurs, but the material perfectly meets in a plastic state with maximum tension of shear k in all its extension. In accordance with the description carried through for Choudhury and Rao (1999), to the measure that the wearing of flank hf grows, appears two secondary forces, a parallel and another normal one to the worn surface. With this, the following expressions are had during the evolution of the wearing:

$$Fct = Fco + Fc^* \quad (1)$$

$$Fat = Fao + Fa^* \quad (2)$$

Where, Fct e Fat are the cutting and thrust forces totals, respectively,
Fco e Fao are the cutting and thrust forces begins, respectively and
Fc* e Fa* are the cutting and thrust forces due the flank wear, respectively.

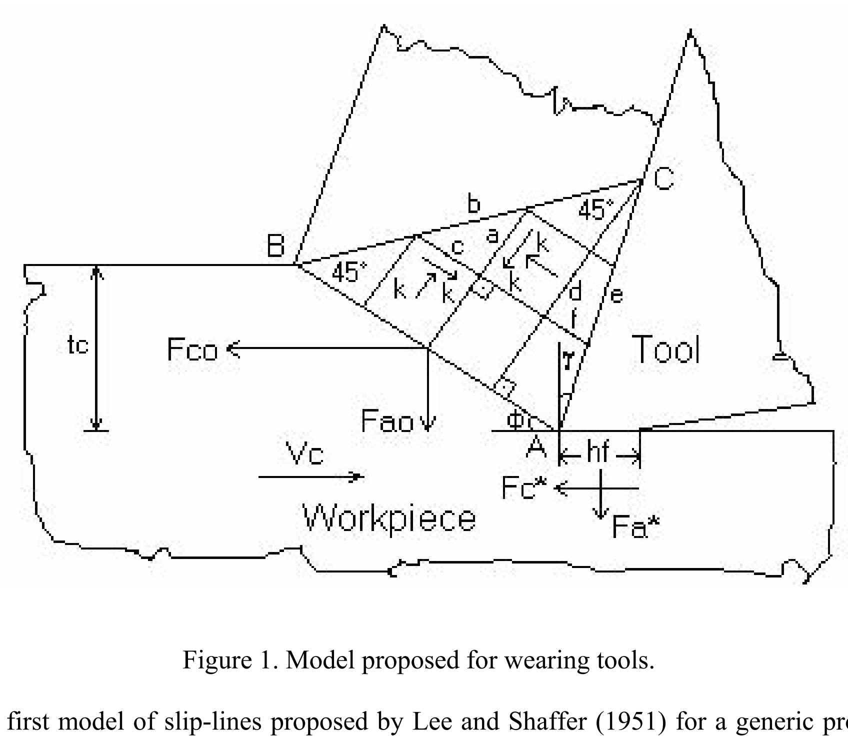

Figure 1. Model proposed for wearing tools.

According to the first model of slip-lines proposed by Lee and Shaffer (1951) for a generic process of machining, without wearing, under conditions of orthogonal cut:

$$Fco = kwt_c\left(cot\,\phi + 1\right) \quad (3)$$

$$Fao = kwt_c\left(cot\,\phi - 1\right) \qquad (4)$$

Where:

tc = undeformed chip thickness,
w = width of tool,
k = yield shear stress of the workpiece, and
Φ = shear plane angle.

2.1. Cutting and thrust forces due the flank wear

With elapsing of the time, forces due to the wearing in the cut and thrust directions, Fc* and Fa* respectively appear in the cutting process. Figure 2 illustrates the process.

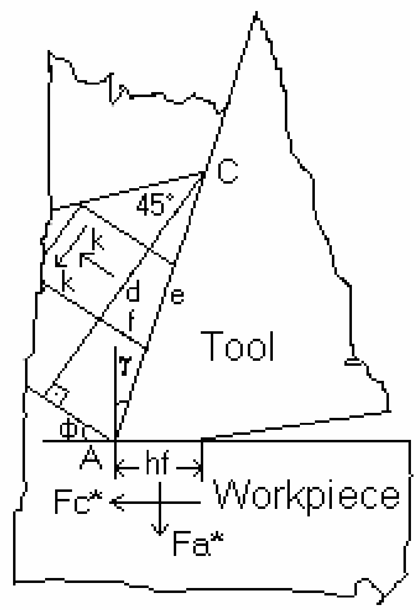

Figure 2. Cutting and thrust forces due the flank wear.

