ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ
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ХАБАРЛАРЫ

ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ
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N E W S

OF THE ACADEMY OF SCIENCES
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KAZAKHSTAN
Satbayev University

SERIES
OF GEOLOGY AND TECHNICAL SCIENCES

2 (452)

MARCH – APRIL 2022

THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

ALMATY, NAS RK

«Известия НАН РК. Серия геологии и технических наук».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Собственник: Республиканское общественное объединение «Национальная академия наук Республики Казахстан» (г. Алматы).

Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и общественного развития Республики Казахстан **№ KZ39VPY00025420,** выданное 29.07.2020 г.

Тематическая направленность: *геология, химические технологии переработки нефти и газа, нефтехимия, технологии извлечения металлов и их соеденений.*

Периодичность: 6 раз в год.

Тираж: 300 экземпляров.

Адрес редакции: 050010, г. Алматы, ул. Шевченко, 28, оф. 219, тел.: 272-13-19

http://www.geolog-technical.kz/index.php/en/

Адрес типографии: ИП «Аруна», г. Алматы, ул. Муратбаева, 75.

***NEWS** of the National Academy of Sciences of the Republic of Kazakhstan*
SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224-5278
Volume 2, Number 452 (2022), 89-103
https://doi.org/10.32014/2022.2518-170X.162

UDC 621.9.02

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RESEARCH OF THE STRESS-STRAIN STATE OF HOLES WITH NEW BROACH DESIGNS

Abstract. The treatment of internal surfaces with increased requirements for accuracy and location is broaching – due to the high concentration of cutting teeth simultaneously involved in the work.

The article presents the results of research work on the development of metal-cutting tools to improve the quality (physical and mechanical properties) and processing performance – the design of two-stage progressive and two-stage slotted broaches.

The use of two-stage progressive broaching for processing cylindrical holes will increase processing productivity, reduce stretching and vibration forces, specific pressure on the teeth of the broach, the depth of the defective layer, thereby increasing its durability, the quality of processing cylindrical holes and physical and mechanical properties.

The use of two-stage split broaching with a straight profile of single-cut slots with peripheral and lateral cutting allows you to reduce the number of cutting teeth, the length of the broach and the cost of tool material and increase economic efficiency.

Thus, the use of the proposed broach designs improves the stress-strain state, increases processing productivity, reduces stretching and vibration forces, specific pressure on the teeth of the broach, and, consequently, increases the resistance of the broach, the quality of processing, savings of tool material and economic efficiency.

Key words: broaching, accuracy, quality, stress-strain state, efficiency, tool materials, productivity.

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ТЕСІКТЕРДІҢ КЕРНЕУЛІ ДЕФОРМАЦИЯЛАНҒАН КҮЙІН ТАРТАЖОҢҒЫШТАРДЫҢ ЖАҢА КОНСТРУКЦИЯЛАРЫМЕН ЗЕРТТЕУ

Аннотация. Бір уақытта жұмыс істейтін кесу тістерінің жоғары концентрациясына байланысты тартажону – ішкі беттерді өңдеудің жоғары талаптары мен орналасуы дәлдігі болып табылады.

Мақалада екі сатылы прогрессивті және екі сатылы оймакілтекті тартажоңғыштардың конструкциялары сапасын (физика-механикалық қасиеттері) және өңдеу өнімділігін арттыруға арналған металл кесетін құралдарды әзірлеу бойынша ғылыми-зерттеу жұмыстарының нәтижелері келтірілген.

Цилиндрлік тесіктерді өңдеу үшін екі сатылы прогрессивті тартажоңғышты қолдану өңдеу өнімділігін арттырады, тарту күші мен дірілді азайтады, тартажоңғыштың тістеріндегі нақты қысым, ақаулы қабаттың тереңдігі, оның тұрақтылығын, цилиндрлік тесіктерді өңдеу сапасын және физика-механикалық қасиеттерін арттырады. Шеткері және бүйірлік кесу арқылы бір кесу саңылауларының түзу профилімен екі сатылы оймакілтекті тартажоңғышты қолдану кесу тістерінің санын, тартажоңғыштың ұзындығын және аспаптық материалдың құнын азайтуға және экономикалық тиімділікті арттыруға мүмкіндік береді.

