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AN EMPIRICAL ESTIMATION OF CUTTING FORCE FOR FACE MILLING USING A STATIONARY DYNAMOMETER

BY

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Abstract. Being known the lack of information about constants that appear in the Kienzle relationship, this work proposes a solution to reduce the effort required to customize their values.

Applied to face milling, the proposed procedure makes it possible to identify the coefficients in the case of turning, using experiments under certain conditions of similarity, which are then used to calculate the principal cutting force in the case of milling.

The proposed procedure uses a stationary dynamometer both to measure the cutting force in the case of turning and to calculate the tangential force in the case of face milling.

The experiments carried out have tried to simulate a real processing case for industry, the worpiece material being used as supplied by the supplier.

Keywords: specific cutting force; single cutting milling face; stationary dynamometer; cutting force coefficients; dry machining.

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1. Introduction

It is difficult to predict cutting forces in discontinuous processes due to the large number of interacting processing parameters. There are analytical and empirical approaches to predicting these forces.

Analytical methods are based on phenomena that appear on the tool's contact surface when it comes into contact with chips that move during cutting.

For the calculation of the cutting forces these methods use a given experimental series for certain parameters.

Empirical methods are an alternative to calculating the cutting forces employed by industry. The empirical approach is based on the use of constants and curve fitting, generally linear interpolations. These methods use coefficients and constants which are determined by experiments.

Empirical methods are based on the notion of cutting resistance or specific cutting force k_c introduced by Kienzle and Victor.

The specific cutting force k_c is based on the relationship between the theoretical thickness of undetached h_D chip and two constants, $k_{c1.1}$ and m_c constants, according to relationship:

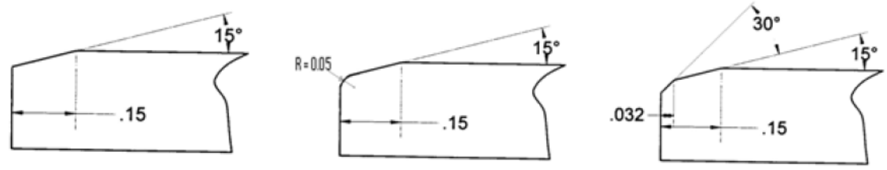
$$k_c = \frac{k_{c1.1}}{h_D^{1-m_c}} \tag{1}$$

where $k_{c1.1}$ could be called the unit-specific cutting force and m_c is the exponent of the specific cutting force.

It should be noted that although heavily dependent on the mechanical characteristics of the processed material, k_c cannot be designated as a physical characteristic because it depends on the combination of phenomena that occur on both the mating and clearance faces of the tool (Stahl and de Vos, 2014). For this reason, k_c cannot be used to characterize the processing of a particular material (Toenshoff and Denkena, 2013).

Usually, the values of both the specific cutting force and the two constants are specified in the documentation provided by industrial firms. Based solely on practical experiment, the values of these constants may not be translated under different conditions.

It is of particular importance in the establishment of the $k_{c1.1}$ and m_c constants the preparation of cutting edge, especially the presence of different negative lands on the rake face and edge rounding (Fig. 1, Rech, 2005).



Chamfered edge

Chamfered + honed edge

Double-chamfered edge

Fig. 1 – Some typical edge preparation on c-BN insert.

For the empirical method of predicting forces to be useful, the two constants in the Kienzle relationship should be specified for each geometry of the cutting tool (existing or future) and for each material to be processed.

As regards the materials currently used in industry, the following can be specified:

- characteristics of workpieces often differ from their standard specifications (higher or lower values for hardness and/or breaking strength);
- the materials processed by cutting are permanently diversified, which makes it unlikely that the two constants will be determined beforehand.

All these observations lead to the conclusion that the accuracy of the empirical prediction of the chipping forces is significantly affected by the lack of such data.

The present work proposes a solution that "shortens" the laborious work to customize the values of the constants in the Kienzle relationship for each possible edge geometry and for each material processed by cutting.

