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STRUCTURAL IMPROVEMENT OF FACE MILLS DESIGNS BASED ON SYSTEMS APPROACH

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Summary. *The article is devoted to the designs improvement of face mills with round inserts on the basis of a systems approach. The increasing a cutting efficiency with face mills is provided by improving their designs in the following aspects: increasing the tool life, accuracy and productivity, improving the quality of the machined parts surface. Analysis of the operating conditions of the milling cutters is carried out element by element (body, shank, inserts and their location, etc.), these components are considered as one system. The technological system (machine, holder, workpiece, tool) is presented as a supersystem, which is under the influence of active, intermediate acting, reactive and derivative factors. The article decomposes into elements (cutting, body, base and fastening parts) of a standard face mill with round inserts and performs their system analysis relatively the occurrence of adverse cutting conditions. On the basis of this the scheme of structural improvement aspects of face mills designs is developed. As a result of structural improvement and variants synthesis, the authors propose concepts of face mills designs for different machining conditions.*

Key words*: face mill, systems approach, structural analysis, design of mills.*

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Statement of the problem. Efficiency improvement of face milling is an important task for metalworking production. It is especially significant for machining of structural materials of group H and S [1], with their cutting being accompanied by severe cutting edge wear of tool.

Face mills (FM) with round inserts are increasingly used as they are universal and employed both for heavy face milling and profile machining.

One of the main ways of increasing the cutting efficiency is improvement of face mill designs which can be achieved by the following areas: improvement of durability, accuracy and machining productivity, surface layer quality enhancement.

Evaluation of known research findings. Theory and methodology of cutting tools design, including FM, are presented by works of Granovskii G. I., Semenchenko I. I., Rodin P. R., Ravska N. S., Senkin Ye. M. and others. Contemporary theoretical works are also well-known and they describe major design methods for face mills, develop general mathematical models of their design and highlight priorities of improving face mills designs for different machining conditions [2–7].

The vast majority of research on face milling process deals with specific problems regarding the quality assurance of the surface being machined. Thus, works [8, 9] provides mathematical and simulation models for prediction of surface topography which is formed in the process of face milling. The presented articles provide possibility to determine best cutting conditions and geometrical parameters of mill's cutting edge. The work [10] presents the method of fractal analysis which was first adapted to describe the surface area of micro-relief being formed by face milling at various feed values.

Experimental study of milled surface quality dependent on specific factors is brought into a sharp focus. For instance, the influence of FM hard alloy insert wear on the surface roughness under different cutting conditions is studied in work [11]. Profound theoretical investigation on geometric accuracy of surfaces, machined by face mills, are presented in works [12–14]. Evaluation model of various types of flatness deviations during face milling with different insert wear and milling parameters is proposed in work [12]. Work [13] is devoted to the development of technique to determine elastic displacement of spindle assembly joint of vertical milling machine and face mill with the help of software product SolidWorks. It provides possibility to prognosticate flatness deviations during face milling of flat surfaces. The article [14] suggests a new approach to improve the quality of a surface being machined by means of workpiece optimization scheme. Authors obtained analytical equations for workpiece elastic deformation depending on gripping force and optimization model for workpiece deformation minimization has been developed.

Description of mill cutting edge wear mechanism during machining of various structure materials is done in works [15–18]. Failure types of face mills during machining of hardened steel were studied in [15]. Fatigue failure was stated to be the major mechanism of hard alloy plates' destruction. The article [16] is an experimental study on the influence of rounding radius of mill edge on its wear mechanism during steel milling. The work [17] determines the most typical failures for mills of special forms employed in wheel milling machines for recovering of wheelset operating profile. The work [18] describes an original approach to determine the tool wear by observing the change of spindle rpm during milling. Authors of this study determined the criteria for critical inserts' wear both in timely and frequency manner.

The works [19–25] give insights into the problems of influence of the cut layer parameters and cutting modes on cutting power characteristics of various metals by face mills of different designs using experimental, mathematical and simulation methods.