Осылайша, ұсынылған тартпа конструкцияларын қолдану кернеулі және деформацияланған күйді жақсартады, өңдеу өнімділігін арттырады, тарту және діріл күштерін азайтады, тартажоңғыштың тістері нақты қысым жасайды, демек, тартажоңғыштың тұрақтылығы, өңдеу сапасы, құрал-саймандық материалды үнемдеуге септігін тигізетіндіктен, экономикалық жағынан да тиімді болады.

Түйін сөздер: тартажонғыш, дәлдік, сапа, кернеулі және деформацияланған күй, тиімділік, құралдар, өнімділік.

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ИССЛЕДОВАНИЕ НАПРЯЖЕННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ ОТВЕРСТИЙ НОВЫМИ КОНСТРУКЦИЯМИ ПРОТЯЖЕК

Аннотация. Обработка внутренних поверхностей с повышенными требованиями к точности и расположению является протягивание, одновременно участвующих в работе из-за высокой концентрации режущих зубьев.

В статье приведены результаты научно-исследовательской работы по разработке металлорежущих инструментов для повышения качества (физико-механические свойства) и производительности обработки – конструкции двухступенчатой прогрессивной и двухступенчатой шлицевой протяжек.

Применение двухступенчатой прогрессивной протяжки для обработки цилиндрических отверстий позволит увеличить производительность обработки, уменьшить усилия протягивания и вибрации, удельное давление на зубья протяжки, глубину дефектного слоя, тем самым увеличить её стойкость, качество обработки цилиндрических отверстий и физико-механические свойства.

Применение двухступенчатой шлицевой протяжки с прямобочным профилем шлицев одинарного резания с периферийным и боковым резанием позволяет уменьшить число режущих зубьев, длину протяжки и затраты на инструментальный материал и повысить экономическую эффективность.

Таким образом, применение предлагаемых конструкций протяжек улучшают напряженно-деформированное состояние, повышает производительность обработки, уменьшает усилия протягивания и вибрации, удельное давление на зубья протяжки, а, следовательно, увеличивается стойкость протяжки, качество обработки, экономия инструментального материала и экономическая эффективность.

Ключевые слова: протяжка, точность, качество, напряженно-деформированное состояние, эффективность, инструментальные материала, производительность.

Introduction. The modern development of mechanical engineering is characterized by ensuring high-quality processing with the use of advanced high-performance equipment and tools that have increased strength, rigidity, vibration resistance, durability and accuracy. These indicators of the cutting tool are formed both at the design stage and in the process of its manufacture.

One of the main directions of mechanical engineering is metalworking with the development of advanced high-performance processing methods and technological processes. As an element of the technological system, the cutting tool plays a leading role in achieving the specified economic and technological indicators of the metalworking process.

The most productive processing method is broaching due to the high concentration of simultaneously working teeth, i.e., the efficiency of broaching is ensured by increased productivity, as well as physical and mechanical properties, endurance, durability and reduction of its length, providing high accuracy of the shape and dimensions of the processed surface (Ambrosimov S.K. et. al, 2017).

Broach is a multi-tooth cutting tool, its main movement is translational and sometimes rotational. A distinctive feature of the tooth of the broach is that the height of each subsequent tooth increases, ensuring the removal of metal from the processed surface of any shape (Donenbayev B. et. al, 2021)

Broaching is used for surface treatment with a quality of IT 7-8 and a roughness up to R_a0.32 microns. Compared to other methods, productivity increases by 3-12 times. A very significant economic effect if the shapes of the treated surfaces and their sizes are normalized.

During the cutting process, the chips are removed by each tooth of the broach, with a broaching speed of 2–15 m per min usually, and placed in the cavities between the teeth, otherwise the broach will jam and break (Arrazila P.J. et.al, 2021).

Basically, broaches are used to obtain parts with a diameter or width from 6 to 100 mm or more.

According to the nature of the treated surfaces, broaches are divided into two main groups: internal and external.

Internal broaches process various closed surfaces, and external – semi-closed and open surfaces of different profiles.

