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# INFLUENCE OF OBLIQUE GEOMETRY OF CUTTING INSERTS OF FINISHING FACE MILLS ON CUTTING FORCES

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***Summary.*** *The feasibility of using face milling for the final formation of the parts surface layer is confirmed by a large number of scientific works. At the same time, there are significant advantages of technological processes using face mills for oblique cutting, equipped with superhard materials, with a spiral-stepped arrangement of cutting inserts. This work is devoted to the study of the influence of the inclination angle of the oblique face mill cutting edge on the cutting forces when processing the workpiece flat surface made of gray cast iron and carbon tool steel using the Deform-3D program. The influence of the cutting edge inclination in the range from 0 to -45º on the smoothness of penetration of the face mill inserts into the workpiece is discussed.*
***Key words:*** *face milling, simulation, oblique cutting, cutting forces, finishing*

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**Statement of the problem.** The increasing requirements for the reliability of machines make it necessary to improve the technological processes of manufacturing products with the use of new finishing machining methods. Ensuring the high quality of the surfaces of machine parts by technological methods is one of the urgent tasks of modern engineering production.

One of the parameters characterizing the competitiveness of machines and mechanisms is the reliability of their operation, which is always limited by one or another detail or component unit. This is especially relevant if the unit operates under the influence of aggressive environments, without lubrication, in contact with particles of abrasive materials, etc. Therefore, it is urgent to increase the service life of machine parts by using new materials and innovative technologies. Ensuring the reliability of products for difficult operating conditions requires the improvement of technological processes that guarantee the high quality of the surfaces of parts during mechanical processing.

One of the ways to enhance the quality of forming the surface layer is to improve the existing and develop new designs of cutting tools based on the analysis of kinematics and characteristics of the machining process. Recently, face milling processes using tools equipped with superhard materials (SHM) have become widespread [1–4]. Processing with SHM cutters is characterized by high productivity, quality characteristics of the surface layer, etc. However, most designs of face mills implement a conventional cutting scheme with distribution of allowance by feed, which significantly reduces the actual number of cutters involved in cutting and worsens the dynamics of the milling process. Designs of spiral-stepped cutters for oblique cutting with vertexless cutting inserts made of SHM have significant advantages. The use of such cutters makes it possible to increase productivity and quality of machining, to foster the process of cutting the minimum thicknesses of the cut layers, which are typical for fine machining, and monotonous cutting edges with relatively large radii allow to reduce the load per unit length of the cutting edge, which increases wear resistance and machining productivity [5–7]. At the same time, the non-stationarity of the cutting process, which is characteristic of

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face milling processes, leads to variable deformations of the technological system. During machining, significant cutting forces occur, which change their magnitude and direction of action, and lead to processing errors in the transverse direction due to dynamic deformations of the technological system. In the longitudinal direction (in the feed direction), machining errors are primarily related to the variability of the milling width in the areas where the cutter cuts into the workpiece and at the exit. The variable milling width leads to fluctuations in the cutting forces at the entry/exit of the cutting inserts into/from the cutting zone, to variable deformations of the technological system and longitudinal profile errors. Therefore, the reduction of machining errors in order to increase the accuracy of the processed part and improve the physical and mechanical properties of the surface layer is of crucial importance in finishing face milling [8–10].

**Evaluation of the latest researches and publications.** A number of studies [5–10] have established the high efficiency of the application of face stepped milling cutters of oblique cutting, equipped with SHM for semi-finishing and finishing of flat surfaces of cast iron and steel hardened parts.

In works [11–13], the authors investigated a number of factors (machining conditions, nature of wear and destruction, etc.) that affect the performance of face mills equipped with SHM during finish milling of gray cast iron and hardened steels. Based on the obtained results, the authors draw conclusions about the expediency of using a certain brand of tool material: Hexanit-R (composite-10), Elbor (composite-1), Kyborit. The specified tool materials provide the ability to perform processing at high cutting speeds and maintain high cutting capacity. In [14, 15], the cutting properties of various composites and their significant differences during intermittent cutting of hardened steels are described. The authors [15] showed that composite 10 has the greatest resistance under such conditions. However, with increased allowances for milling on the cutting edges, the appearance of thermal cracks perpendicular to the main cutting edges is possible, which leads to chipping of the tool material particles and ultimate wear [ 9, 16, 17].

