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Calculation of multi-blade rotary-friction tool shaft for strength

Abstract. *The leading place in the technology of modern mechanical engineering production is occupied by cutting processes. In many branches of mechanical engineering, especially in mass production, their labor and production costs reach 40-60% of the total costs of metalworking. Nowadays, no more or less complex machine can be made without the use of cutting tools. Thus, we can rightfully assert that cutting machining has retained its predominant influence on the development of mechanical engineering technology and its importance will be steadily increasing in the future, largely based on the use of fundamentally new machining methods. And the latter can be rightly attributed to the so-called rotary cutting. The authors have developed a design of a special multi-blade rotary-friction tool for machining cylindrical surfaces of parts made of hard-to-machine materials. This paper presents the results of the calculation of the most loaded node of the multi-blade rotary-friction tool of the part "shaft". Calculation of the bending strength of the shaft has been performed. The results of the calculation have been checked through the program Apm Winmachine which has confirmed their correctness. This research is funded by the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP14972884).*
Keywords. *Rotary-friction tool, cup cutter, strength, stiffness, bending moment, cutting force.*

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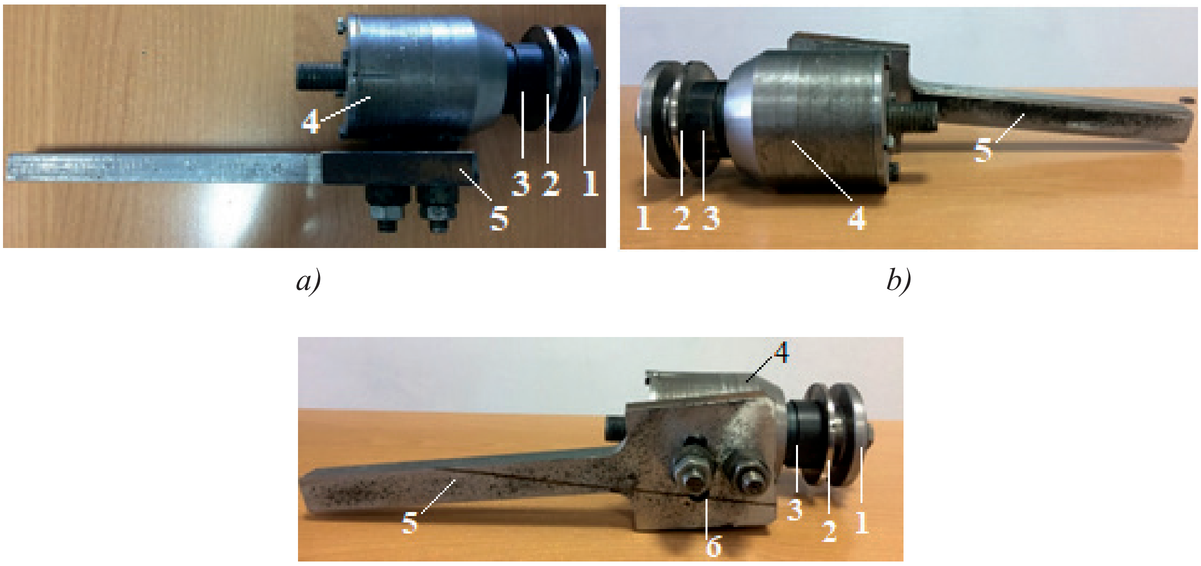
Introduction

Rotary cutting of materials belongs to progressive machining methods. It is based on replacing the traditional sliding friction between the working surfaces of the cutting element and the machined material by rolling friction. This is achieved by equipping the rotary tool with a rotating cup with a circular cutting edge that allows continuous additional rotation around its axis. It can be forced by a special drive or by frictional forces from the descending chips and in contact between the tool and the workpiece [1]. When designing a cutting tool design, the designer relies on his experience to create a new design or modify a known design and then performs verification calculations for strength. This leads to multiple repetitions of calculations and requires significant costs in selecting the best option. Development of methods for the optimal design of the disk, taking into account working conditions and strength requirements, implemented in the form of an automatic design system on the computer, is more effective.