There are the following types of broaches according to the forms:

- round broaches are used for processing cylindrical holes. the accuracy of hole processing is 0.05 mm and even higher;
- square broaches are intended for processing tetrahedral holes. the accuracy of processing with square broaches is the same as for round broaches;
- single-pin broaches are used for processing keyways in base holes with an accuracy of 0.06 mm and higher in diameter and width of the groove;
- split broaches are used for processing slotted holes. the processing accuracy of these broaches is the same with round and square broaches;
- screw multi-pin broaches are used for processing screw multi-pin grooves. when working, the broach receives two strictly coordinated movements - longitudinal (axial) and rotational;
- polyhedral broaches are used for processing faceted holes with any number of sides;
- coordinate broaches work in a set of several pieces and are intended for processing different holes or grooves with exact dimensions and their exact location relative to the base surfaces of the workpiece. the processing accuracy of these broaches is 0.04 mm and higher;
- external broaches are used for processing external flat and shaped profile surfaces both by the method of free and by the method of coordinate stretching;
- sealing broaches are used to seal the pre-treated surface, improve the structure of the surface layer, wear resistance and cleanliness. calibration firmware is used to remove a very small allowance. Precise calibration is performed to obtain a clean and smooth surface with an accuracy of 0.01 mm.

Broaches are made of high-speed steel R18 and tool alloy steel of the HVG brand. In order to save expensive tool steel, in addition to solid ones, prefabricated broaches are manufactured, in which, after the calibration teeth, an additional sleeve is inserted, having several teeth that fully correspond to the parameters of the calibration teeth of the broach. With a decrease in the size of the calibration teeth of the broach due to overflows, their role is performed by the teeth of replaceable bushings. There are also keyed prefabricated broaches with plug-in knives (Arrazola P.J. et.al, 2020) (Itybayeva G.T. 2019).

The main advantages of broaching:

1) high productivity due to the large total length of the simultaneously working cutting edges;

2) provides high quality processing with surface roughness up to R_a0.32 microns;

3) high durability;

4) highly skilled workers and complex equipment are not required.

Disadvantages of broaches are complexity of its manufacturing and sharpening; high cost; highly specialized tools; big length with relatively small cross-sectional dimensions; impossibility of making a “Blind” hole (Akhmedov A.B. et.al, 2020)

For many years, the Department of Mechanical Engineering and Standardization of Toraigyrov University and scientists from other universities have been working to develop metal-cutting tools to improve and secure favorable cutting conditions (Dudak N. 2019; Lobanov D. et.al, 2014).

Materials and research methods. The broaching process is carried out with different cutting schemes. The basic cutting schemes are as presented: profile cutting; progressive or variable cutting; generator cutting (Arrazola P.J. et.al, 2020; Muknov R.B. et.al, 2020)

The profile cutting scheme is characterized by the fact that, starting from the first tooth, the contour of all teeth is similar (equidistant) to the final profile of the processed surface. As a result, all the teeth of the cutting part, except for the last one, make preliminary processing to form a given profile on a workpiece. The accuracy and quality of the processed surface of the workpiece is determined by the last tooth of the cutting part. The length of the main cutting edge of this tooth is maximal, so, to reduce the cutting force, S_z for the tooth should be minimal. The main disadvantage of the profile cutting scheme is the technological complexity of manufacturing the profile of the teeth of the cutting part.

With a progressive cutting scheme, the allowance is cut with teeth of a shortened length of the main cutting edges. The cutting tooth of the broach is divided by length, and the lift on the tooth is S_z. Thus, instead of one tooth, the layer of metal is cut with two teeth of the cutting part. This allows one to distribute the load on the broach teeth evenly along the entire length of the cutting part, but at the same time causes an increased required number of cutting teeth.

With the generator cutting scheme, each tooth partially forms the final profile contour of the processed part with its auxiliary tooth. The first tooth of the main cutting edge has the largest length. Then their length decreases gradually and gets minimal for the last tooth. This gradual reduction of the cutting force has a positive effect on the working conditions of the teeth of the calibrating part, and increases the accuracy and quality of the treated surfaces. In addition, the teeth of broaches designed to work according to the generator cutting scheme are easier to manufacture and sharpen. The disadvantage of the generator scheme is the large length of the cutting edge of the first teeth and its curvature, which makes it difficult to roll the chips out. The broach for the generator cutting scheme turns out to be very difficult to manufacture, because each tooth needs to be processed separately, therefore, it is not widely used for hole-processing.

With a profile cutting scheme, and a progressive cutting scheme, the broach teeth work outside the riveted layer, so the resistance of the broach increases and the roughness decreases.