According to the results of research [5], the high efficiency of using tipless cutters of oblique geometry, equipped with composite 10, with negative angles of inclination of cutting edges (λ) and the use of rear cylindrical surfaces of cutting inserts with radii of 6–14 mm was confirmed. Data analysis shows that cutting speed affects all components of cutting forces Fx, Fy, Fz. At λ=0º and λ=+45º, the components of the cutting forces have higher values than at λ=-45º, that is, more intensive wear of cutter inserts can be assumed at λ=0º and λ=+45º. Therefore, the use of negative values of the angle of inclination of the cutting edge reduces the Fx, Fy, Fz components of the cutting force, which in turn allows to reduce the specific loads per unit length of the cutting edge. In [18], it was also noted that when the angle λ increases from 0º to +45º, the force Fz acting in the direction of the cutting speed vector increases by no more than 5%, and when the angle is λ >45º, the force Pz increases sharply. The obtained data indicate an increase in the stability of the tools when the angle λ increases, while it is determined that the optimal value of the inclination angle of the cutting edge lies within λ = +60º...75º (for hardened steels and hard-to-machine materials). According to [19], an increase in the angle of inclination λ from +40º to +60º leads to a decrease in stability by 1.5 times, which is explained by a decrease in the active area of the cutting edge and an increase in the load per unit of its length.

In works [20, 21], when turning samples from alloyed steels ХВГ (similar to 107WCR5, 48–50 HRC) and ШХ-15 (similar to 100Cr6, 60–62 HRC), it was established that the cutting speed exerts the greatest influence on the temperature in the contact zone υ and the angle of inclination λ of the cutting edge of the tool, and the cutting depth and feed have a smaller effect, although the temperature increases less intensively with the increase of the latter than with the increase of the cutting depth. Analysis of experimental data shows that with an increase in the inclination angle of the cutting edge λ, the cutting temperature increases. So, according to the calculation, when the angle of inclination of the cutting edge λ increases from +30 to +60° (t = 0.1 mm, v = 1.4 m/s, hz = 0.1 mm, f = 0.67 mm /rev) the average contact temperature increases from 800 to 1030 °C [20]. It has been shown that the life of oblique single–sized tools and inserts having cylindrical rake face in turning the hardened steel (60–62 HRC) with feeds up to 0.6 and 1 mm/rev is from 40 to 110 min, respectively [21].

Literary sources on the values of the components of cutting forces in oblique tipless face milling are quite scarce, and the reviewed sources, when researching cutting forces, show that it is necessary to take into account the entire set of processing conditions in each specific case. The study and solution of the considered issues, which are aimed at increasing the performance of spiral-stepped face mills equipped with SHM, for the finishing of flat surfaces is an urgent task and has a great importance for mechanical engineering.

To reduce the amount of real-time research of cutting processes, simulation of machining processes by the finite element method (FEM) in such programs as Abaqus, AdvantEdge, Ansys, Deform-3D, etc. has become widely used at present [22–26]. To simulate the face milling process, the Deform-3D program was chosen, which is characterized by relative ease of use, a convenient interface and allows obtaining a stable result.

**Research objective**. To determine the influence of the negative inclination angle of the oblique face mill cutting edge on the cutting forces when machining the workpiece flat surface of gray cast iron and carbon tool steel using the Deform-3D program.

**Objective statement.** On the basis of the designed computer model [27] in the DEFORM-3D program, which is based on the finite element method, for the conditions of face oblique milling with a single insert equipped with an superhard tool material (hexanite-P), it is necessary to investigate the influence of negative angles the inclination of the cutting edges λ on the cutting forces when the insert blade cuts into the workpiece.

Simulation conditions: oblique milling of gray cast iron СЧ21 (similar to EN-GJL-200, 170HB) and carbon steel У8 (C80W, 46 HRC); cutting speed v = 2.5 m/s; feed fz = 0.625 mm/tooth; cutting depth t = 0.12 mm; the tool is a single-tooth face mill with a diameter of 360 mm, the tool material is hexanite-R, the simulation time is 0.21 ms. Geometry of cutting plates: flat front surface, front angle γ = -10º, rear angle in the direction of the cutting speed vector $\alpha_v$ = 12º (Fig. 1–2). The angle of inclination of the main cutting edges varied from λ=0º to λ= -45º.

The 3D model of the workpiece with a preliminary cut was developed in the SolidWorks Motion module according to the method described in [22]. The calculation in Deform-3D took into account the mechanical behavior of the processed materials, which is described by the Johnson-Cook equation [28, 29].

