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EXPERIMENTAL RESEARCHES REGARDING CUTTING FORCES IN ASYMMETRICAL FACE MILLING

BY

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Abstract. In order to use the valuation models of face milling forces in mechanical design, it is necessary to carry out experimental tests to show their validity and applicability in real situations, but also to find out the manner they could be improved if necessary. The values of force’s components in face milling will be determined in different working conditions, both in terms of variation of milling specific elements (milling depth, number of teeth that simultaneously cut, contact angle between cutter and work piece) and cutting regime (feed per tooth).

Key words: cutting force’s components acting on a tooth; number of teeth that simultaneously cut; measured values of face milling forces.

1. Introduction

Theoretical and experimental researches in the last years suggest the development of analytical models for the evaluation of milling forces describing as realistic as possible the situations encountered in practice. Measuring forces

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in metal cutting is an essential requirement, due to their link with the cutting tool design, power consumption, vibrations that may occur and the machining accuracy. The purpose of measuring forces is to provide a better understanding of cutting mechanism, namely the influence of cutting variables upon the forces, the workpiece machinability, chip formation process, the tool wear occurrence etc. (Korkut I. et al, 2007; Kuljanic E. et al, 2005; Sekulić M. et al., 2007).

The methodology of experimental researches carried out in order to verify the proposed theoretical models of face milling forces (Bocăneţ & Cozmîncă, 2014) consists of the following steps:

- establishing the type of the material being cut by comparing the chemical composition from Romanian standard with the one experimentally verified - one work piece measuring about 152×93×49 mm was used, (according to the Inspection Certificate made by Bulgarian company "Stomana Industry S.A", the material sample is *C45*);
- performing experimental tests in order to verify the Brinell hardness of the material sample by using the universal hardness tester Wilson Wolpert, type 751 N;
- measuring the work piece dimensions and preparing it for machining;
- selecting and preparing the piezoelectric dynamometer equipment in order to carry out the measurements – a 3-components piezoelectric dynamometer Kistler, 9257BA type, was used; dynamometer can be used to measure three orthogonal components F_x, F_y and F_z in surface finishing, turning and milling. For data acquisition and assessment, the software DynoWare, from Kistler company, was used.
- performing the tests by processing the work piece in every variant of face milling and measuring the radial depth of cut and the number of teeth that simultaneously cut for each variant – one used the universal milling machine CNC *DMU 50 eco* and face milling cutter EMP02-063-A22-AP11-08 from ZCC-CT company, equipped with inserts *APMT11T3DSR-MM* type;
- collecting chips after processing in every variant of face milling in order to find out the experimental value of chips contraction coefficient C_d;
- processing the experimental results of measuring F_Z, F_X and F_Y components for all variants of face milling in order to verify the analytical models.

2. Results of Measurements Regarding the Cutting Force's Components in Asymmetrical Face Milling with Contact Angle $\Psi \leq 90°$

Positioning and fixing the workpiece on dynamometer were made according to Fig. 1 by using four screws which required the construction of four holes, with negative impact on the measurement of force's components in milling.

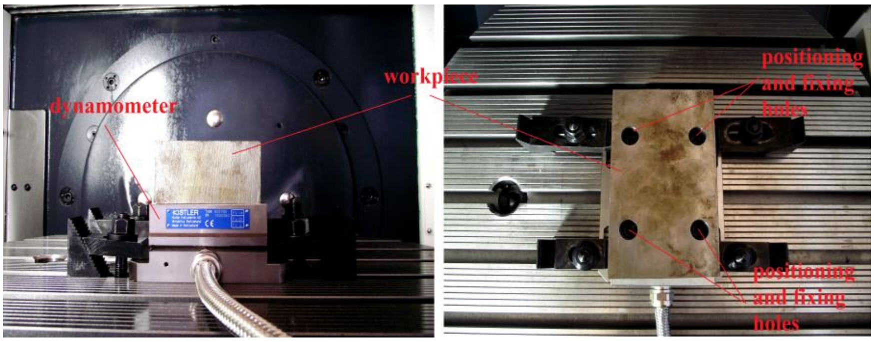
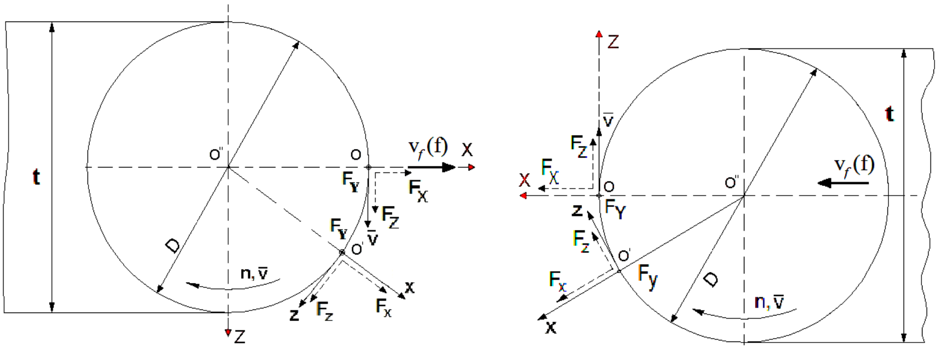