At the beginning of the broaching process, after centering in the preliminary hole along the front guide, the first teeth of the broach start the operation, then the second ones follow, etc. Therefore, in the process of broaching, the cutting force changes abruptly due to a variable number of simultaneously working teeth (Fig. 1).

After a time t equal to the ratio of the cutting speed V and the pitch of the teeth q of the broach, there is a decrease in the number of simultaneously working teeth per one tooth, and the cutting force decreases. As a result, the stress-strain state of the technological system and vibrations change, increasing the roughness and accuracy of the geometric shape of the hole, as the resistance of the broach decreases (Taskarima A. et.al, 2016)

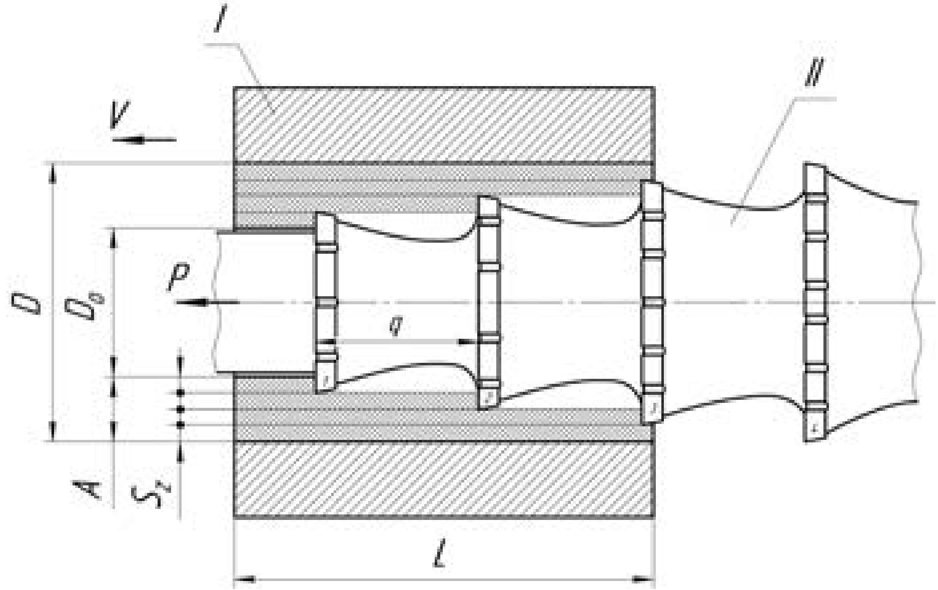

Figure 1. Diagram of the broaching process. I – part to be processed; II – tool; D – diameter of the hole to be processed; D_o –diameter of preliminary hole; A – side allowance; S_z – cut per tooth; P – broaching force; V – broaching speed; q – teeth pitch of broach; L – length of broaching; 1, 2, 3 and 4 – first and following teeth of broach.

Results and discussion. Broaches for processing round holes contain front and rear guides, a shank, a working part consisting of cutting and calibrating teeth separated by chip grooves of a curved V-shaped profile that go staggered-order when moving from one tooth to another. The chip-splitting grooves have a depth of 0.4...1.0 mm and a width of 0.6...1,2 mm depending on the diameter of the broach.

With a progressive cutting scheme, the cutting thickness is as follows: all cutting teeth are divided into groups or sections consisting of 2...5 teeth, so the teeth of one group have the same diameter. The thickness allowance is divided between groups of teeth, and width allowance is divided between the teeth of the group due to wide fillets placed in staggered order. Each tooth removes parts of the allowance by sections of the cutting edge. With an increase in the thickness of the cut to 0.3...0.4 mm when processing steel and to 1.0...1.2 mm when processing cast iron, a significant reduction in the length of the cutting part of the broach is possible. The feed to the tooth does not exceed 0.2...0.4 mm.

This broach ensures the processing of holes with an accuracy of 7...9th quality, and surface roughness of R_a up to 0.63...2.5 microns. The disadvantage of this broach is the increased complexity of its manufacturing process, as it contains a large number of elements that require precise processing such as chip grooves; low productivity and quality of the processed hole.

A broach for processing holes, authors Gaev I.V. and Khrolenko T.I. according to the patent USSR patent No. 1152794A, contains front and rear guides and with a working part consisting of cutting and calibrating teeth separated by chip grooves with a curved profile, and a shank. To increase the reliability and performance of broach, the curved profile of the grooves is made in hyperbolic contour.