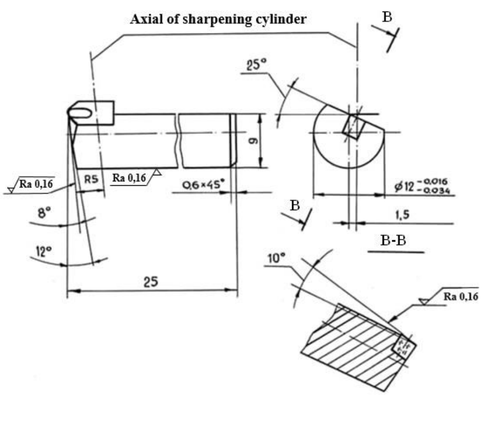


**Figure 1.** Design of the cutting insert [3]

**Figure 2.** 3D-model of the cutting insert

The obtained results of the maximum values of the cutting force components Fx, Fy, Fz during the time interval of cutting the insert into the workpiece depending on the angle of inclination of the cutting edge λ for processing gray cast iron and carbon tool steel are shown in Fig. 3 and 4.

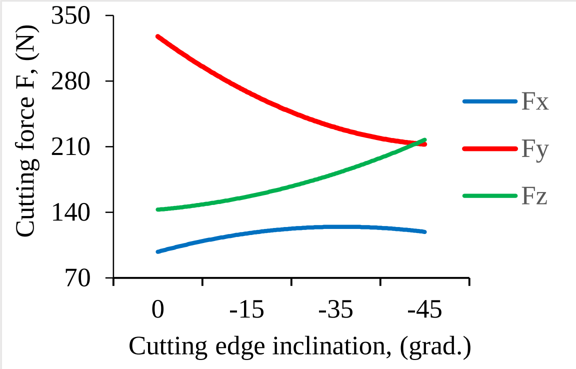


**Figure 3.** Dependence of the cutting force components Fx, Fy, Fz on the cutting edge inclination during milling of gray cast iron

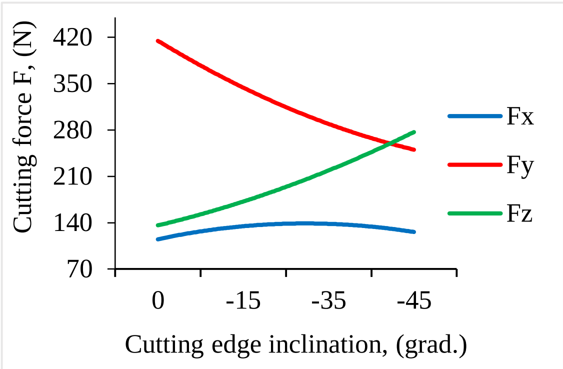


**Figure 4.** Dependence of the cutting force components Fx, Fy, Fz on the cutting edge inclination during milling of hardened carbon tool steel

The simulation results make it possible to conclude that the use of negative values of the angle of inclination of the cutting edge λ significantly reduces the component of the cutting force F, which in turn will reduce the load per unit length of the cutting edge and increase the wear resistance of the cutting plates. At the same time, the Fz component increases and the axial Fx component changes slightly. Despite the relatively small values of the axial cutting force Fx, they cause elastic movements of the cutter body. Fluctuations in cutting forces lead to constant changes in these movements, as a result of which there is an imprint of the cutting elements that form the surface of the part. This causes processing errors, while their values determine the deviation from the ideal trajectory of the cutting edge of the tool, which affects the shape of the parts and the quality characteristics of the surface layer [30–35].

Figures 5–7 demonstrate the graphs of the dependence of the cutting force components on the cutting edge inclination λ when cutting the insert of an face mill into a workpiece made of gray cast iron.

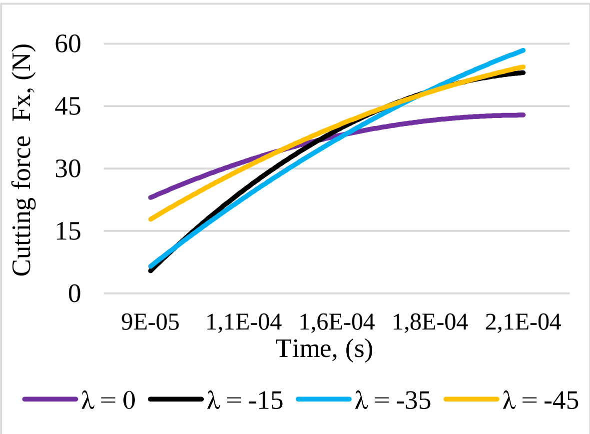


**Figure 5.** Dependence of the cutting force component Fx on the cutting edge inclination λ when cutting the insert into the workpiece made of gray cast iron