With this , for F_c*:

$$F_c{}^* = A_r.\tau \qquad (5)$$

Where A_r is the area worn in flank and τ it is the shear stress which the material is submitted

$$A_r = hf.w \qquad (6)$$

Where w is the width of the tool and hf is the width of the wear.

Considering:

$$\tau = m.k \qquad (7)$$

where $0 < m \leq 1$ and k is a constant value and equal the yield shear stress.

Substitution of the Eq. (6) e (7) in Eq. (5) gives:

$$F_c{}^* = m.hf.w.k \qquad (8)$$

To F_a* it had:

$$F_a{}^* = A_r.\sigma \qquad (9)$$

Here, σ is the normal stress to which the material is submitted.

Considering:

$$F= \mu_2 . N \quad (10)$$

Dividing the Eq. (10) by A_r , results:

$$\tau = \mu_2 . \sigma \quad (11)$$

With this:

$$\sigma = \frac{\tau}{\mu_2} \quad (12)$$

Where, μ_2 is the coefficient of attrition changeable operating in the flank of the tool.

Combining the Eq. (6), (7) and (12) and substituting in Eq. (9) gives:

$$F_a * = m_1 .hf .w.k \quad (13)$$

Where:

$$m_1 = \frac{m}{\mu_2} \quad (14)$$

2.2. Adhesive model to tools wear

The adhesion was proposal as the mechanism of predominant wearing in the model. The mark of flank wear increases with elapsing of the time, making with that the forces of cut and thrust due to the wearing, Fc* and Fa* respectively, grow continuously also. For analysis effect, and considering the fact of this being normally the biggest region of work for the cut tools, ho is foreseen a wearing initial, and the work is based on the study of second stage of flank wearing, which possess soft and approximately linear growth (Altintas, 2000).

In accordance with the basic law of the adhesion proposal for Burwell and Strang (1952), the volume worn for adhesion in a flank for unit of cut length is proportional the Fa*, or either:

$$\frac{dV_A}{dl} \alpha Fa * \quad (15)$$

Then:

$$\frac{dV_A}{dl} = CFa * \quad (16)$$

With:

$$C = \frac{Z_{average}}{HB} = cons\tan t \quad \text{(Choudhury and Rao, 1999)} \quad (17)$$

where dV_A is the volume consumed for adhesion, $Z_{average}$ is the average coefficient of wearing for one determined combination tool-workpiece, V_c is the cutting speed and HB is the number of Brinnel hardness of the material of the workpiece.

Since:

$$dl = Vc.\ dt \quad (18)$$

The following expression is obtained:

$$\frac{dV_A}{dt} = C.Fa * .Vc \tag{19}$$

Figure 3 shows the volume consumed for adhesion in the flank of the tool, dV_A, in some instant, during a time interval Δt.

