

MODERNIZATION OF THE TECHNIQUE FOR ROTARY SHAPE-FORMATION OF OUTER PROFILED SURFACES

A. Vasyliiev

PhD, Associate Professor*

E-mail: 7331@i.ua

S. Popov

PhD, Associate Professor*

E-mail: psv26@i.ua

Ie. Vasyliiev

PhD, Associate Professor

Department of Construction Machinery and Equipment**

E-mail: vas.eugene@gmail.com

A. Shpylka

Senior Lecturer*

E-mail: anshpilka@gmail.com

V. Vovchenko

Teacher

Poltava Oil and Gas College of Poltava National

Technical Yuri Kondratyuk University

Hrushevskoho str., 2a, Poltava, Ukraine, 36021

E-mail: bnasva79@gmail.com

*Department of Manufacturing Engineering**

**Poltava National Technical

Yuri Kondratyuk University

Pershotravneviy ave., 24, Poltava,

Ukraine, 36011

Запропонований спосіб одержання зовнішніх профільних поверхонь, який характеризується широкою доступністю і незначною вартістю оснащення, яке використовується. Спосіб ґрунтується на тому, що звичайний обертовий центр закріплюється у різцетримачі токарного верстата особливим способом. У якості профілювальної матриці використовується звичайна голівка накидного ключа потрібного профілю. Обертанням різцетримача забезпечується кут зламу осі обертального центра відносно осі обертання заготовки. Значення кута зламу сягає $1,5^\circ$. Кромка торцевої поверхні матриці здійснює зворотньо-поступальний рух за кожен оберт патрона токарного верстата по поверхні заготовки. При цьому контакт торцевої поверхні матриці і заготовки відбувається в одній точці, заглиблюючись на величину подачі за кожен оберт патрона.

Використання даного способу є альтернативою існуючому способу ротаційного формування зовнішніх профільних поверхонь, для впровадження якого необхідне спеціалізоване оснащення і спеціалізований різальний інструмент, вартість якого дуже значна (відповідно 2035 і 215 у. е.). Крім того, зміна розмірів або форми потрібного профілю потребує встановлення нового різального інструменту, при заміні якого необхідне додаткове налагодження.

Випробування здійснювалися при виготовленні дванадцятигранної зовнішньої поверхні розміром S10. Аналізом віброграм процесу формування визначений найбільш раціональний варіант оснастки для виготовлення профільних зовнішніх поверхонь. Проведені пробні виготовлення зовнішніх профільних поверхонь, таких як шестигранна розміром S10, поверхня TORX розміром E14 та інші. Ці випробування підтвердили успішну можливість виготовлення різних профільних зовнішніх поверхонь з використанням запропонованої оснастки.

Використання запропонованого способу, який має незначну вартість і не потребує наявності спеціалізованого оснащення, дозволить розширити галузь використання спряжених поверхонь профільної форми у машинобудуванні

Ключові слова: профільні зовнішні поверхні, обертовий центр, ротаційне прошивання, торцева голівка

1. Introduction

When constructing new machines, in addition to cylindrical, more and more widespread are the profile connections: joining the parts of machines along the surface of their mutual contact, which has a smooth non-circular contour [1]. The profile connections are reliable, though technologically complex as they require specialized equipment [2], which limits the scope of application for this type of connections. However, such connections are increasingly popular in the medical, aerospace, automotive, and plumbing industries; almost every manufacturer proposes, accordingly, its original, new and advanced shapes of profiled surfaces [3]. In order to maintain or repair the joints of parts of these connections, a traditional technique in manufacturing is milling, chiseling, or broaching. However, the specified techniques are not al-

ways applicable under conditions of small-scale production, or require specialized equipment.

The object of research is the process of fabricating profiled surfaces on parts of machines using the rotational shape-formation [4, 5]. The profiled surfaces are made on machine tools of the turning group. A shape-forming technique implies that a workpiece is mounted in a holder at a machine tool and the shape-forming tool rotates freely with its axis not coinciding with the axis of the workpiece.

The process can occur using drilling machines, but a workpiece in this case is fixed, while the mandrel that holds a tool rotates. It is possible to significantly extend the range of application of a given process if the cutting tools, a matrix, are the spanner wrench socket heads. The range of socket heads is very wide both in terms of a profile shape and their size, while their mechanical properties are almost identical to

actual cutting tools. Applying socket heads as matrices in order to form the shape of outer profiled surfaces would significantly reduce the cost of manufacturing process. The largest share of cost for technological equipment is taken by a rotary head, which we propose should be replaced with a standard rotating center, mounted using a specialized technique.