Fig. 1 − Positioning the work piece on dynamometer

Figs. 2 and 3 present the orientation of cutting force's components from the normal plane to cutter's axis, according to which the improved models for evaluating F_Z, F_X and F_Y were developed (Bocăneţ & Cozmîncă, 2014), and respectively, the orientation of dynamometer's coordinates system according to which the dynamometer is measuring the values of force's components.



a) b)

Fig. 2 − Orientation of cutting force's components from the normal plane to cutter's axis: a) conventional face milling; b) climb face milling

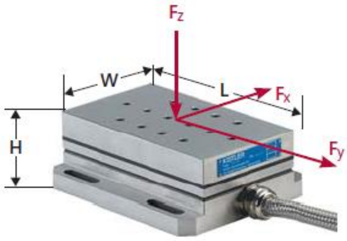


Fig. 3 − Orientation of dynamometer's coordinates system

Between the orientation and positioning of coordinates systems there are differences and therefore, in order to correctly appreciate the forces values, equalization of the two systems is necessary.

To experimentally verify the analytical models for face milling forces evaluation, for every processing, a set of data was registered, where the tangential force F_y is corresponding to component F_Z, F_x is the radial force corresponding to component F_X and F_z is the axial force corresponding to component F_Y in face milling.

Several experimental measurements were performed in order to verify the proposed valuation models of forces in asymmetrical face milling with contact angle $\Psi \leq 90°$, both in cut-up and cut-down milling, for three different values of feedrate. For both types of milling the adopted working regime is the following one: *speed* n = 505 rpm; *cutting velocity* (*peripheral velocity*) v_c = 100 m/min; *axial cutting depth* a_p = 1 mm; *feed per tooth* f_1 = 0.10 mm/tooth; f_2 = 0.14 mm/tooth; f_3 = 0.18 mm/tooth. It will differ the radial depth of cut (a_e), the number of teeth that simultaneously cut (z_s) and the contact angle (Ψ) between cutter and workpiece, so we'll have the following values: a_e = 31.5 mm, z_s = 2 – calculated (Cozmîncă *et al.,* 2010) for face milling with $\Psi = 90°$; a_e = 20 mm, z_s = 1.5 – calculated (Cozmîncă *et al.,* 2010) and $\Psi = 68.58°$ for face milling with $\Psi < 90°$. The machining was performed using coolant.

Fig. 4 illustrates some images captured during the experimental tests.

Asymmetrical cut-down milling with $\Psi < 90°$ *Asymmetrical cut-up milling with $\Psi < 90°$*

Fig. 4 − Images from the experimental tests

Depending on the relative position between cutter and workpiece and the values of feed per tooth, for asymmetrical face milling with contact angle $\Psi \leq 90°$ we performed a series of experimental tests and the results are presented as data registrations and graphics.

The details regarding the cutting conditions and variation of force's components in face milling are presented in Figs. 5 – 8.