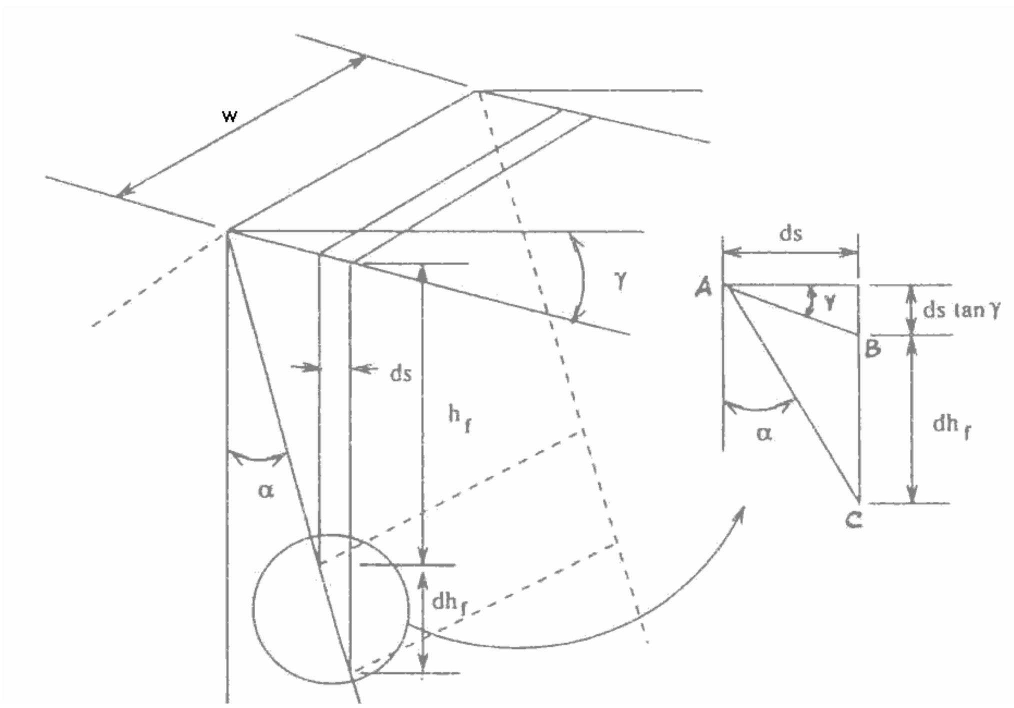

Figure 3. Geometry of the worn tool.

$$dV_A = w.\left[hf.ds + \frac{1}{2}.ds.\left(dhf + ds.tan\,\gamma\right) - \frac{1}{2}.ds.(\,ds.tan\,\gamma\,)\right] \tag{20}$$

Where γ = rake angle.

Canceling the terms ds^2 results:

$$dV_A = w.ds.\left(hf + \frac{dhf}{2}\right) \tag{21}$$

Considering the ΔABC and being α the clearance angle, an expression for *ds* is obtained:

$$ds = \frac{dhf.\,tan\,\alpha}{1 - tan\,\alpha.\,tan\,\gamma} \tag{22}$$

Therefore, combining the Eq. (21) and (22):

$$dV_A = w.\left(\frac{dhf.\,tan\,\alpha}{1 - tan\,\alpha.\,tan\,\gamma}\right).\left(hf + \frac{dhf}{2}\right) \tag{23}$$

Disdaining the term dhf^2,

$$dV_A = w.hf.\left(\frac{dhf.\,tan\,\alpha}{1 - tan\,\alpha.\,tan\,\gamma}\right) \tag{24}$$

$$dV_A = w.hf.\psi_o.dhf \tag{25}$$

Where:

$$\psi_0 = \frac{tan\,\alpha}{1 - tan\,\alpha . tan\,\gamma} \tag{26}$$

$$K_2 = \omega . \psi_0 \tag{27}$$

With this, K_2 is constant for one given tool geometry.

Considering the Eq. (25) with relation to the variation in the time:

$$\frac{dV_A}{dt} = K_2 . hf . \frac{dhf}{dt} \tag{28}$$

Equaling the Eq. (19) with the Eq. (28):

$$C.F_a * .V_c = K_2 . hf . \frac{dhf}{dt} \tag{29}$$

Substituting the Eq. (13) in the Eq. (29):

$$C.m_1 . hf . w.k.V_c = K_2 . hf . \frac{dhf}{dt} \tag{30}$$

Manipulating the Eq. (30), results:

$$C.m_1 . w.k.V_c \int_{t_0}^{t} dt = K_2 . \int_{ho}^{hf} dhf \tag{31}$$

Integrating:

$$C.m_1 . w.k.V_c .(t - t_0) = K_2 .(hf - ho) \tag{32}$$

With this,

$$hf = ho + K_3 . V_c .(t - t_0) \tag{33}$$

Where,

$$K_3 = \frac{C.m_1 . k}{\psi_0} \tag{34}$$

ho is a constant value of initial wearing reached in the time t_0 and t is the time in seconds.

In the remain of this work the time t_0 will be adopted equal the zero ($t_0 = 0$).

3. VALIDATION OF THE PROPOSED MODEL

The proposed model was validated with the experimental results published by Rao and Lal (1977), which they had supplied given that they make possible the verification of the consistency of the achieved equations. For machining in high speed, varying of 5.57 m/s up to 7.93 m/s.

All the values had been gotten for an operation of turning the dry one under conditions of ortogonal cutting, and the main used parameters are described in Tab. 1.

Table 1. Used conditions of cutting for validation of the model (Rao and Lal, 1977).