The calculation of the spatial stress state became possible due to the development of the finite element method (FEM), which allows the implementation of well-developed procedures for solving the elastic-plastic problem, and the introduction of CAE systems of sufficiently high efficiency. When calculating the design of cutting tools, it is also necessary to take into account the effects of the environment. For this purpose, refined calculation methods implemented on a computer have been developed [2]. The authors developed the design of a special multi-blade rotary-friction tool. Figure 1 shows a prototype of a special multi-blade rotary-friction tool.

Bowl cutters are mounted on the rotating shaft of a multi-blade rotary-friction tool, which is most often the tool spindle.

The multi-blade rotary-friction tool consists of a bearing unit 4 and a shaft 3, which rotates freely using bearings. Heating 1 and cutting cup cutters 2 are mounted on the shaft. The tool is fastened to the tool holder of the lathe using tool holder 5. A heating cup cutter 1 is made from medium-carbon structural steel of any grade, and a cutting cup cutter 2 is made from R6M5 (rapid) steel. The purpose of the heating cup cutter is to soften the machined surface and thus create a favorable cutting condition during the machining of the cutting cup cutter.



a) *b)*

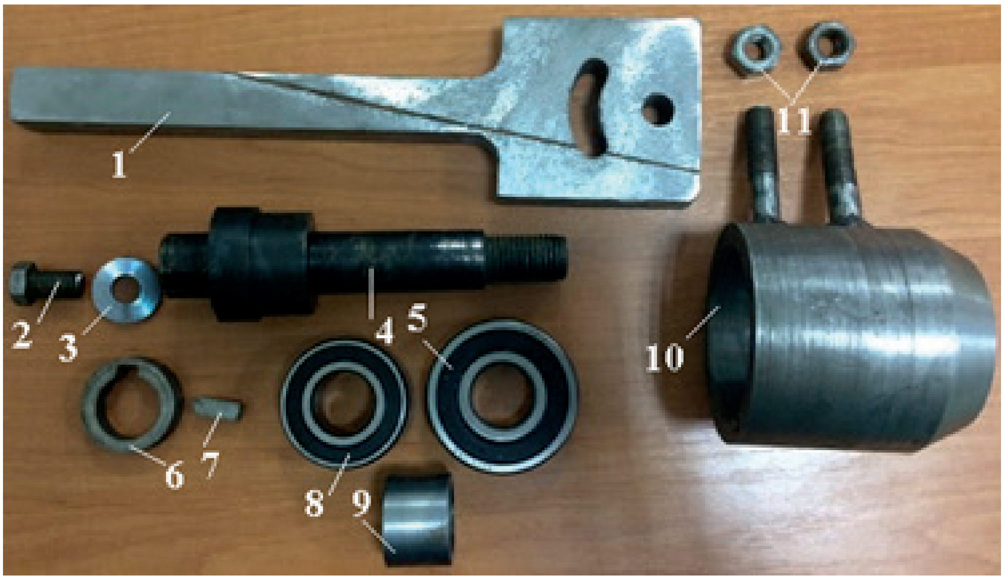
c)

a - top view; b, c - side view; 1 - heating cup cutter; 2 - cutting cup cutter; 3 - shaft; 4 - bearing unit; 5 - holder; 6 - holder holes to adjust the angle of the cup cutters

Figure 1. Multi-blade rotary friction tool

The final formation of the machined surface and its quality is provided by the cutting cup cutter.

Figure 2 shows photos of parts of a multi-blade rotary-friction tool.



1 - holder; 2 - bolt; 3 - washer; 4 - shaft; 5,8 - bearings; 6 - bushing between cup cutters; 7 - key; 9 - bushing between bearings; 10 - bearing housing; 11 - nut

Figure 2. Parts of a multi-blade rotary friction tool

Experimental studies on testing a prototype of a multi-blade rotary-friction tool have shown that the part "shaft" is the most loaded in the process of tool operation.

In this regard, research aimed at ensuring the rigidity and strength of the tool design, in particular the shaft part, is an urgent task.

In work [3] strength and rigidity of cup cutters of multi-blade rotary-friction tools in the process of machining with the use of the Ansys WB software package was investigated. The strength and stiffness of cup cutters were investigated under different values of cutting force and temperature. It was found that the cup cutters have sufficient strength and stiffness. Works performed in this scientific field were also investigated.