A preliminary analysis of the resulted graphics highlights the following aspects:

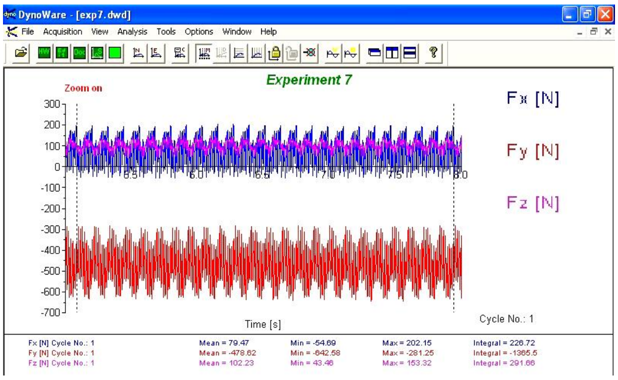
- the time for measuring the forces was 30 seconds;
- due to the presence of holes for positioning and fixing the workpiece on dynamometer, in order to measure the minimum, maximum and mean values of

forces, a period of time from 1 to 4.5 seconds was choosen, when the process is considered to be stabilized;

– registrations show the evolution of forces for every cutting in or out of the tooth;

– the shape of evolutionary forces diagrams shows the complex nature of the milling process, since many factors are involved during processing, both of technological system (vibration type and rigidity, work environment) and of milling process (shocks generated by the entry and exit of the cutting teeth, appearance and removing the material deposition on the cutting edge, changes of tool geometry due to wear, chip thickness variation, etc).

Some of the results are presented below.



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Fx [N] Cycle No.: 1     Mean = 79.47     Min = -54.69     Max = 202.15     Integral = 226.72
Fy [N] Cycle No.: 1     Mean = -478.62   Min = -642.58    Max = -281.25    Integral = -1365.5
Fz [N] Cycle No.: 1     Mean = 102.23    Min = 43.46      Max = 153.32     Integral = 291.66
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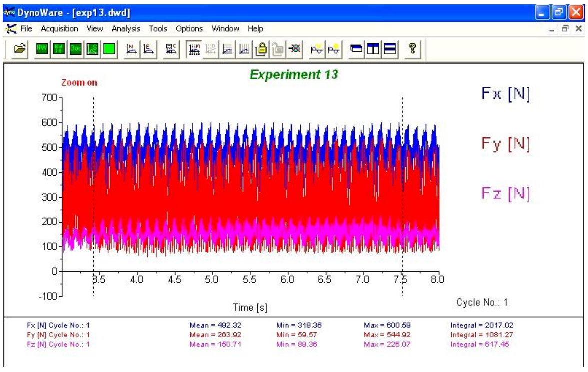
Fig. 5 − Variation of cutting forces in asymmetrical cut-down face milling with Ψ = 90°, feed per tooth $f_2 = 0.14$ mm/tooth.

Cutting conditions: $v_c = 100$ m/min; $v_{f2} = 565$ mm/min; $a_e = 31.5$ mm; $a_p = 1$ mm; work: C 45.



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Fx [N] Cycle No.: 1     Mean = 492.32    Min = 318.36     Max = 600.59     Integral = 2017.02
Fy [N] Cycle No.: 1     Mean = 263.92    Min = 59.57      Max = 544.92     Integral = 1081.27
Fz [N] Cycle No.: 1     Mean = 150.71    Min = 89.36      Max = 226.07     Integral = 617.45
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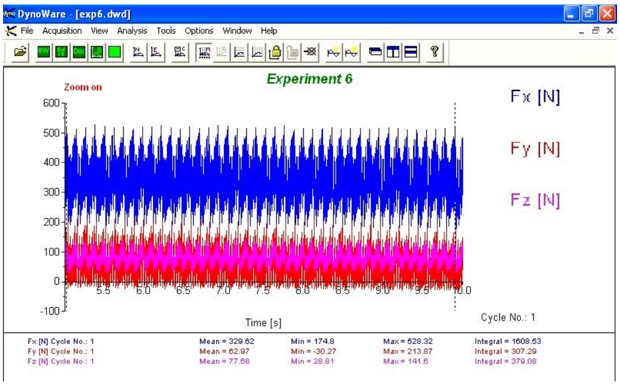
Fig. 6 − Variation of cutting forces in asymmetrical cut-up face milling with Ψ = 90°, feed per tooth $f_3 = 0.18$ mm/tooth.