The disadvantage is the of chip grooves that increase the complexity of its manufacture and the length of the broach, and consequently reduce the processing performance.

A broach for surface treatment, according to the USSR Patent No. 11712239A of author Mosina E.F. (1985), including a front guide, where a conical inlet part with longitudinal chip-splitting grooves and a cutting part with rough, finishing and calibrating teeth are made. The rough teeth are grouped into two sections with the same number of teeth, equal lift and diameters of the first teeth. The chip-splitting grooves coinciding in the direction with the chip-splitting grooves of the inlet part located on the same diameter and equal to them in width b, calculated as b =(0.8 ...1)l, where l is the length of the cutting edge of the tooth, are provided on the first section. The feed to the tooth does not exceed 0.2...0.4 mm.

The disadvantage is that when processing surfaces with this broach, the feed to the rough teeth does not exceed 0.2 ... 0.4 mm and the number of the teeth is the same for both sections, therefore the length of the broach increases reducing its productivity. There are also fluctuations that reduce the quality of processing (both roughness and deviation from a given geometric shape of the hole increase).

The improvement of cutting conditions, the roughness of the broached hole and the use of progressive designs made it possible to develop a two-stage progressive broach design for processing cylindrical holes (Application for the grant of a patent for an invention No. 2021/0436.1 of the Republic of Kazakhstan dated 15.07.2021). It allows increased processing productivity, reduced stretching and vibration forces and specific pressure on the teeth of the broach, thereby increasing the resistance of the broach and the quality of processed cylindrical holes (Fig. 2).

The broach processes round holes as follows: a two-stage progressive broach (Fig. 2) is installed in a prepared hole of the workpiece and fixed with the front shank 1 in the tool slide of the machine (not shown in Fig. 1) and moved with it relatively to the workpiece along the axis of the workpiece hole.

By means of a transition cone 3, the broach is self-centered and along the front guide 4, moving along the hole of the workpiece.

Cutting teeth z_1 of the first stage 5 along the generatrix of the processed hole cut through protrusions of a width b and diameters di_1, that gradually get increased by the amount of feed S_{z1} up to 0.3...0.6 mm. Therefore they cut the side allowance a_1 of the first stage. Then two pre-calibrating teeth with split straight-edge cutting protrusions 6 of the first stage pre-clean calibrate the split hole. The transitive part 7 provides a smoother transition from the first stage to the second stage and stabilizes the cutting process, and also serves as exit for the tool when milling and grinding the sides of the cutting protrusions.

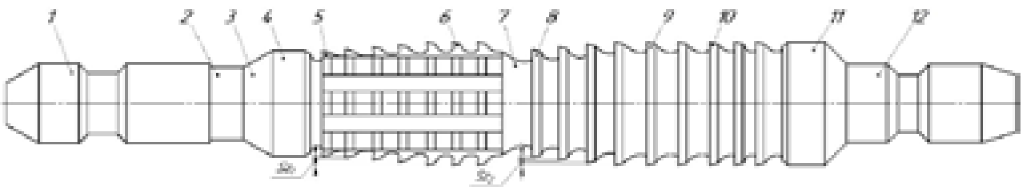

Figure 2. Two-stage progressive broaching. 1 – front shank; 2 – neck; 3 – transition cone; 4 – front guide; 5 – cutting teeth of split straight-edge cutting protrusions; 6 – two pre-calibrating teeth of the first stage; 7 – transitive part; 8 – round cutting teeth; 9 – two pre-calibrating teeth of the second stage; 10 – round calibrating teeth; 11 – rear guide; 12 – rear shank; S_{z1} – feed to the tooth at the first stage; S_{z2} – feed to the tooth at the second stage.

The diameters of the cutting teeth d_{i2} of z_2 at the second stage 8 gradually increase by the amount of S_{z2} up to 0.2. 0.4 mm cutting the side allowance a_2 of the second stage. The hole protrusions formed by the first stage get processed to the final dimensions of the designed hole, and two pre-calibrating round teeth of the second stage 9 pre-calibrate the processed hole.

Since the cutting 5 and calibrating teeth 6 of the first stage cut off the width allowance for the split protrusions, and the cutting 8 and calibrating teeth 9 of the second stage cut off the remaining protrusions in the hole, the chip deformation gets significantly reduced and the chips get rolled up. As a result, the cutting process is facilitated, providing a positive effect on reducing the roughness of the processed holes.