The basic idea of the method is to identify the coefficients $k_{c1.1}$ and m_c in the case of turning and to use them for calculating the tangential cutting force F_c in the case of milling, using identical tools for both turning and face milling.

Experimental research has been carried out under normal working conditions for the industry, the workpiece material being used as supplied by the supplier, without any preliminary heat treatment being carried out.

2. Specific Cutting Force

The Kienzle force model for main component describes the relationship between the effective cutting area A_c (Fig. 2) and the tangential cutting force component as following:

$$k_C = \frac{F_C}{A_C} \tag{2}$$

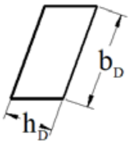


Fig. 2 – Effective cutting area A_C.

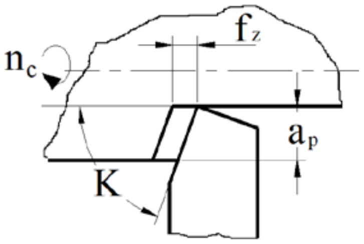


Fig. 3 – Dimensions of the chip in turning.

In turning operation, the effective cutting area is given by relationship:

$$A_C = h_D \cdot b_D = a_p \cdot f_z \tag{3}$$

where:
h_D is the thickness of the chip ($h_D = f_z \cdot \sin K$),
b_D is the width of the chip ($b_D = a_p / \sin K$),
K is the main cutting angle,
f_z is the feed per rotation (Fig. 3),
a_p is the cutting depth.

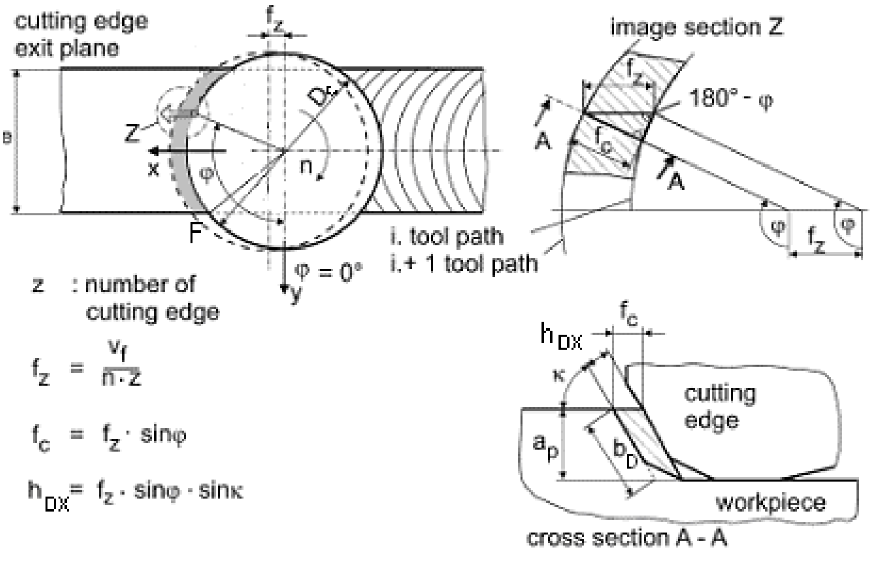


Fig. 4 – Dimensions of the chip in face milling.

During face milling process, the instantaneous thickness of the chip depends on the tooth rotation angle φ (see Fig. 4):

$$h_{Dx} = f_z \cdot \sin\varphi \cdot \sin K \tag{4}$$

where φ is the angular position of the tooth on the arc of contact of the tool with the workpiece.

In this case the instantaneous value of cutting force F_c changes for each angle value of φ according to the relationship below:

$$F_C = k_c \cdot h_{Dx} \cdot b_D = k_c \cdot f_z \cdot a_p \tag{5}$$

or combining with relationship (1):

$$F_C = k_{c1.1} \cdot b_D \cdot h_{Dx}^{1-m_c} \tag{6}$$

3. Describing Method

The aim of the method is to determine by experimental means the cutting force in the case of turning, and the subsequent use of the data for the calculation of the cutting force in face milling case.