Cutting conditions: $v_c = 100$ m/min; $v_{f3} = 727$ mm/min; $a_e = 31.5$ mm; $a_p = 1$ mm; work: C 45.



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Fx [N] Cycle No.: 1    Mean = 329.62    Min = 174.8     Max = 528.32    Integral = 1608.53
Fy [N] Cycle No.: 1    Mean = 62.97     Min = -30.27    Max = 213.87    Integral = 307.29
Fz [N] Cycle No.: 1    Mean = 77.68     Min = 28.81     Max = 141.6     Integral = 379.08
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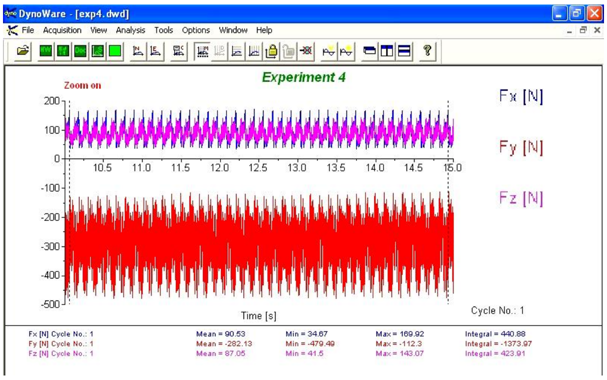
Fig. 7 – Variation of cutting forces in asymmetrical cut-up face milling with $\Psi < 90°$, feed per tooth $f_2 = 0.14$ mm/tooth.
Cutting conditions: $v_c = 100$ m/min; $v_{f2} = 565$ mm/min; $a_e = 20$ mm; $a_p = 1$ mm; work: C 45.



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Fx [N] Cycle No.: 1    Mean = 90.53     Min = 34.67     Max = 169.92    Integral = 440.88
Fy [N] Cycle No.: 1    Mean = -282.13   Min = -479.49   Max = -112.3    Integral = -1373.97
Fz [N] Cycle No.: 1    Mean = 87.05     Min = 41.5      Max = 143.07    Integral = 423.91
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Fig. 8 – Variation of cutting forces in asymmetrical cut-down face milling with $\Psi < 90°$, feed per tooth $f_1 = 0.10$ mm/tooth.
Cutting conditions: $v_c = 100$ m/min; $v_{f1} = 404$ mm/min; $a_e = 20$ mm; $a_p = 1$ mm; work: C 45.

3. Considerations Regarding the Comparative Analysis of New Valuation Models of Face Milling Forces and the Measurement Results

Studying data and records of experimental measurements, further we conducted some comparison charts between the values obtained using the analytical models for evaluation of forces in face milling (Matei (Bocăneţ), 2012; Bocăneţ & Cozmîncă, 2014) and those obtained by measuring, for each variant of milling that was subject of experimental verifications (Figs. 9 – 11).

When determining the theoretical values of face milling forces in these two cases, we considered the cutting forces acting on an insert, working conditions of the tests (radial cutting depth a_p, feedrate f, cutting velocity v_c), geometrical parameters of the cutter and chips contraction coefficient C_d

(Cozmîncă, 2010), both theoretically and experimentally determined. In order to calculate the average value of force's components acting on the insert, from the proposed analytical models, the following values for working regime, geometrical parameters of cutter and material characteristics, were used: $a_p = 1$ mm; $\gamma = 7°$, $\lambda = 8°$, $K = 89°$, $\sigma_0 = 78.7$ daN/mm^2 and $n = 1{,}5$ (from eq. $F_N = \sigma_0 \cdot t \cdot s \cdot C_d^n$ of deformation force) (Cozmîncă, 1995; Cozmîncă *et al.*, 2009), but in practice, as we could observe, this exponent varies with every variant of milling and every component of force.