Cutting conditions	
Machine	HMT LB-25 Precision Lathe.
Tool	Sandvik Corporation throw away tool tip P 30 ISO
	Rake angle $\gamma = 6°$.
	Clearance angle $\alpha = 11°$.
Workpiece	Mild steel with Brinnel hardness 201±2.
	Diameter: 0.145 – 0.275 m. Thickness: 0.005 m.
	Cutting speeds: 5.57 – 7.93 m/s
	Infeed: $0.03.10^{-3}$ m/rev.
	$Z_{average} = 1.05.10^{-6}$ (1)
	k = 100MPa (2)
	m = 1 (2)

(1) : Yang, 1999

(2) : Adjustment of experimental data

Using the data of Tab. 1 it can be calculated:

$$\psi_o = \frac{\tan\alpha}{1 - \tan\alpha.\tan\gamma} = 0.198$$

$$C = \frac{Z_{average}}{HB} = 5.22.10^{-16}$$

3.1. Determination of the attrition coefficient μ_2

For determination of the attrition coefficient μ_2, had been chosen inside of each tested situation, an interval of time and its corresponding wearing of gotten experimental flank of Fig. 4. Table 2 shows the used parameters.

Table 2. Determination of the attrition coefficient μ_2 .

Tested situations	Vc (m/s)	h_0 (m)	Time (s)	h_f experimental (m)	μ_2
Situation "A"	5.57	$4.0.10^{-4}$	250	$5.70.10^{-4}$	2.2
Situation "B"	7.02	$4.0.10^{-4}$	100	$5.25.10^{-4}$	1.5
Situation "C"	7.93	$3.5.10^{-4}$	65	$5.00.10^{-4}$	0.9

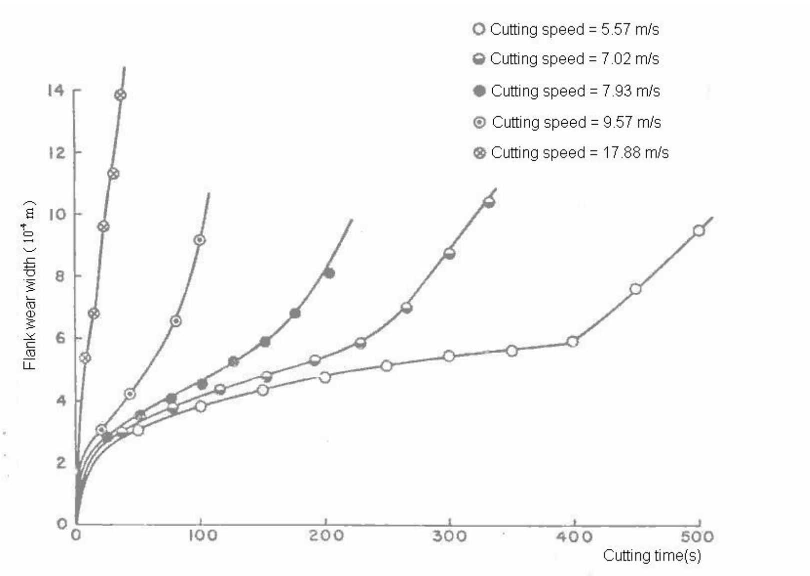

Figure 4. Experimental curves for evolution of the flank wear under several cutting speeds (Rao and Lal, 1977).

For validation of the proposed model the flank wear had been compared, hf, gotten experimentally for Rao and Lal (1977) in Fig. 4, with the situations shown in Tab. 3. A term of initial wearing was considered, ho, with intention to analyze only the linear stretch for progression of the marks of flank wear.

Table 3. Situations used for validation of the model.

Analytical model					
Situation	**V_c (m/s)**	**ho x 10^{-4} (m)**	**t (s)**	**μ_2**	**K_3**
A	5,57	4	100	2,2	$1.199.10^{-7}$
	5,57	4	200	2,2	$1.199.10^{-7}$
	5,57	4	300	2,2	$1.199.10^{-7}$
B	7,02	4	40	1,5	$1.759.10^{-7}$
	7,02	4	80	1,5	$1.759.10^{-7}$
	7,02	4	120	1,5	$1.759.10^{-7}$
C	7,93	3,5	30	0,9	$2.931.10^{-7}$
	7,93	3,5	50	0,9	$2.931.10^{-7}$
	7,93	3,5	75	0,9	$2.931.10^{-7}$

3.2. Calculation of the evolution of the flank wearing

3.2.1. Situation "A"

Substitution of the values for situation "A", gives:

$$hf = 4.10^{-4} + 6.68.10^{-7}.\ t \qquad (35)$$

Table 4 shows the joined percentile error in each time analyzed for situation "A".