4...8 calibrating teeth 10 pieces (its number depends on the accuracy of the hole being processed) form the final shape and dimensions of the round hole.

The broach doesn't have a complex shape, since there are no chip-separating grooves on the round teeth of the second stage, therefore the complexity of its manufacturing process decreases.

The split broach has a tail part, front and rear guides and a cutting part that included chamfered, round and split teeth with split protrusions of a sectional structure, while the main split teeth are followed by a group of three to five additional split teeth, the split protrusions of which have lateral cutting edges (Utility model patent No. 71087 IPC B23D 43/00). This broach can't ensure achieving the required quality of processing.

A split broach for straight-line splits has front and rear shanks, front and rear guides, neck, transition cone, cutting part consisting of cutting (rough, transition and finishing teeth) and calibrating teeth. Each subsequent cutting tooth is higher than the previous one by a feed value in the range of 0.03...0.06 mm and has split chip grooves and the front and rear angles. The cutting of the allowance layer is carried out by a group of 2 teeth. The first split tooth cuts off part of the allowance in the middle of the processed groove. The second tooth is a stripping tooth, it forms the parts of the lateral surfaces of the rectangular groove. This broach ensures the 7...9th quality of processed holes and a surface roughness of $R_a \leq 2.5$ microns. The disadvantage of this split broach for straight-line splits is that when processing splits with a splits broach, each tooth along the length of the working part does not cut off the chips at the corners of the groove, but tears them off creating additional friction along the processed groove, and reducing roughness and increasing cutting forces.

Moreover, with broaches of this design the cut chips are cut from several surfaces of the grooves. It also worsens chips rollability and placement in the chip grooves. And because of the large shrinkage, the chips often jam in the grooves and degrades the treated surface and so R_a value doesn't exceed 5 microns.

The improvement of cutting conditions and the quality of the hole being processed, as well as the use of progressive designs, led to the development of a new more efficient metal-cutting tool: a two-stage split broach with a straight profile of the splits (Fig. 3).

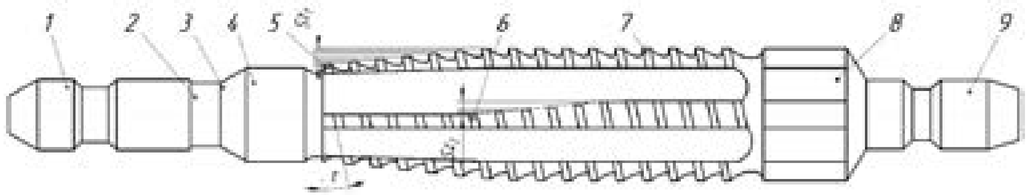

Fig. 3. Two-stage split broach. 1 – front shank; 2 – neck; 3 – transition cone; 4 – front guide; 5 – first stage of cutting part of broach with periphery-cutting (i.e. along outer diameter) teeth; 6 –second stage processing sides of splits; 7 – calibrating part; 8 – rear guide; 9 –rear shank; τ – angle of inclination; S_{z1} – feed to tooth at first stage; S_{z2} – feed to tooth at second stage.

A two-stage split broach with a straight profile of the splits has a front shank 1, a neck 2, a transition cone 3, front 4 and rear 8 guides, a calibrating part 7 and a rear shank 9. The cutting part is two-stage with an inclination angle τ of the cutting teeth up to 10° to the axis of the broach. The cutting teeth of the first stage 6 of a width b_1 gradually get bigger remaining within the scope S_{z1} = 0.3…0.6 mm of the splits protrusions relative to the diameter of the depressions d_i to the diameter of the split projections D_e. The cutting teeth of the second stage of a width of b_2 gradually get bigger within the scope S_{z2}= 0.3...0.6 mm relative to the width of the split projections b_0.

The proposed two-stage split broach with a straight profile of the splits is made with a two-stage cutting part with the cutting teeth inclined relative to the axis of the broach: the cutting teeth of the first stage gradually increase in height of the split projections and cut narrow grooves with a width equal to half the width of the split projections; the cutting teeth of the second stage gradually increase and expand the split grooves to the width of the split projections, thereby reducing the pulling force and ensuring high quality of the processed split hole.