In order to improve the process of shape-formation of the profiled surfaces, we performed a technological audit, aimed at determining the typical shortcomings in existing techniques for the shape-formation of the profiled surfaces applying the specified technique. One of the most problematic areas within this technological process is that its implementation requires specialized equipment, as well as specialized cutting tools, which is very expensive (2,035 and 215). The high price of the equipment does not make it possible to implement the process due to its economic inexpediency, which significantly slows down the industrial implementation of such an innovation as the profiled connections in mechanical engineering.

That explains why the specified technology is not commonly employed, and the scope of its application is limited. In addition, changing the size or shape of a profile requires the introduction of new cutting tools, and the installation of the new cutting tools, that are different in size, would require additional adjustment.

2. Literature review and problem statement

We can consider such an alternative to specialized equipment as a broaching head, which was proposed for machining the through and blind shaped holes in parts at the drilling and milling machines, which was suggested by domestic scientists in 1968 [6]. The device includes (Fig. 1) casing 6 to which, by means of screws, a flange with shank 5 is tightly attached. The inner hole of casing 6 is made at angle $\alpha=1-2^\circ$ to the axis of shank 5; mandrel 7, on shafts 2 and 3, is mounted into the hole of the casing. Cutting tool 1 is held in mandrel 7 so that it could ensure the convergence between a plane of the cutting edge and the point of intersection of axes, which is at distance l from the bottom end of mandrel 7.

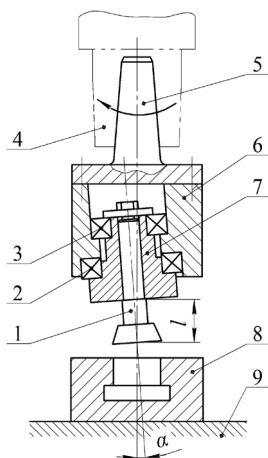


Fig. 1. Broaching head for machining the shaped holes

Machined part 8 with a pre-machined opening is placed on table 9 of the drilling machine. Cutting tool 1 is fed to part 8. Casing 6, through shank 5, is set into rotary motion and feed motion, while mandrel 7, together with cutting tool 1, when touching workpiece 8, does not rotate. Cutting tool 1 is ro-

tated on shafts 2 and 3 relative to casing 6, thereby executing circular oscillatory movements around the axis of workpiece 8.

Points at the cutting edge of the tool perform reciprocating movements per each turn of the spindle, with the contact between a cutting tool and the machined workpiece occurring in one point, which moves along a closed contour of the shaped hole, going deeper by the magnitude of feed per every turn of spindle 4.

The above design of the broaching head had not become widespread due to a series of shortcomings. Design of the broaching head is quite complicated and its fabrication can be carried out only at specialized machine-building enterprises. Cutting tools to the specified head should possess good cutting properties and particularly individual in terms of size that relates to the size of the required profiled surface. When replacing a cutting tool, the entire structure of the broaching head requires preliminary adjustment.

The same principle of rotary broaching was used when constructing the broaching heads [7]. The operation is performed at machine tools from the turning or drilling groups applying the appropriate equipment – broaching heads and broaches as tools [8, 9]. Fig. 2 shows broaching rotary heads made by different manufacturers, as well as broaches that are fixed in broaching heads depending on the required profile.

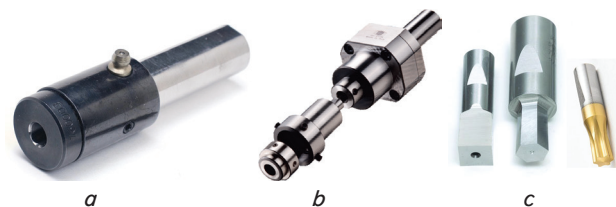


Fig. 2. Physical appearance of broaching heads by different manufacturers, and broaches: *a* – Slater Tools (United States of America); *b* – Brighetti Meccanica (Italy); *c* – broaches for making holes, respectively, rectangle-shaped, hexahedron-shaped, TORX

In terms of design, broaching heads made by different manufacturers differ only in their physical appearance. These tools almost do not differ in their structure, as they are based on the same principle of work [10, 11], which implies tilting the axis of the inner spindle relative to the axis of a workpiece rotation. The spindle holds the tool at a small angle to the axis of a broaching head (Fig. 3, *a*). In most cases, the tilting angle accepts a value of up to 2 degrees.

The spindle rotates freely inside a broaching head and is set into motion by a contact with a rotating workpiece. Thus, while rotating, pressure on each corner of the broach changes constantly. This forms the principle of rotary broaching at the time when the broach, fixed in a broaching head, is simultaneously fed through the workpiece to the required depth. The shaped holes are broached at a frequency of the workpiece rotation to 1.200 rpm; the broaching process takes approximately 10–15 seconds.