It should be mentioned that vast majority of face mills used in industry employs generator cutting scheme. One of the exceptions is stepped mill Sandvik Coromant [26]. Besides, there is a number of works, which proves the efficiency of using stepped cutting scheme for face mills applied both for finishing and roughing machining of flat surfaces of parts manufactured from difficult-to-machine materials [19, 21, 26–29].

Another aspect for further study is the use of FM cylindrical rake face inserts. This problem is brought into focus in works [21, 30–32], which confirm the positive influence of cylindrical rake face inserts on FM durability, as well as reduction of specific pressure on insert blades.

FM body designing was dwelt on in the study [33], where authors found critical cutting conditions that lead to tool failure. Leading cutting tool manufactures use aluminum as a material for bodies of large-size mills. This reduces FM weight and provides machining stability, which is significant for cartridge type mills [34].

A number of studies are known regarding the improvement of FM shanks and mandrels [35–37]. Developed designs of shanks allow increased rigidity and accuracy of tool grip in the spindle as the more rotational speed of the spindle is, the more grip power it produces.

Energy efficiency of face milling are highlighted in the works [38, 39], in which the authors are suggesting multifunctional integrated optimization model to minimize energy consumption that includes operation factors of cutting tools and cutting modes.

Thus, a great number of diversified studies on face milling are known nowadays, however these studies lack consistency, post narrow scope and their findings have limited applications. Therefore, there is an urgent need of applying systems approach [5, 40, 41] to scientifically ground the main ways of improving FM designs for machining parts, which are manufactured from group H and S materials.

Objective. Based on systems approach, new FM design conceptions employing round inserts should be developed to increase durability, accuracy, machining performance and quality of the surface layer.

Statement of the task. More profound and complete analysis of FM operation can be achieved when it is viewed as a system [40] consisting of the following elements: body, shank, inserts and their position, etc. Then, the technological system (TS), which includes milling machine, holding devices, workpiece and tool itself, can be viewed as a super-system of (TS) [5, 40, 41]. Interaction of functional relations during the face milling process (operation of TS super-system) is shown on Fig. 1.

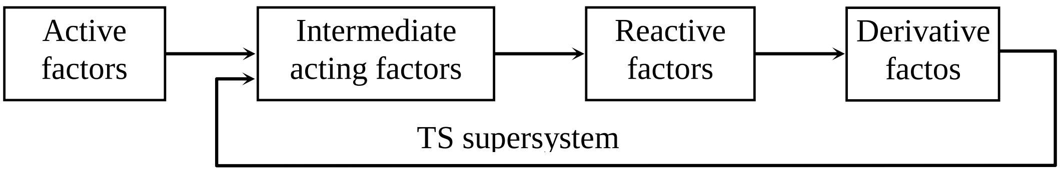

Figure 1. Interaction scheme of physical bonds during milling process

Active factors include torques and angular velocities from the engine to the cutting area.

Intermediate acting force factors include: cutting forces; inertia moments of body, FM, spindle; inertia force [42] at bending and displacement of the mandrel, as well as heat formation on the milling cutter blades during cutting process.

Reactive factors include deformation and displacement of the tool and workpiece with negative or positive feedback, as well as heat dissipation from the cutter blades.

Derivative factors: vibrations with trajectory and cutting speed change; generation of strain fields within the cutting zone and FM inserts wear. The clearest effect of derivatives in the super-system is manifested on the newly sharpened cutting tool, which occurs at the beginning of cutting when instead of effective machining intensive wear takes place, i.e. during the initial cutting period. Through the TS super-system these factors adjust the effect of initial active factors.

Research findings. To design enhanced FM with round inserts one should perform profound systems analysis and analysis of already existing standard FM (ISO 6462:2011 «Face milling cutters with mechanically clamped indexable inserts»): mill diameter – 100–200 mm, insert diameter – 16 mm; no. of inserts – 10–16; maximum cutting depth – 4 mm (see table 1).