Table 4. Found percentile error (situation "A").

Time (s)	hf x 10^{-4} (m)	$hf_{exp.}$ x 10^{-4} (m)	E(%)
100	4.67	4.75	1.7
200	5.34	5.40	1.1
300	6.00	6.00	0

Figure 5 shows the evolution of the analytical and experimental flank wearing, hf and hf_e, respectively, for situation "A".

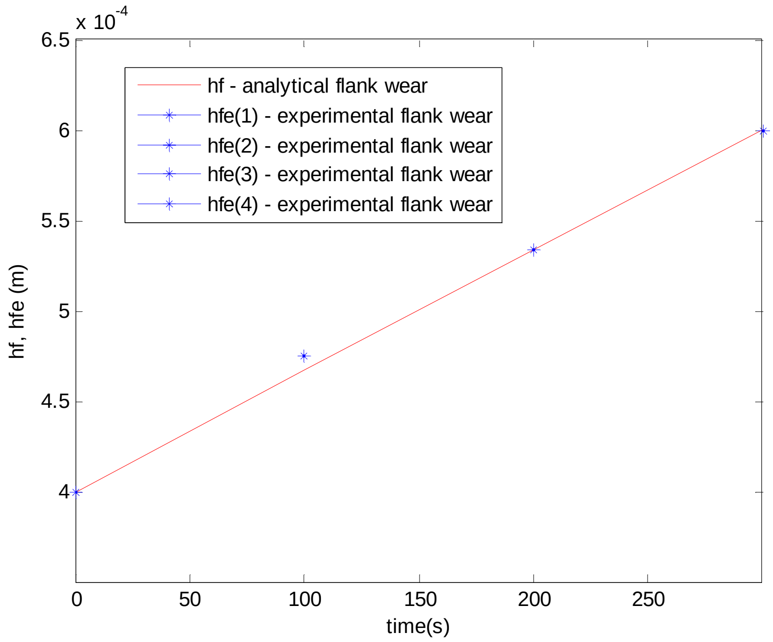

Figure 5. Evolution of the analytical and experimental flank wearing (situation "A").

3.2.2. Situation “B”

Substitution of the values for situation “B”, results:

$$hf = 4.10^{-4} + 1.23.10^{-6}.\ t \qquad (36)$$

Table 5 shows the joined percentile error in each time analyzed for situation "B".

Table 5. Found percentile error (situation “B”).

Time (s)	hf x 10^{-4} (m)	$hf_{exp.}$ x 10^{-4} (m)	E(%)
40	4.49	4.40	2.0
80	4.99	4.90	1.8
120	5.48	5.40	1.5

Figure 6 shows the evolution of the analytical and experimental flank wearing, hf and hf_e, respectively, for situation "B".