The proposed method involves going through the next steps:

- determining the constants of Kienzle Eq. (1) in turning case;
- calculation of the cutting force F_c (main cutting force) in the case of face milling by means of the relationship (6);
- experimental checking of the force F_c calculated using the relationship (6).

In order to increase the experimental rate and to increase the precision of the experiment, the two experiments should be carried out under identical conditions, *i.e.*:

- the materials of the two workpieces must be identical;
- the geometric parameters of the two cutting tools must be identical (especially the microgeometry of the cutting edge);
- use of a single experimental data acquisition unit for both turning and milling operations.

4. Experimental Procedure and Evaluation of Cutting Forces

4.1. Process Parameters for Turning

The two workpieces were made from the same bar of cold rolled steel of Ck22 (DIN Germany) or OLC 20 (STAS 880), 1020 (AISI), 1044 (DIN).

The chemical composition of the specimen we used is the following: C=0.219%, Mn=0.698%, Si=0.155%, Cr=0.148%, Cu=0.130%, P=0.03%, and its medium hardness is 190 $HB_{2.5/62.5}$.

Fig. 5 – Cutting tool for turning.

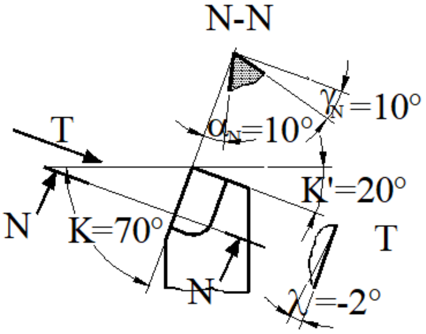


Fig. 6 – Geometry of turning tool.

The turning experiments were performed on a conventional lathe SNA 560x1500 in dry conditions.

The cutting tool selected during both machining experiments (turning and milling) was a P20 ISO carbide insert (Fig. 5) having the geometry given in Fig. 6:

- major cutting angle K=70°, minor cutting angle K'=20°;
- major clearance angle $\alpha_N = 10°$;
- major rake angle $\gamma_N = 10°$, (cutting angle $\delta_N = 80°$), inclination angle $\lambda=0°$;
- experimental checking of the force F_c calculated calculated using the Eq. (6);
- nose radius R < 0.05 mm.

Table 1 shows the cutting conditions for turning experiments.

Table 1

Cutting Conditions for Turning

Workpiece geometry	cylinder
Outer diameter [mm]	60
Length [mm]	100
Depth of cut, a_p [mm]	1
Feed per revolution [mm/rev]	0.16, 0.20, 0.25
Spindle rotation (rot/min)	400
Cutting speed [m/min]	75.4
Cutting type	dry cutting

4.2. Process Parameters for Face Milling

The milling experiments were performed on a conventional milling machine type FUS 32.

The cutting tool was a fly cutter which allows the use of the turning tool used in the turning experiment (Fig. 7).

Fig. 7 – Fly cutter utilized for face milling.

Table 2 shows the cutting conditions for milling experiments.