In [4] a new design of a multi-blade rotary tool was investigated. The design of the tool contributed to the creation of a new milling system that eliminates vibration during machining. This method of milling allows the machining of plastic materials that become stronger when deformed. It is also possible to process heat-resistant and complex alloys, titanium, and its alloys.

In [5] the simulation of the process of thermal friction disk operation during cutting metal workpieces was performed. Modeling of the cutting disk operation is performed in two variants (as a rod system – in the form of a non-jointed circular arch and as a two-dimensional system – in the form of a thin circular isotropic plate with holes) and the results (in the form of stresses and displacements) are quite close to each other, which indicates the reliability of the initial theoretical assumptions. Calculations have been made by two methods: by the analytical method of forces - for a non-jointed arch (manual calculation); by the numerical method of finite elements – for a plate in the form of a "semicircle" (machine calculation - based on the Lira 9.6 software package).

In the paper [6] a scientific-theoretical study of the stability condition of the circular saw blade for thermal friction cutting by calculation method in the form of a circular non-jointed arch is carried out. A calculation method for determining the state of circular saw blade stability is proposed, which is based on the application of a rod model in the form of a circular non-jointed arch for half of the circular saw blade, penetrating the body of the material to be cut. The computational scheme of the non-jointed circular arch, the bending moment diagram, and the diagram of transverse and longitudinal forces are given. The form of stability loss of the non-jointed arch is also determined.

In works [7] processes of rotary cutting machining which provide updating also contact surfaces of the tool are investigated. These studies determined the conditions under which sliding friction is partially replaced by rolling friction, which provides increased tool life [8].

Rotary cutting is also accompanied by an increase in the length of the cutting blade, parts of which periodically participates, in the removal of the allowance from the workpiece and are cooled outside the cutting zone, which also contributes to the durability of the rotary tool [9].

The paper [10] analyzes the mechanics of rotary milling and presents the results of experimental studies of the effect of friction forces on the cutting process of carbon materials. The hypothesis of the mechanism of reducing rotary tool wear and increasing its durability is proposed.

In [11], the results of parametric optimization of the stress components of a rotating friction tool using virtual experiments in ANSYS WB are presented. The calculation is performed by the finite element (FE) method. The most widely used Johnson-Cook model has been chosen as the criterion for fracture of the elements of the FE mesh. The validity of the model confirms the sensitivity of cutting force and temperature to changes in cutting speed by modern concepts: with increasing cutting speed, the cutting force decreases, and the temperature increases. It is experimentally established that the quality and accuracy of machining are directly influenced by the right choice of parameters and dimensions of the tool.

Materials and methods

The freely rotating shaft is the main component of a special multi-blade rotary-friction tool, so the strength of the shaft determines the reliability of the tool.

To calculate the bending strength of a shaft, it is necessary to establish the acting cutting forces. The constituent forces P_x, P_y, P_z characterize the loads that exist during the operation of the rotary cutter, they are convenient for calculating the strength and stiffness of the cutter assemblies and the bearing capacity of the bearings installed in them [12].

The main component P_z of the cutting force is directed tangentially to the machined surface, the pushing-down component P_y acts in the radial direction, and the lateral component P_x runs parallel to the axis of the workpiece (Figure 3).