Table 1

Description of the analogue, decomposition into elements and their analysis

	Defects	Outcomes
Cutting part	Runout of cutting edges	1. Not all cutting edges perform shaping function. 2. Cutting function is performed by only few cutting edges, which enhances milling unevenness. 3. The reason for degradation of machined surface quality lies in the interaction between individual inserts: the most «protruding» inserts change operating conditions of inserts with less thickness of the cut including shaping insert. 4. Reduction of machining productivity is caused by sharp decrease in the number of inserts which perform milling. 5. Decrease in FM strength is caused by intense wear of the most heavily loaded inserts.
	Placement of cutting edges on the same surface of rotation indicates on the division of chips only by cut thickness (generator cutting scheme)	Runout of cutting edges
	Maximum cutting edge angle is equal to 62 and reached at maximum cutting depth	Immediate elastic deformation may occur when FM is inaccurately fixed on the spindle.
	Non-free orthogonal cutting	Expansion of the chip edges and their partial «smearing» onto the crests of surface microroughness of the workpiece being machined
	Overlapping of functions of allowance removal and shaping	Decrease in general strength, deterioration of surface machined quality
	Lack of overall number of cutting elements, even less number of inserts which perform milling function	Low machining productivity, poor quality of machined surface
Body part	When installation of the insert on the body, a pre-stress in the direction of the main component of the cutting force is not formed	Absence of rigid connection with the body, the insert is being displaced resulting in its chipping and hence deterioration of the machined surface
Base and fastening part	The size of the base face surface is much smaller than the operating diameter of the FM (mounted FM)	FM locating accuracy deterioration which causes the runout of cutting edges
	Radial base of FM has significant diameter	Significant value of diameter allowance increases cutting edges radial runout
	Gripping errors occur due to non-parallelism of opposite base and fastening surfaces of FM and the mandrel, and/or non-perpendicularity of the thread axis and operating nut face	Different clamping stiffness of FM along the spindle contour is created, which promotes oscillation excitation (especially harmful at the initial period of FM wear)

When machining flat surfaces with mills, negative effects may occur such as impacts at entering and withdrawal in the contact area with workpiece, cutting edges damage, uneven milling blade loads, etc., which lead to reduction of FM tool life, machining accuracy and productivity, deterioration in quality of surface layer. This can be avoided by improving the shape of cutting edges, geometric parameters, cutting schemes, which will smooth the milling dynamics, control cutting speed, etc.

Intensification of initial impact processes from cutting forces is the most dangerous in deformed FM elements and their joints. When cutting begins with just sharpened FM cutters, instead of efficient workpiece machining, the intensive wear occurs, which causes impact entering-withdrawal of inserts from the cutting area, but in most cases – oblique impact, i.e. impact being applied not along the bisector of the cutting angle. These are major factors for wearing of the initial cutting period, therefore it is important to make time extension for the initial cutting period in order to smooth and minimize the aforementioned factors. For this purpose, the most effective will be the technical decisions connected with improvement of FM designs at the expense of a choice: cutting type and schemes; shape, number of active inserts and optimal values of geometric parameters; body and shank of FM, etc.

Significant smoothing of the FM machining dynamics can reached by applying oblique cutting with circular inserts, which reduce wear intensity, especially at the initial cutting period.

When designing FM it is necessary to choose such cutting schemes, which would produce the lowest specific cutting forces by providing greater thickness and smaller chip width [29]. This is due to the predominance of the value of the destructive shear deformation for the allowance layer relative to the amount of compression deformation, as well as a decrease in the hydrostatic pressure observed within the cutting area. This approach to cutting schemes realization was used by authors [27, 29] in designing FM with rectangular arrangement of cylindrical inserts on Fermat spirals. Proposed FM design provided formation of type cut “fish scale”. It was found that the developed cutting scheme helped to increase the dynamic stability of the machining process, and, as a result, increase in the tool life and the quality of the machined surface.

It is recommended to increase the number of inserts involved in milling at the same time to 3 or more, as this reduces the negative effect of impact phenomena during machining, instability of the machine kinematics, workpiece deformations, etc.

The geometrical parameters of FM inserts determine the cutting scheme (elements of the cut layer) and are intended for specific machining conditions. The comprehensive analysis of the influence of geometric parameters on the cutting scheme, especially for stepped FM, requires the development of mathematical models of the tool cutting edges load [19]. They allow determining the optimal geometric parameters for each step of the milling cutter.