Table 2

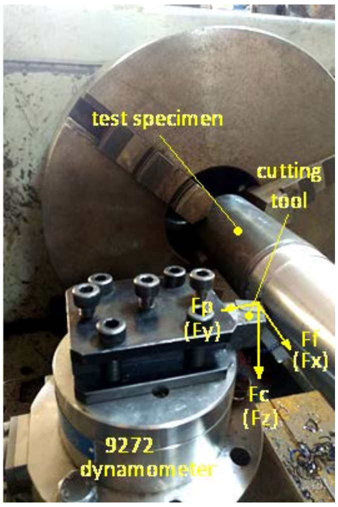
Cutting Conditions for Milling

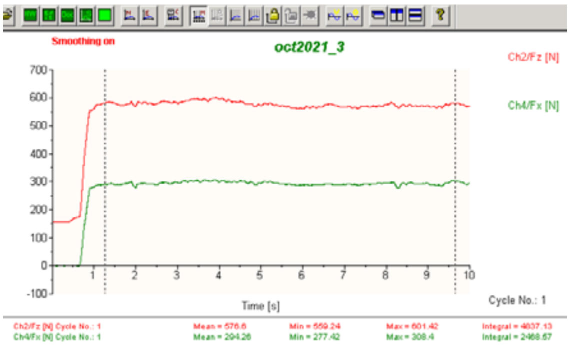
Workpiece geometry	parallelepiped
Dimensions of workpiece [mm]	100x50x25
Axial engagement a_p [mm]	1
Feed per revolution [mm/rev]	0.162
Spindle rotation (rot/min)	400
Cutting speed [m/min]	78.5
Feed rate [mm/min]	40.5
Diameter of cutter [mm]	100
Cutting type	dry cutting

4.3. Experimental Equipment

A measuring system comprised a stationary four component dynamometer (Kistler 9272), Kistler 5070 charge amplifier and a DynoWare type 2825A was utilized to measure the cutting forces in both sets of experiments (turning and milling).

For each experiment, were recorded the evolution of components F_z (F_c), F_x (F_f) and were calculated their average values (Fig. 8 and Fig. 9).





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Ch2/Fz [N] Cycle No.: 1    Mean = 576.6     Min = 559.24    Max = 601.42    Integral = 4837.13
Ch4/Fx [N] Cycle No.: 1    Mean = 294.26    Min = 277.42    Max = 308.4     Integral = 2468.67
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Fig. 8 – Experimental set-up for turning.

Fig. 9 – Registration of the cutting force components.

Since the stationary dynamometers do not allow direct measurement of the chipping force in the case of milling (Grigorievna *et al*., 2015), a previously validated methodology (Croitoru and Bocăneț, 2020) has been adopted, consisting of the following:

- the dynamometer measurement of the components F_x and F_y of the fixed Mxy system (Fig. 10);

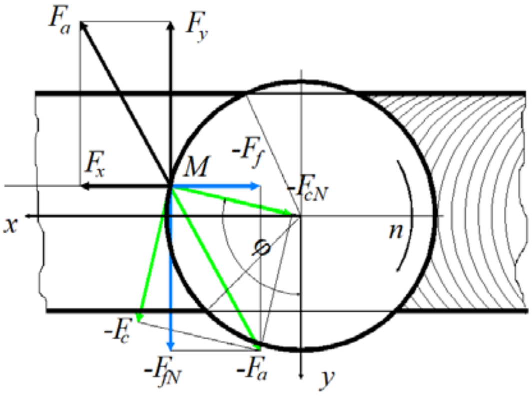

Fig. 10 – Decomposing of cutting force in face milling.

- calculation of the active force F_a;
- determination by calculation of the cutting force F_c.

The measurement of components F_x and F_y was carried out according to the set-up shown in Fig. 11, the position of the tool in relation to the workpiece being that shown in Fig. 12.

The calculation of the active component F_a and the cutting component F_c (tangential component) has been carried out in accordance with the previously submitted methodology (Croitoru and Bocăneț, 2020).

The two components F_x and F_y have been recorded (collected) at an acquisition rate of 1000 Hz. In this way it was possible to record forces for every 1.5° degrees of the cutter's movement.

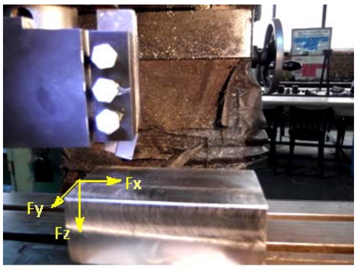

Fig. 11 – Experimental set-up for milling.

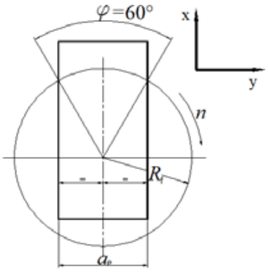

Fig. 12 – Position of the cutter against workpiece.