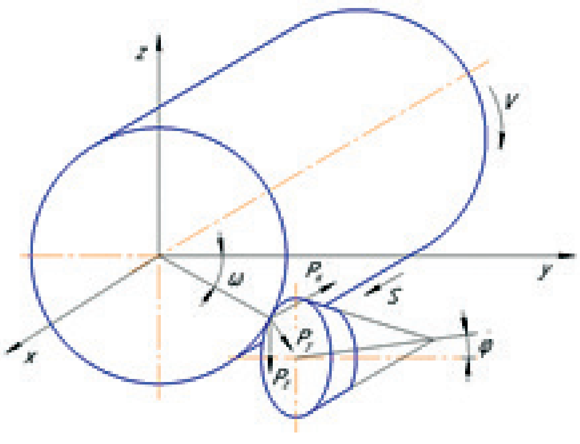


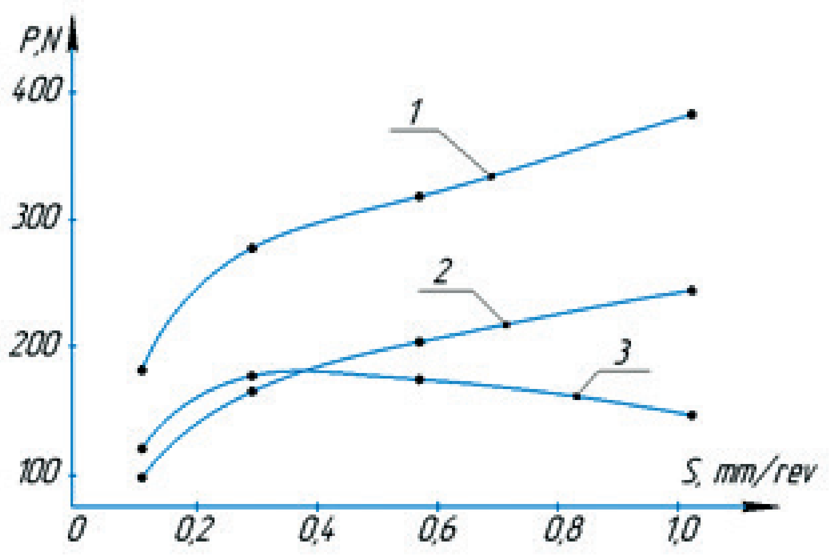
Figure 3. Location of the cup pick concerning the workpiece

The variation of the component forces depending on the setting angles of the cutter cup is defined as follows (1):

$$\begin{cases} P'_x = P_x cos\varphi + P_y sin\varphi, \\ P'_y = P_y cos\varphi cos\omega - P_x sin\varphi cos\omega + P_z sin\omega, \\ P'_z = P_x sin\varphi sin\omega - P_y cos\varphi sin\omega + P_z cos\omega. \end{cases} \quad (1)$$

where P_x, P_y, P_z - components of cutting force in the point of contact of the part with a rotary cup cutter, N; φ - the angle of the cutter axis rotation in the horizontal plane, deg; ω - the angle of the cutter axis installation in the vertical plane, deg.

The cutting forces are influenced by many factors, such as the cutting tool setting angle, feed, and lubrication of the machined surfaces. According to studies [12], the cutting forces depending on the feed changes as follows (Figure 4).



1 - P_z, 2 - P_x, 3 - P_y

Figure 4. Dependence of force components on feed

These three components of the cutting force are mutually perpendicular. In this regard, the direction of the resultant force P (2) is defined as the diagonal of the parallelepiped [12],

$$P = \sqrt{P_x^2 + P_y^2 + P_z^2}. \quad (2)$$

To calculate the bending of the shaft, the support reactions, and the maximum stress are determined and compared with the allowable bending stress of the given material. Figure 5 shows diagrams of forces and support reactions.

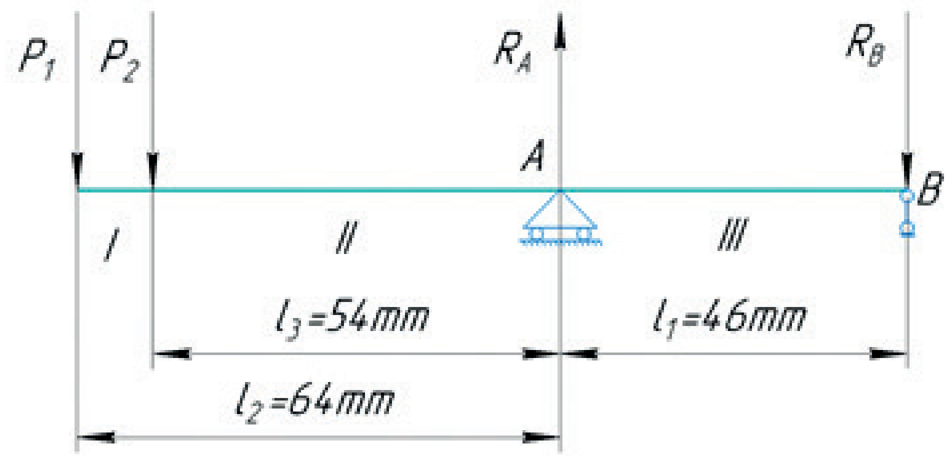


Figure 5. Diagrams of forces and support reactions

The reference reactions are calculated from the equilibrium level as the sum of the moments of all the forces at point B (3) and from the equilibrium level as the sum of the projections of all the forces on the vertical axis (4):