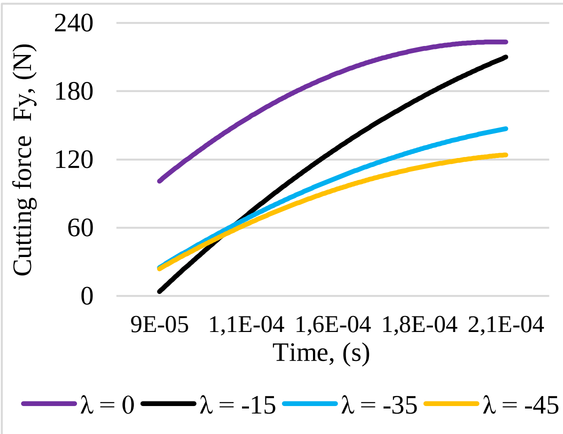


**Figure 6.** Dependence of the cutting force component Fy on the cutting edge inclination λ when cutting the insert into the workpiece made of gray cast iron

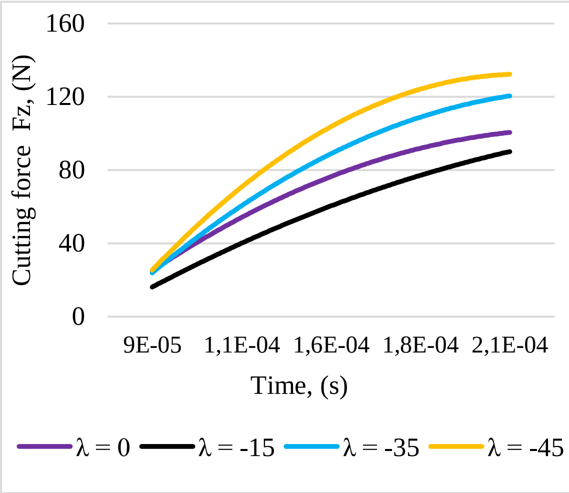


**Figure 7.** Dependence of the cutting force component Fz on the cutting edge inclination λ when cutting the insert into the workpiece made of gray cast iron

The following conclusions can be drawn from the above results of computer simulation (Figs. 5–7) of the process of penetration of the cutting edge of an oblique end mill into a workpiece made of gray cast iron. The use of negative values of the angle of inclination of the cutting edge λ during cutting significantly reduces the component of the cutting force Fy for λ=-35º and λ=-45º, which, in turn, will have a positive effect on the milling process. Simultaneously, when employing the cutting edge angle of λ=-45º, the Pz component increases significantly, compared to angles of λ=0º, λ=-15º. The obtained results on the axial component of Px indicate that when using the angles λ=-15º, λ=-35º, a smoother cutting of the cutting blade into the workpiece will be ensured in comparison with λ=0º, λ=-45º.

Figures 8–10 show the graphs of dependence of the cutting force component Fz on the cutting edge inclination λ when cutting the insert into the workpiece made of carbon steel.

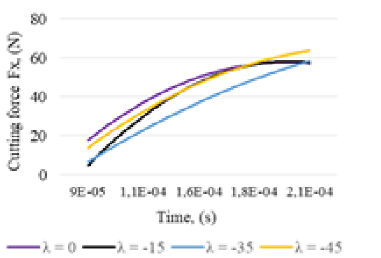


**Figure 8.** Dependence of the cutting force component Fx on the cutting edge inclination λ when cutting the insert into the workpiece made of hardened carbon tool steel

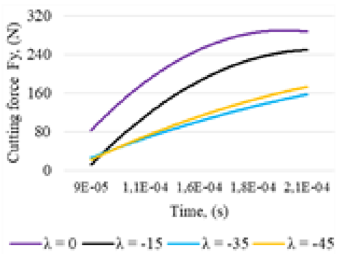


**Figure 9.** Dependence of the cutting force component Fy on the cutting edge inclination λ when cutting the insert into the workpiece made of hardened carbon tool steel