5. Results and Discussion

The experiments carried out in the case of turning have been carried out in random order, according to data presented in Table 3.

Table 3

The Average of Measurement Component F_c (F_z)

f_z [mm/rot]	b_D [mm]	a_p [mm]	F_c (F_z)
0.160	1.06	1	451
0.200	1.06	1	524
0.235	1.06	1	576

Applying the logarithm function to Eq. (6), the linear equation is considered:

$$\log\frac{F_c}{b_D} = \log k_{c1.1} + (1 - m_c)\cdot\log h_D \tag{7}$$

Following the methodology set out (Croitoru *et al.*, 2015), the data presented in Table 4 were calculated.

Table 4

$\log\frac{F_c}{b_D}$ *and* $\log h_D$, b_D*= 1.06 mm and* b_D*= 1mm*

f [mm]	0.16	0.20	0.235
h_D [mm]	0.15	0.187	0.18
$\log h_D$	-0.8239	-0.7281	-0.6289
F_c [N]	451.13	523.96	576.6
$\frac{F_c}{b_D^*}$	451.13	523.96	576.6
$\frac{F_c}{1}$ [N]	425.59	494.3	543.96
$\log\frac{F_c}{1}$	2.629	2.694	2.735

b_D^*=1.06 mm

Using the values in Table 4, the interpolation line of Eq. (7) is plotted as seen in Fig. 13 representing the interpolation line that particularizes the Eq. (7) as (8).

$$\log\frac{F_c}{1} = 3.08061 + 0.5428 \cdot \log h_D \tag{8}$$

From this relationship were deducted values of the two constants $k_{c1.1}$ and m_c:

- $k_{c1.1}$ = 1202 N/mm^2
- m_c = 0.4572

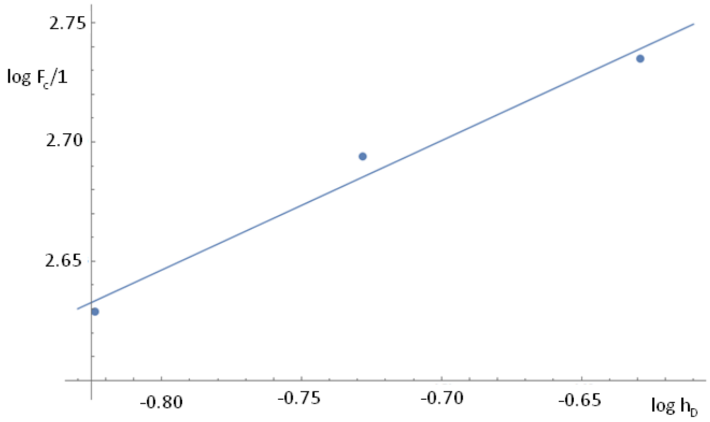

Fig. 13 – Plot of experimental data in log F_c and $\log h_D$ coordinates.

Calculation of the active force F_a has been deduced from the geometric relationship (Fig. 10):

$$F_a = \sqrt{F_x^2 + F_y^2} = \sqrt{F_f^2 + F_{fN}^2} \tag{9}$$

This equation was used to plot the graph of active force F_a shown in Fig. 14.

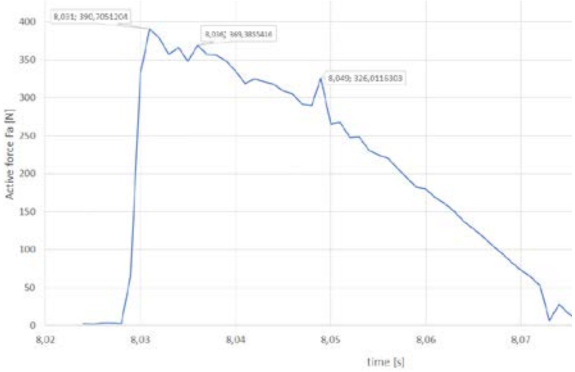

Fig. 14 – Calculated force component F_a.