$$\sum \grave{I}_{\hat{A}} = -P_1(l_1+l_2) - P_2(l_1+l_3) + R_A l_1 = 0; \tag{3}$$

$$\sum Y = -P_1 - P_2 + R_A + R_B = 0; \tag{4}$$

where P_1, P_2 - the forces acting on the cup cutters, R_A, R_B - the reaction of the supports, l_1, l_2, l_3 - the distances.

If we impose a force $P_1=P_2=3100N$, then the support reactions get R_A=14152,2N,R_B=-7952,2N, and the maximum moment is equal to -365,8 Н·м. The maximum bending stress (4) on the shaft with a diameter of 25 mm is 239 MPa, and the maximum allowable bending stress for steel 45 is 240 MPa. The maximum bending stress of the shaft does not exceed the allowable stress.

Based on the results, we build the bending moment diagrams (Figure 6).

$$\sigma_{\max} = \frac{M_{\max}}{W} \leq [\sigma]; \tag{5}$$

where [σ] - maximum allowable bending stress for steel 45, M_{max}- the maximum moment, W - axial moment of resistance (for a section with a diameter of 25 mm will be 1,5•10-6m3).

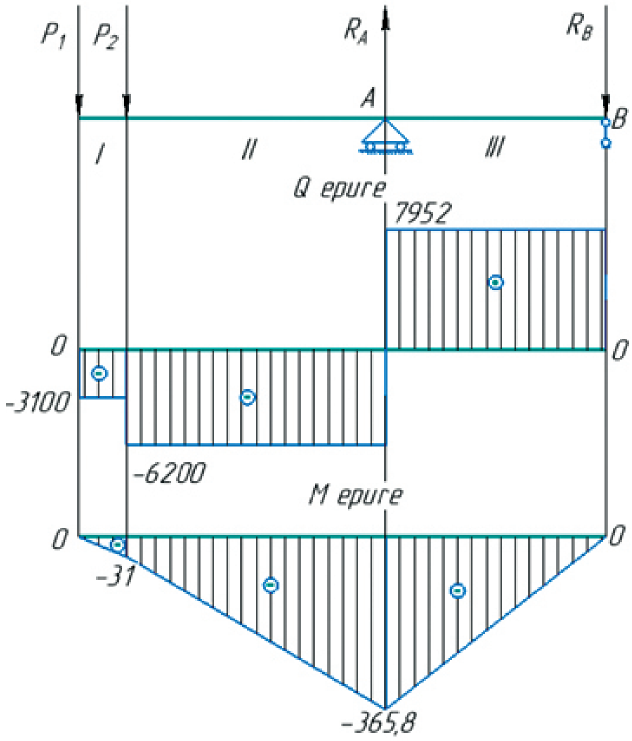


Figure 6. Moment and force epures

Check the calculations with the program Apm Winmachine. Sketch of the shaft and specify the supports and forces (Figure 7).

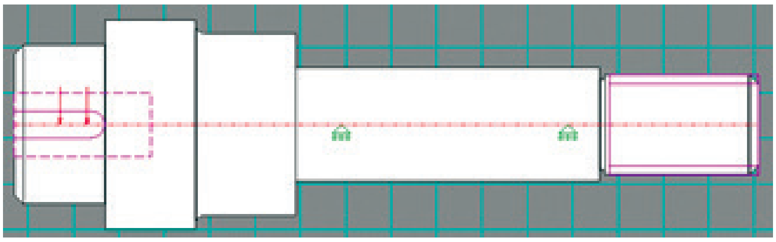


Figure 7. Sketch of a shaft in the Apm Winmachine program

After entering the data, the program plots the bending moment diagram (Figure 8).