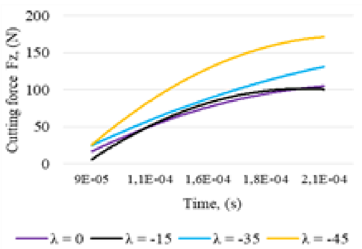


**Figure 10.** Dependence of the cutting force component Fz on the cutting edge inclination λ when cutting the insert into the workpiece made of hardened carbon tool steel

The following conclusions can be drawn from the results of the computer simulation of the process of penetration of the cutting edge of an oblique end mill into a workpiece made of carbon steel (Fig. 8–10). The use of negative values of the angle of inclination of the cutting edge λ during milling significantly reduces the component of the cutting force Fy for λ=-35º, λ=-45º. However, when using the inclination angle λ=-45º, the Fz component increases significantly. At λ=-35º, a decrease in the values of the axial component of the cutting force Fx is observed. Based on the obtained results, it can be said that the application of an inclination angle of λ=-35º will ensure the smoothest penetration of the cutting plate into the workpiece, which, in turn, will have a positive effect on the quality of the machined surface and the efficiency of the milling process as a whole.

Thus, as the obtained results show, by changing the angle of inclination of the cutting edge of the face mill insert from λ=0º to λ=-45º, it is possible to significantly influence the value and ratio of the cutting force components during the time interval of cutting the insert into the workpiece.

**Conclusions.** Using computer simulation of the process of cutting of an oblique face mill insert into a grey cast iron and carbon steel workpiece, the influence of the cutting edge inclination angle in the range λ=0º to λ=-45º on the Fx, Fy, Fz cutting forces components was determined. It was found that the use of negative values of λ significantly reduces the Fy component of the cutting force, which in turn reduces the load per unit length of the cutting edge and increases the wear resistance of the inserts. However, the Fz component increases and the Fx component of the cutting force changes slightly.

The application of the angle of inclination λ=-35º ensures the smoothest cutting of the insert into the workpiece, which increases the stability of the tool and the quality of the machined surface.

The obtained results can be applied in the design of oblique cutting tools of various types, the prediction of the technological system deformations and the quality of the flat surfaces of the parts to be machined.

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# ВПЛИВ КОСОКУТНОЇ ГЕОМЕТРІЇ РІЗАЛЬНИХ ЕЛЕМЕНТІВ ЧИСТОВИХ ТОРЦЕВИХ ФРЕЗ НА СИЛИ І ТЕМПЕРАТУРИ РІЗАННЯ

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***Резюме.*** *За даними аналізу опублікованих робіт авторів, які досліджували процес фінішної лезової обробки деталей, встановлено доцільність застосування процесів торцевого фрезерування для остаточного формування поверхневого шару деталей, що виготовляються. При цьому значні переваги мають технологічні процеси з використання торцевих фрез косокутного різання, оснащених надтвердими матеріалами, зі спірально-ступінчастим розташуванням різальних елементів. Відомо, що* *косокутна геометрія фрез забезпечує плавне врізування різальних пластин у заготовку і плавний вихід із зони різання, що сприяє зменшенню ударних навантажень на різальні елементи при вході-виході з контакту із заготовкою. За рахунок застосування косокутної геометрії різальних пластин виявляється можливим значно підвищити стійкість торцевих фрез та обробляти поверхні з високою якістю. Дана робота присвячена дослідженню впливу кута нахилу різальної кромки в діапазоні значень від λ=0º до λ=-45º на величину сил різання у процесі обробки плоскої поверхні заготовок із сірого чавуну СЧ-21 та вуглецевої сталі У8 (46 HRC) одним зубом торцевої косокутної фрези за допомогою програми скінченно-елементного аналізу Deform-3D. У результаті комп'ютерного моделювання процесу торцевого фрезерування визначено часові реалізації складових сил різання Px, Py, Pz для наступних умов обробки: подача $S_z$ = 0,625 мм/зуб; швидкість різання v = 2,5 м/с; глибина різання t = 0,12 мм. Обговорено характер залежності складових сил різання Px, Py, Pz від величини кута нахилу різальної кромки в діапазоні від'ємних значень та взаємозв'язок зі зносостійкістю різальних пластин. Отримані результати будуть застосовані для подальшої оптимізації геометричних параметрів при проектуванні торцевої косокутної фрези, прогнозуванні деформації технологічної системи з метою підвищення ефективності оброблення плоских поверхонь деталей з чавуну та вуглецевої сталі.*

***Ключові слова:*** *торцеве фрезерування, моделювання, косокутне різання, сили різання, чистова обробка*.

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