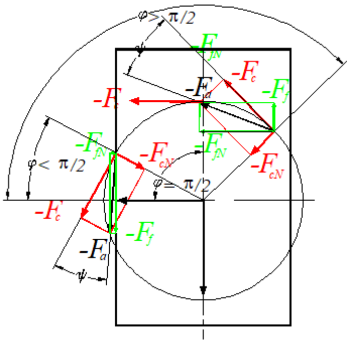

Fig. 15 – Dependence of F_c of φ angle.

For the calculation of the cutting force F_c, were used relationships depending on position of the tooth on the contact arc (see Eq. (1), (2), and (3) from Croitoru and Bocăneț, 2020):

$$F_c = F_a \cdot \cos\psi = F_a \cdot \cos\left(\varphi - \arccos\frac{F_f}{F_a}\right) \tag{10}$$

if $\varphi < \pi/2$;

$$F_c = F_a \cdot \cos\psi = F_a \cdot \cos\left(\varphi + \arccos\frac{F_f}{F_a} - \pi\right) \tag{11}$$

if $\varphi > \pi/2$;

$$F_c = F_{fN} = F_y \tag{12}$$

if $\varphi = \pi/2$,

where φ is the angle of the position of the tooth on the contact arc and ψ is the angle between F_c and F_a (Fig. 15).

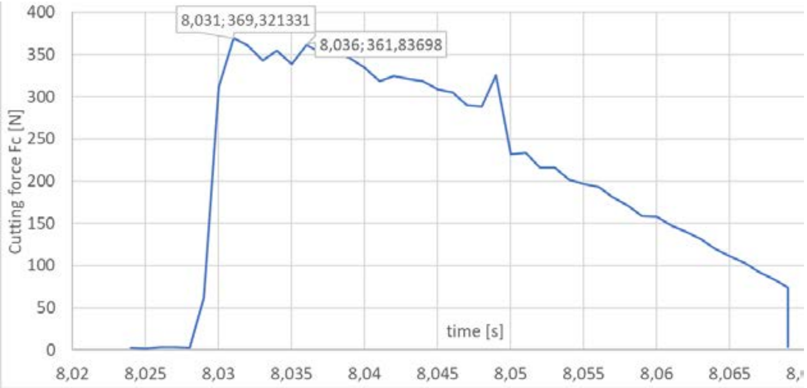

Fig. 16 – Calculated force component F_c.

Using these values, the graph of calculated cutting force F_c was plotted as seen in Fig. 16.

The following remarks can be made with regard to the magnitude of the values of forces measured or calculated in this work:

- the average measured value of the cutting force F_c (F_z) when turning is 451 N (Table 3);
- the maximum calculated value of the cutting force F_c is 369 N for face milling (Fig. 16);
- the difference between the measured value (in the case of turning) and the calculated value (in the case of milling) is 81 N, representing 18% of the measured value;

The result can be considered satisfactory given view of the following:

- both workpieces were made of the same cold rolled steel bar without heat treatment (steel without annealing);
- the lack of annealing treatment can be the cause of large differences in the hardness of the workpiece (HB_{min}=178, HB_{max}=209).

With the help of the relationship 6, the theoretical evolution of cutting force F_c for the contact arc of the tool with the workpiece in Fig. 14 was plotted. The following observations can be made by comparing the calculated force development F_c (Fig. 16) with the theoretical evolution (Fig. 17):

- the peak value of the force F_c calculated from the relationship 6 is very close to that of the mean value measured in the case of turning (difference of approximately 3%) which theoretically confirms the approach taken;
- the experimentally determined curve F_c (Fig. 16) shows an eccentricity in relation to the axis of symmetry of the workpiece, the explanation

of which may be the positioning error of the tool and/or the non-parallelism between the axis of symmetry of the workpiece and the direction of the feed movement.