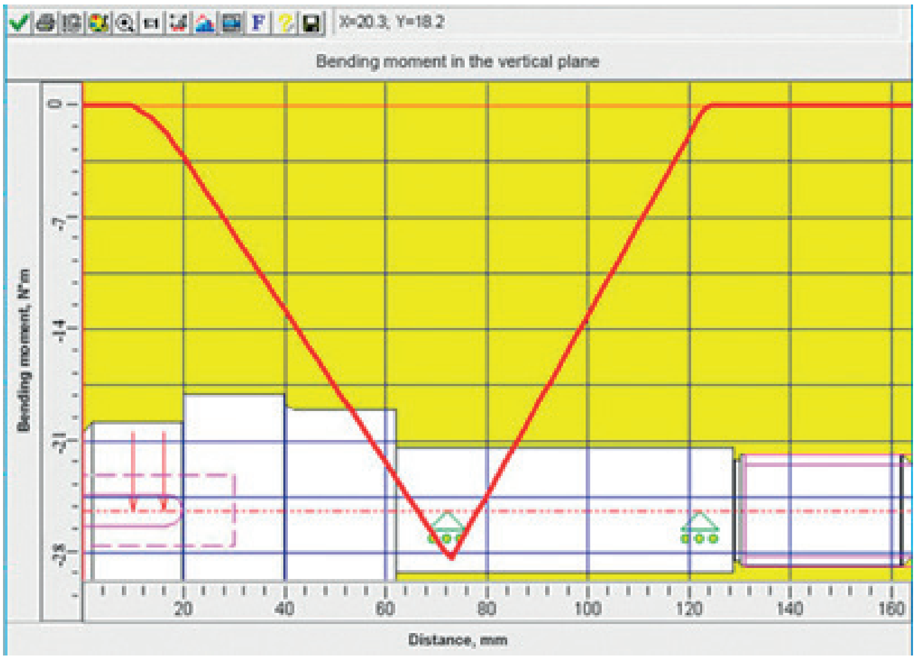


Figure 8. Bending moment diagram obtained in Apm Winmachine

Figure 9 shows a graph of the fatigue safety factor.

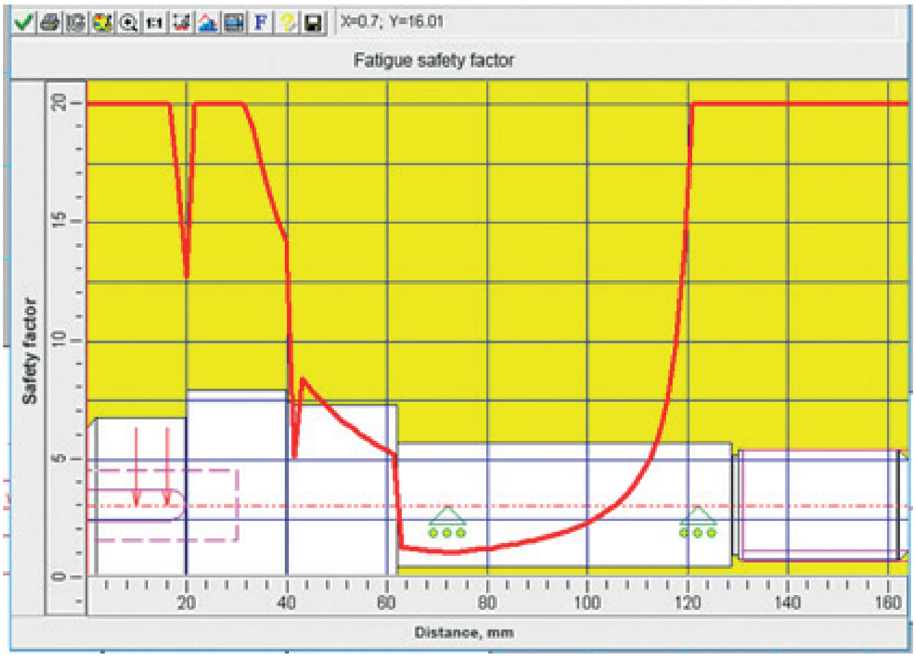


Figure 9. Fatigue safety factor diagram

Results and discussion

It was found that the direction and magnitude of the cutting force acting on the cutter during rotary machining differ significantly from the values obtained during conventional cutter operation, due to fundamental differences in tool kinematics and their installation relative to the machined surface (see Fig. 2).