A two-stage split broach with a straight profile of the split (Fig. 3) is inserted into a prepared hole of the workpiece, gets fixed with a front shank 1 in the tool slide of the machine (not shown in Fig. 3) and gets moved together with it along the axis of the hole relative to the workpiece.

By means of a transition cone 3, the broach gets self-centered along the front guide 4 moving along the hole of the workpiece.

The cutting teeth of the first stage 6 cut narrower grooves along the generatrix of the processed hole with a width b_1 equal to half the width of the split projections b, with a gradual feed to the tooth of S_{z1} = 0.3...0.6 mm in height from the diameter of the depressions d_i to the diameter of the split projections D_e. The cutting teeth of the second stage 7 expand the resulting grooves of width b_1 with their gradual increase by a value of S_{z2}=0.3…0.6 mm up to the value of the width of the split projections b_0.

Since the cutting teeth of the first 6 and second 7 stages cut off the less width of the split projections, the chip deformation is significantly reduced and the chips are rolled up. As a result, the cutting process is facilitated, so it has a beneficial effect on reducing the roughness of the sides of the split holes of the end product. Under the influence of the angle of inclination τ of the cutting edges to the broach axis, the chips cut and curled into rolls are forwarded to the base of the split protrusion of the tooth away from the lateral surface of the groove, thus protecting it from damage. The roughness of the surface of the sides of the grooves decreases to R_a=1.6 microns, at the same time increasing the roughness of the split grooves of the product in width and the accuracy of their placement relative to the axis of the hole, eliminating the need in additional processing of the product.

The calibrating teeth 8 form the final shape and dimensions of the split hole (Application for patent for invention No. 2021/0607.1 of the Republic of Kazakhstan dated 11.10.2021).

The use of two-stage split broaching with a straight profile of single-cut splits with peripheral and lateral cutting allows one to reduce the number of cutting teeth, the length of the broach and the cost of tool material and increase economic efficiency.

Conclusions. One of the main areas of mechanical engineering is metalworking. As an element of the technological system, the cutting tool plays a leading role in achieving the specified economic and technological indicators of the metalworking process.

Based on the analysis of scientific and technical literature, the designs of metal-cutting tools, namely broaches for cylindrical and slotted holes, are proposed and developed. Applications for the invention of the Republic of Kazakhstan have been submitted for these designs of broaches. At the same time, the accuracy of surface treatment with a quality of IT 7-8 and a roughness up to Ra 0.32 microns at a speed of 2–15 m per min usually.

Compared to other methods, productivity increases by 3-12 times. A very significant economic effect if the shapes of the treated surfaces and their sizes are normalized.

Broaches are made of high-speed steel R18 and tool alloy steel of the HVG brand.

The use of two-stage progressive broaching for processing cylindrical holes will increase processing productivity, reduce stretching and vibration forces, specific pressure on the teeth of the broach, the depth of the defective layer, thereby increasing its durability, the quality of processing cylindrical holes and physical and mechanical properties.

The use of two-stage split broaching with a straight profile of single-cut slots with peripheral and lateral cutting allows you to reduce the number of cutting teeth, the length of the broach and the cost of tool material and increase economic efficiency.

Thus, the use of the proposed broach designs improves the stress-strain state, increases processing productivity, reduces stretching and vibration forces, specific pressure on the teeth of the broach, and, consequently, increases the resistance of the broach, the quality of processing, savings of tool material and economic efficiency.

Financing. The research was carried out within the framework of grant funding for young scientists for 2021–2023 under the project IRN AP09058231 “Research and design of resource-energy-saving metal cutting tools”, funded by The Science Committee of the Ministry of education and science of the Republic of Kazakhstan.

Acknowledgments. The authors are grateful to A. Baltabekova, K. Assylova and G. Strautmanis (Sherniyazov M.A. et.al.2002) for preparing and collecting materials for this publication.

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ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Редакторы: *М.С. Ахметова, А. Ботанқызы, Д.С. Аленов, Р.Ж. Мрзабаева*
Верстка на компьютере *Г.Д.Жадыранова*

Подписано в печать 19.04.2022.
Формат 70x90$^{1}/_{16}$. Бумага офсетная. Печать – ризограф.
11,5 п.л. Тираж 300. Заказ 2.

Национальная академия наук РК
050010, Алматы, ул. Шевченко, 28, т. 272-13-19