Stepped cutting schemes are characterized by changing operating conditions of inserts at different steps. Therefore, to realize a gradual uniform transition from rough to shape-forming finishing inserts, it is necessary to apply a spherical or torus cutting surface, which can be obtained through the appropriate shapes of the body using the same protrusion of the inserts relative to the body.

Tool life and the quality of the processed surface also depend on its installation accuracy on the machine. The enhancement of installation accuracy can be achieved by improving the design of the FM shank (milling mandrels). One of the aspects of such improvement is the design provision for increasing the rigidity of joint FM with the spindle of the milling machine [13].

The application of a spherical shape of the FM body compared to the torus, has a large difference in cutting speeds on inserts of different steps, as well as a smaller width of the machined surface. In addition, the torus body has a smaller size and therefore less weight, so the torus shape of the body is more rational. The use of materials with low specific weight for manufacturing of bodies of large-sized FM (titanium – 4.5 g/cm^3, aluminum – 2.5 g/cm^3, magnesium alloys – 1.8 g/cm^3) reduces the load on the operating parts of the machine and ensures the stability of the machining process.

Based on a systems approach and the above considerations, a scheme of the main ways in improvement of FM designs with round inserts was developed (see Fig. 2).

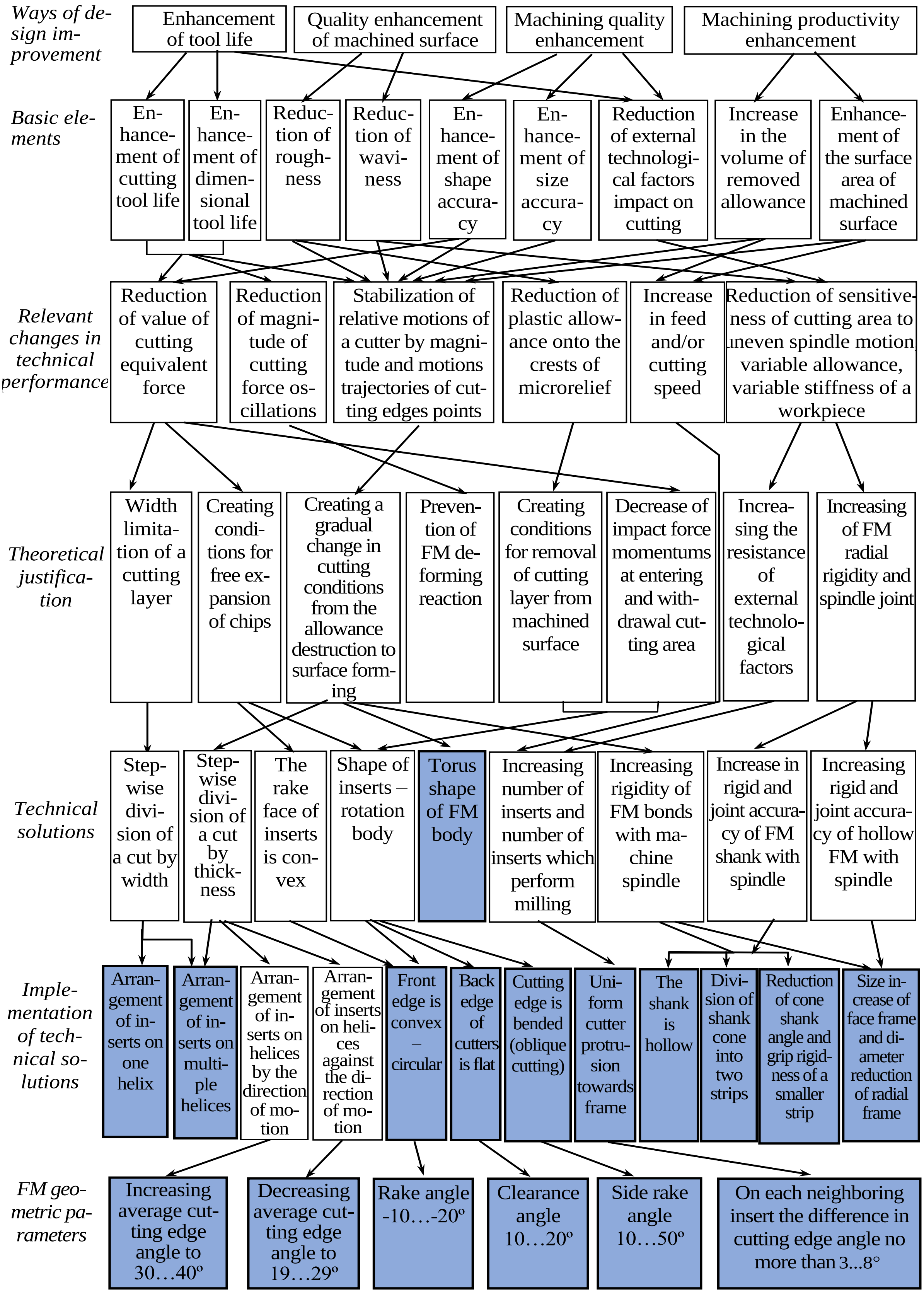

Figure 2. Ways of design improvement of face mills

Based on the above systems approach to the design of FM with round inserts, recommendations for their structural improvement were developed (selected cells in Fig. 2) and a synthesis of variants of improved FM for different machining conditions was proposed (Table 2).

Table 2

Variants of synthesis of advanced face mills designs