From the diagram (see Fig. 8) it can be seen that the maximum moment is equal to – 365.8 N·m and proves the correctness of the previously conducted calculation of the shaft for strength.

From the graph (see Fig. 9) we can see that the value of the safety factor for fatigue strength is greater than zero. The obtained results confirm the correctness of the chosen parameters of the part "shaft" and at the same time its strength and stiffness, as well as the carrying capacity are ensured.

Conclusion

It has been revealed that the most loaded node of the multi-blade rotary-friction tool is a part "shaft." Calculation of the bending strength of the shaft was performed. Calculation results were checked with the Apm Winmachine program, which confirmed their correctness.

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Ротациялық-фрикциялық құрал білігінің иілу кезіндегі беріктігін есептеу

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Андатпа. Қазіргі заманғы машина жасау технологиясында кесу процестері жетекші орын алады. Машина жасаудың көптеген салаларында, әсіресе жаппай өндірісте олардың еңбек шығындары мен өндірістік шығындары жалпы металл өңдеу шығындарының 40-60% құрайды. Қазіргі уақытта кескіш құралдарды қолданбай көп немесе аз күрделі машинаны жасау мүмкін емес. Осылайша, біз кесу арқылы өңдеу машина жасау технологиясының дамуына өзінің басым әсерін сақтап қалды және болашақта оның мәні прогрессивті жаңа өңдеу әдістерін қолдану арқылы тұрақты түрде артады деп толық құқықпен айта аламыз. Соңғысына ротациялық кесу әдісін жатқызуға болады. Авторлар өңдеуге қиын материалдардан жасалған бөлшектердің цилиндрлік беттерін өңдеуге арналған арнайы көп жүзді ротациялық-фрикциялық құралының құраламын әзірледі. Бұл мақалада ротациялық-фрикциялық құралының ең көп жүктелген түйіні «білік» бөлшегінің есептеу нәтижелері келтірілген.

Иілу үшін біліктің беріктігін есептеу орындалды. Есептеу нәтижелері Apm WinMachine бағдарламасының көмегімен тексерілді, бұл олардың дұрыстығын растады. Бұл зерттеуді Қазақстан Республикасының Ғылым және жоғары білім министрлігі қаржыландырады (грант № AP14972884).

Түйін сөздер: ротациялық-фрикциялық құрал, дискілі кескіш, беріктік, қаттылық, иілу моменті, кесу күші.

Расчет прочности вала ротационно-фрикционного инструмента на изгиб

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Аннотация. Ведущее место в технологии современного машиностроительного производства занимают процессы резания. Во многих отраслях машиностроения, особенно в массовом производстве, их трудозатраты и производственные затраты достигают 40-60% от общих затрат на металлообработку. В настоящее время ни одно более или менее сложное изделие не может быть изготовлено без использования режущих инструментов. Таким образом, мы можем с полным правом утверждать, что обработка резанием сохранила свое преобладающее влияние на развитие технологии машиностроения, и в будущем ее значение будет неуклонно возрастать, во многом за счет использования прогрессивных новых методов обработки. И последнему по праву можно отнести так называемое ротационное резание. Авторами разработана конструкция специального многолезвийного ротационно-фрикционного инструмента для обработки цилиндрических поверхностей деталей из труднообрабатываемых материалов. В данной статье приводится результаты расчета самого нагруженного узла многолезвийного ротационно-фрикционного инструмента детали «вал».

Выполнен расчет прочности вала на изгиб. Результаты расчета были проверены с помощью программы Apm Winmachine, который подтвердил их правильность. Данное исследование финансируется Министерством науки и высшего образования Республики Казахстан (грант № AP14972884).

Ключевые слова: ротационно-фрикционный инструмент, чашечный резец, прочность, жесткость, момент изгиба, сила резания.

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