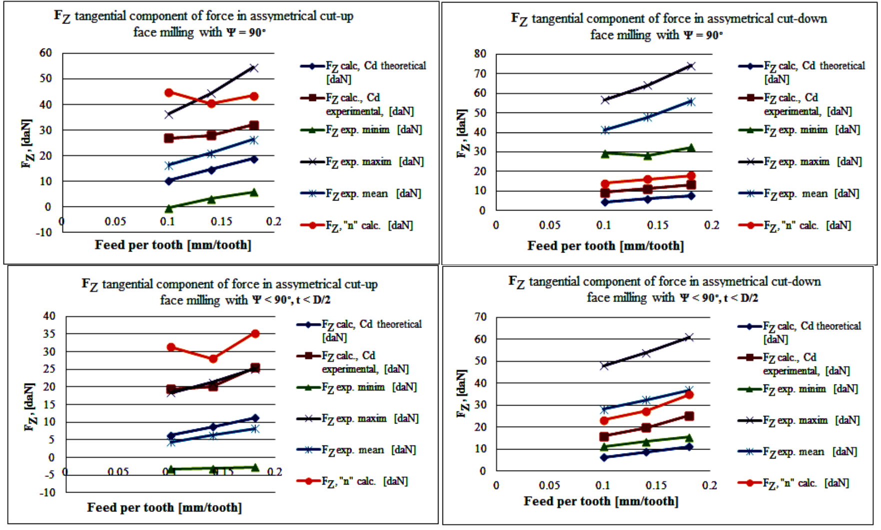

Fig. 9 − Values of tangential component F_Z of the force depending on the milling variant and feed per tooth

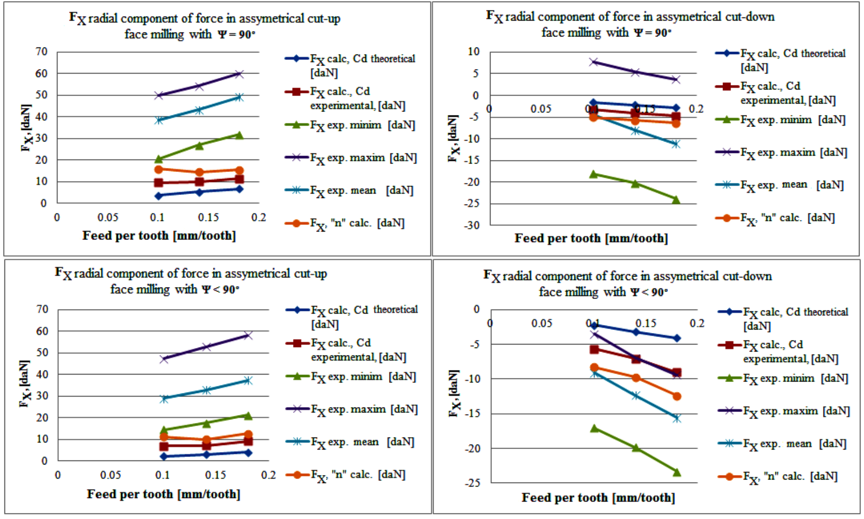

Fig. 10 − Values of radial component F_X of the force depending on the milling variant and feed per tooth

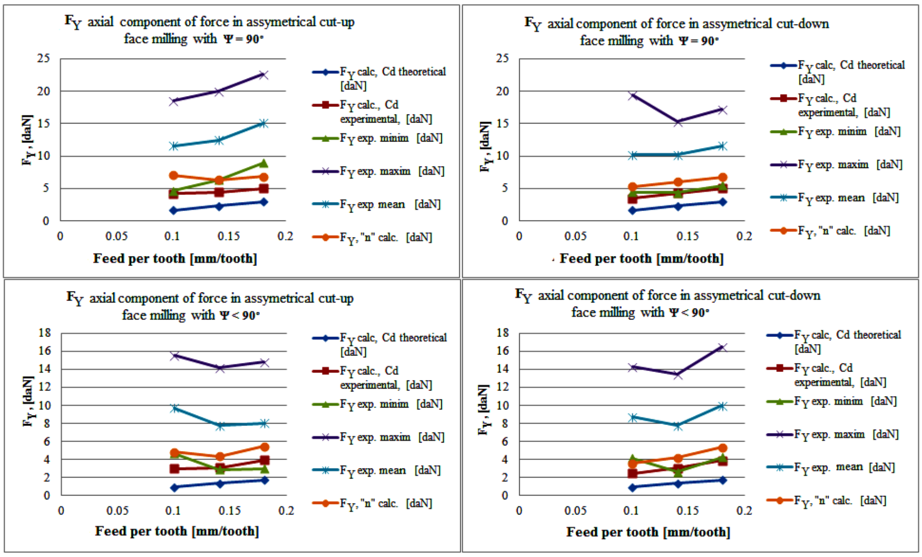

Fig. 11 − Values of axial component F_Y of the force depending on the milling variant and feed per tooth

From diagrams one can see that experimental values of component F_Z follow the same pattern, excepting few situations because of the multiples factors which may interfere. In most of the cases the values F_Z obtained by using the proposed valuating model for conventional and climb milling are close to the ones experimentally verified.