1. Type of milling cutter and its nominal diameter	FM without shank, single-helix, *D* =250 mm	FM without shank, adjustable multihelix, *D* =250 mm	FM with shank, adjustable multihelix, *D* =160 mm	FM with shank, adjustable four-helix, *D* =160 mm	FM with shank, four-helix *D* =160 mm	FM without shank, adjustable multihelix, *D* =250 mm
2. FM Application	Machining of high strength steels			Machining of hardened steels		Machining of titanium alloys
3. Cutting width, mm	240	240	150	150	150	240
4. Cutting depth, mm	14	6–8	6–8	2, 4	2, 4	8–10
5. Body and shank material	40X steel	40X steel	40X steel	40X steel	AL34 Alloy	40X steel
6. Insert, mm	Cylindrical hard-alloy insert, 16×15	Cylindrical hard-alloy insert, 11×10	Cylindrical hard-alloy insert, 11×10	Hexanit (PCBN) bilayer insert, 5,56×3,97	Hexanit (PCBN) bilayer insert, 5,56×3,97	Cylindrical hard-alloy insert, 11×10
7. Inserts location in the FM body	Cylindrical hole and face of regulating screw					
8. Inserts protrusion, mm	5	3	2,5	1,5	1,5	3
9. Fixturing of inserts on the body	Elastic wedge element with a screw	Wedge element with a screw				
10. Clearance angle, gr.	12…16	12…16	12…16	16…20	16…20	12…16
11. Number of inserts	18	18	12	28	28	20
12. Body	Torus with angular holes	Torus with slots		Torus with angular holes		Torus with slots
13. FM body location	Alongside of cylindrical surface of spindle hole and increased face belt		Alongside of hollow shank			Alongside of spindle face and frame shaft

Thus, on the basis of the systems approach variants of the improved designs of face mills were developed, one of which is given in fig. 3, namely adjustable stepped FM for machining of high strength steels with cylindrical cutters located on the torus body with 3 Fermat helices, with a shank, characterized by increased rigidity of the joint with the machine spindle.

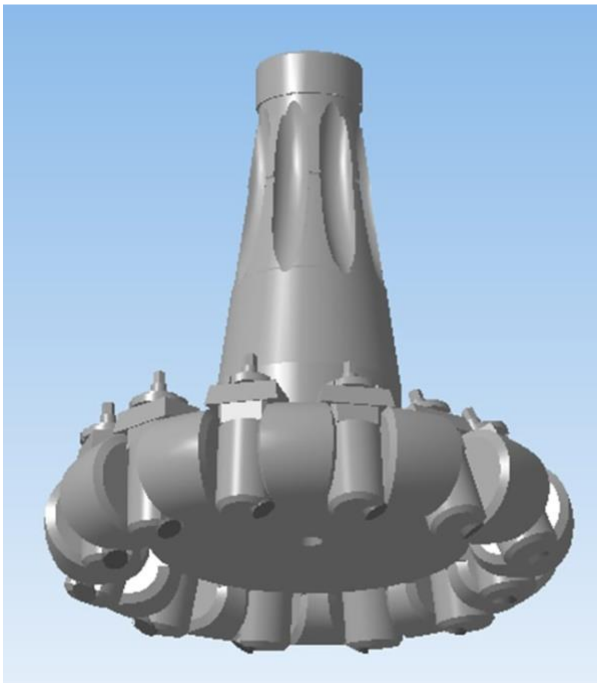

Figure 3. General view of the adjustable square shoulder face mill for high-tensile steels machining [27]