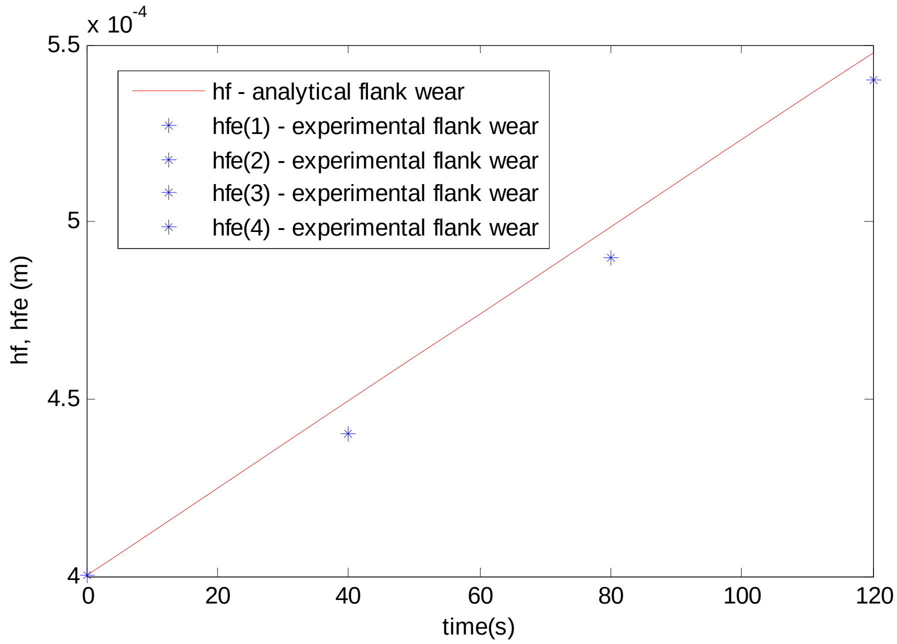

Figure 6. Evolution of the analytical and experimental flank wearing (situation “B”).

3.2.3. Situation “C”

Substitution of the values for situation “C”:

$$hf = 3.50.10^{-4} + 2.32.10^{-6}.\ t \qquad (37)$$

Table 6 shows the joined percentile error in each time analyzed for situation "C".

Table 6. Found percentile error (situation “C”).

Time (s)	hf x 10^{-4} (m)	$hf_{exp.}$ x 10^{-4} (m)	E(%)
30	4.20	4.10	2.4
50	4.66	4.60	1.3
75	5.24	5.30	1.1

Figure 7 shows the evolution of the analytical and experimental flank wearing, hf and hf_e, respectively, for situation "C".

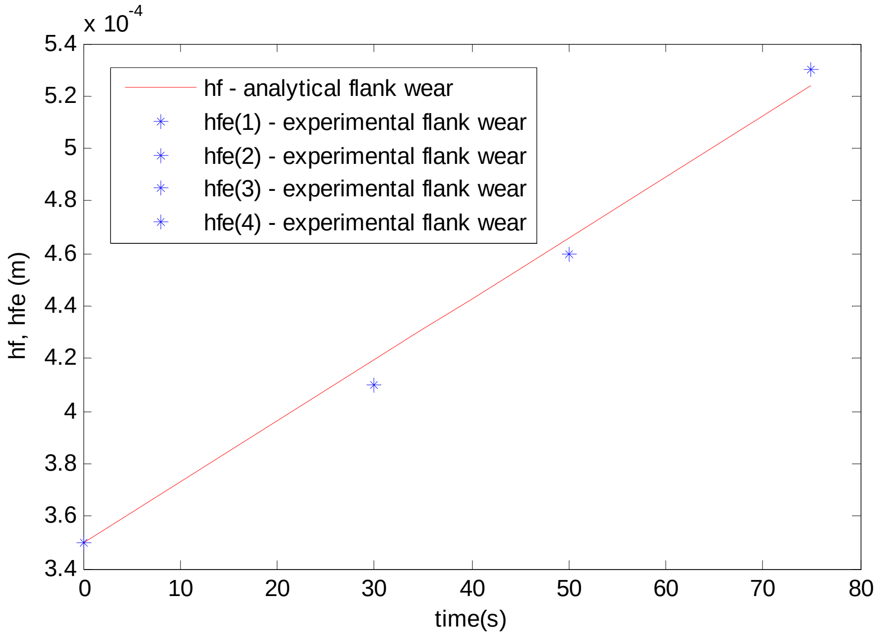

Figure 7. Evolution of the analytical and experimental flank wearing (situation “C”).

4. CONCLUSION

It was evidenced that the attrition coefficient μ_2, in the tool face where the flank wear progresses, diminishes as the cutting speed increases, as the comments carried through for Grzesik (1999). Already the rake face, the attrition coefficient μ_1 was considered constant to make possible comparisons with published experimental data.

For validation of the considered model the data published for Rao and Lal had been used (1977), where the speeds of 5.57m/s, 7.02m/s and 7.93m/s. had been used As foreseen, to the measure that the cut speed increased, the diminishes coefficient of attrition μ_2, to know, 2.2, 1.5 and 0.9 respectively for each presented speed.

An analysis of the error found between the experimental data published and the model proposed for each time and cutting speed tested was also made. The found maximum error was of 2.4% for cutting speed of 7.93 m/s.

After the analysis of the results, is verified that despite the complex mechanisms and the high number of variable that involve the attrition tool-workpiece during the machining processes, the proposed model presented good convergence with the experimental results.

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