Regarding F_X component, the comparison charts show a higher variation of the calculated values compared to experimental ones, some possible causes of these differences being as follow:

- when developing the new valuation models for cutting force's components in face milling we took into account a series of simplifying assumptions and among them, that the forces acting on a tooth are equal for all z_s teeth that simultaneously cut;
- when developing the new valuation models for cutting force's components in face milling we took into account the average value of chip's thickness calculated (Cozmîncă, 1995; Cozmîncă *et al*, 2009), while in practice the chip's thickness varies along the contact angle;
- to evaluate the force's components acting on a tooth, the forces from turning were used, but the results can differ in milling.

Regarding the calculated value of F_Y component, this is smaller than the mean experimental value and very close to minimum experimental value.

Although the value of exponent „n" differs from one milling variant to another, in engineering calculations it is considered sufficient using a mean value of 1.5.

4. Conclusions

1. The comparison charts of values obtained by calculation using the proposed models and experimental values obtained for face milling force's components show that, in most cases, the theoretical values are smaller than the average experimental ones. Therefore, to assess these values, the real value of exponent "n" of chips contraction coefficient C_d should be used in the valuation models of forces acting on a tooth (Matei (Bocăneţ), 2012).

2. In order to do this correction it is necessary to carry out a new set of experimental measurements for face milling using a cutter with a single tooth. Values thus obtained are compared with the theoretical-experimental relationships and defines the real values of the exponent "n". In most cases, the exponent "n" will probably take values much higher than 1.5 and will differ for each of the three forces components F_z, F_x and F_y acting on the tooth. With this correction of the exponent "n", it becomes possible to use in face milling the theoretical values of components F_z, F_x and F_y acting on a tooth, previously experimentally verified in turning (Cozmîncă, 1995; Cozmîncă *et al*., 2010).

3. Following the conclusions we have reached to this point, we intend to continue our researches in order to verify the analytical models proposed for the evaluation of forces when milling with more than 50% of the cutter. In this regard, in order to achieve the experimental measurements, we'll use the values for working parameters considered in the previous approach.

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CERCETĂRI EXPERIMENTALE PRIVIND COMPONENTELE FORŢEI DE AŞCHIERE LA FREZAREA FRONTALĂ ASIMETRICĂ

(Rezumat)

Pentru utilizarea în proiectare a modelelor matematice propuse pentru evaluarea componentelor forţei de aşchiere la frezarea frontală asimetrică având unghiul de contact dintre freză şi semifabricat $\Psi \leq 90^o$, este necesară realizarea unor determinări experimentale de natură să arate validitatea şi gradul de aplicabilitate al acestora, dar şi modul în care pot fi îmbunătățite.

Modelele de evaluare a componentelor forţei la frezarea frontală au la bază influenţele factorilor care apar la nivelul unui dinte, dar şi interdependeţele dintre acestea, influenţele elementelor specifice frezelor, variantele de frezare posibile (frezare simetrică plină, frezare simetrică incompletă şi frezare asimetrică), numărul de dinţi care aşchiază simultan şi poziţia relativă freză – semifabricat (frezare în sensul avansului şi frezare în contra avansului). Dacă influenţele la nivelul unui dinte au fost deja verificate experimental, elementele specifice procedeului de frezare frontală care au stat la baza studiului teoretic trebuie şi ele verificate experimental, fiecare în parte şi în măsura în care este posibil.

Mărimea componentelor forţei la frezarea frontală a fost determinată în condiţii de lucru diferite, atât în ceea ce priveşte variaţia elementelor specifice frezării (adâncime de frezare, număr de dinţi care aşchiază simultan, unghiul de contact dinte – semifabricat), cât şi regimul de aşchiere (avansul pe dinte).