Some elements of the developed design solutions have already been used in modern engineering, such as the use of stepped cutting schemes [26] and hollow shanks [35–37]. The advantage of the proposed design concepts is the integrated application of new technical solutions, which are based on a systems approach, which will increase the efficiency of face milling of flat surfaces of parts made of group S and H materials.

Conclusions. It is suggested to analyze the FM operating conditions element by element: the body, shank, inserts and their location, etc., and consider these components as a system. In this case, the technological system, which includes the milling machine, holding device, workpiece and a tool, can be represented as a supersystem, which is under the influence of active, intermediate acting, reactive and derivative factors. For a standard face mill with round inserts, decomposition into elements (cutting, body, base and fastening parts) was done and their systems analysis of the occurrence of adverse cutting conditions was performed. The design improvement of FM elements made it possible to propose technical solutions that are aimed at significant increase of FM tool life, accuracy, machining productivity and quality enhancement of the machined surface of the part. The main suggestions for improving the design of FM are to make a torus-shaped body, stepped arrangement of inserts on Fermat helices, employment of a cylindrical rake face of the inserts and the shank with increased rigidity of the joint by dividing the conical surface into two strips reducing the angle of the cone and hollowing its angle.

As a result of design improvement and synthesis of variants, the development of concepts of improved FM designs for different machining conditions of flat surfaces made of group S and H structural materials has been realized. The proposed systems approach can be further developed and applied to improve the design of cutting tools of different types.

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СТРУКТУРНЕ УДОСКОНАЛЕННЯ КОНСТРУКЦІЙ ТОРЦЕВИХ ФРЕЗ НА ОСНОВІ СИСТЕМНОГО ПІДХОДУ

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Резюме. *Присвячено удосконаленню конструкцій торцевих фрез із круглими пластинами на основі системного підходу. Торцеві фрези з круглими пластинами знаходять широке застосування в машинобудуванні, оскільки вони є універсальними та використовуються як для складного торцевого фрезерування, так і для профільної обробки. Підвищення ефективності різання торцевими фрезами можливе через удосконалення їх конструкцій за такими напрямками: підвищення стійкості інструмента, точності та продуктивності обробки, покращення якості поверхневого шару обробленої поверхні деталі. Аналіз умов роботи ТФ здійснюється поелементно (корпус, хвостовик, ножі, їх розташування тощо). Ці складові розглядаються як одна система. Технологічна система (верстат, пристосування, заготовка, інструмент) представлена як надсистема, яка перебуває під впливом активних, проміжних діючих, реактивних та похідних чинників. Проведено декомпозицію на елементи (різальна, корпусна, базова і кріпильна частини) стандартної торцевої фрези з круглими пластинами та виконано їх системний аналіз щодо виникнення несприятливих умов різання. На основі цього розроблено схему напрямків структурного вдосконалення конструкцій торцевих фрез. Запропоновано технічні вирішення, спрямовані на суттєве підвищення стійкості інструменту, точності та продуктивності обробки, а також покращення якості обробленої поверхні деталі. Наведено основні пропозиції щодо вдосконалення конструкцій ТФ: виконання корпусу торової форми, ступінчасте розміщення ножів по спіралях Ферма, застосування циліндричної передньої поверхні ножів та виконання хвостовика з підвищеною жорсткістю з'єднання. В результаті структурного вдосконалення та синтезу варіантів розроблено концепції удосконалених конструкцій ТФ для різних умов обробки.*

Ключові слова: *торцева фреза, системний підхід, структурний аналіз, конструкція фрези.*

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