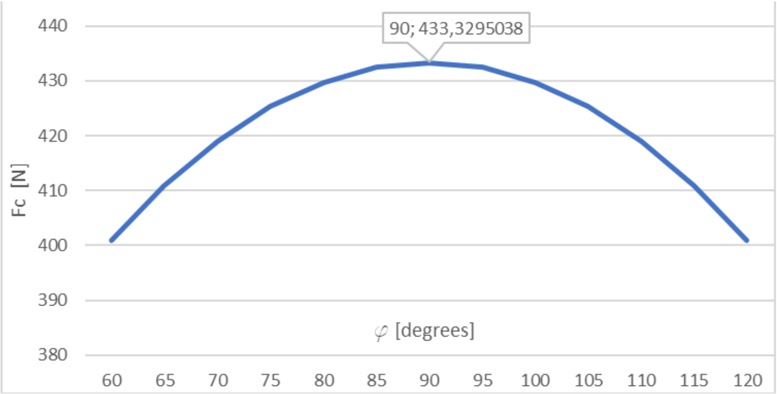

Fig. 17 – Calculated theoretical force component F_c.

6. Conclusions

The present work proposes a shorter alternative to laborious work for customizing constants from the Kienzle relationship, for if the mechanical characteristics of the semi-manufactured material or the geometric parameters of the tool are not found in literature.

The work is experimental and uses a method of identifying the $k_{c1.1}$ and m_c coefficients in the Kienzle relationship when turning and using them for the calculation of the tangential component F_c in the case of trimming, observing the condition of identity between the geometric parameters of the two tools.

The experimental tests were carried out using a stationary dynamometer, which measured cutting force F_c in the case of turning and calculated F_c in the case of face milling (since this dynamometer cannot directly measure the tangential force).

For both phases of the experimental tests, the same cutting tool was used, both workpieces coming from the same piece of steel.

An attempt was made to simulate a real processing case, in the sense that the workpiece material was used as supplied by the supplier, without any preliminary heat treatment being carried out.

As regards the size of the F_c cutting forces measured (when turning) and calculated (when trimming), the result can be said to be satisfactory, with the two values differing by less than 20%. The difference can be attributed to the differences in hardness of the workpieces (the workpieces were made of the same cold rolled steel bar).

With respect to the maximum force F_c calculated for face milling, it is very close to that measured during turning, the difference being less than 3%.

Further study directions can be mentioned:

- diversification of research through the adoption of other types of metallic and non-metallic materials for workpieces;
- use of tools with different micro-geometries (tools reinforced with mechanically clamped cutting inserts, having different lands on the rake face, different edge rounding, overcoating with different materials, etc.).

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ESTIMARE EMPIRICĂ A FORȚEI DE AȘCHIERE LA FREZAREA FRONTALĂ UTILIZÂND UN DINAMOMETRU STAȚIONAR

(Rezumat)

Numărul mare de parametri de prelucrare face ca predicția forțelor de așchiere să fie deosebit de dificilă în cazul prelucrărilor prin frezare.

În prezent pentru predicția acestor forțe există abordări analitice și empirice, fiecare din acestea având nevoie de o serie de parametri sau constante ce trebuie

determinate experimental şi a căror extrapolare în afara domeniului în care au fost realizate este inacceptabilă.

Lucrarea de faţă propune o soluţie care “scurtcircuitează” munca laborioasă pentru particularizarea constantelor din relaţia lui Kienzle (cea mai utilizată pentru metodele empirice de predicţie a forţelor) pentru fiecare geometrie a tăişului şi pentru fiecare material aşchiat.

Ideea de bază a metodei constă din identificarea coeficienţilor din relaţia Kienzle în cazul strunjirii şi utilizarea lor pentru calculul forţei de aşchiere în cazul frezării frontale.

Cercetările experimentale s-au efectuat în condiţii de lucru obişnuite pentru industrie, materialul semifabricatului fiind utilizat aşa cum a fost livrat de furnizor, fără efectuarea vreunui tratament termic preliminar, iar determinarea forţelor s-a realizat cu ajutorul unui dinamometru multi-component.