The process of broaching is possible at continuously rigidly maintaining the axis of the cross-section of the front surface of a broach at the workpiece rotation axis while executing a «wobble swaying» relative to the axis of a workpiece rotation. This type of movement of the broach can be enabled by a rather sophisticated mechanism, whose assembly drawing for broaching heads manufactured by Slater Tools [12] is shown in Fig. 3, *b*.

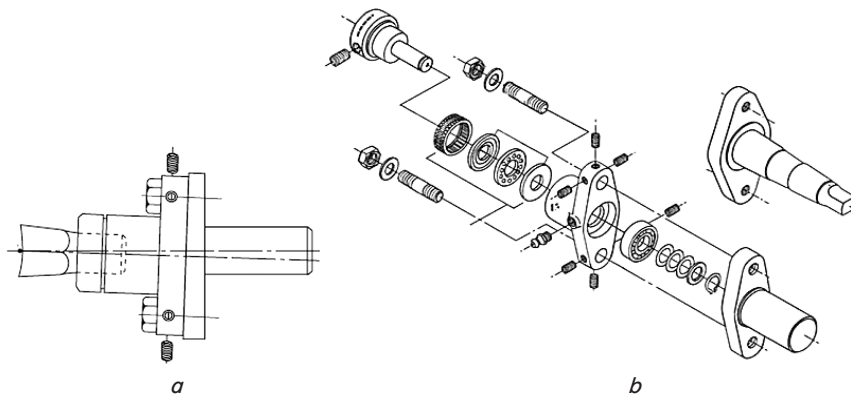


Fig. 3. Structure of the broaching head manufactured by Slater Tools: *a* – principle of operation; *b* – assembly drawing

In addition, the mechanism of a broaching head makes it possible to preliminary adjust it by regulating a match between the axis of the cross-section of the front surface of the broach and the axis of head rotation. Adjustment is performed when changing a broach whose linear size is different from the size of the pre-installed one.

Making outer profiled surfaces, in order to reduce the cost, employs a regular broaching head for producing internal profiled holes. An additional adapter is mounted onto a broaching head, and the adapter holds a matrix for broaching the outer profiled surfaces (Fig. 4).



Fig. 4. Broaching head for making outer profiled surfaces manufactured by Brighetti Meccanica: *a* – equipped with an adapter and a matrix; *b* – broaching head assembly

The specified broaching heads [13] are available in Ukraine as well, for example, at the internet site Prom.ua, in section Brighetti Meccanica. TOV «PROGRESPOSTACH», the city of Dnipro, offers «Broaching head BR-G16L KM4» priced at y. o. 2,035 [14], and «Broach GL 16-E-8» priced at y. o. 215 [15], which is very expensive.

The examined broaching heads, shown in Fig. 2, 3, are different from the head in Fig. 1 only by the improved technological and operational properties, namely the ease of replacing a cutting tool, a simplified procedure for adjustment after replacing the tool, as well as compactness. However, the specified improvements were achieved at the expense of further complexity in the design of the head itself. A possibility for the customized fabrication of a broaching head is out of the question at all. Cutting tools are no longer a unit of production, they are produced in batches, which made it possible to improve their quality and reduce cost. However, the achieved price of the implementation is significant; more to the point, it does not contribute to the machine-building production at industrial scale.

3. The aim and objectives of the study

The aim of this study is to propose a technique to form the shape of outer profiled surfaces under conditions of small-scale or individual production of a wide range of shapes typical for operational maintenance or repair of machines' components.

To accomplish the aim, the following tasks have been set:

- to propose using the matrices, which are a tool for the outer fabrication of profiled surface, based on standard products whose properties are characterized by appropriate mechanical characteristics, low cost, and which are widespread;
- to determine the degree of sharpening a working edge of the matrix as a tool for the outer fabrication of profiled surfaces, in order to rationally improve mechanical properties of the obtained workpiece;
- to determine the suitability of working edges of the matrix as a tool for the outer fabrication of profiled surfaces, following the process of forming the shape of a profiled surface at a workpiece, and to propose ways to improve the operational resource of the matrix;
- to perform experimental tests using the recordings of vibrograms for the process of making outer profiled surfaces in order to define a technique that would ensure the required quality of the surface at minimal preliminary adjustment of equipment.

4. Materials and methods to study the shape formation of outer profiled surfaces

Based on the previously considered designs of broaching heads [16], we propose a greatly simplified structure of broaching equipment (Fig. 5, *a, b*), which exploits a standard rotating center as the primary node.

We shall consider a technique for making profiled holes in Fig. 5, *a*. Workpiece 2 is clamped in chuck 1 of the lathe; it is preliminary machined to the specified size. Standard rotating center 5 is fixed in the tool holder of a lathe using transition bushing 6 of a Morse cone. A plate in the form of a lug is welded to the bushing. Owing to the plate, the bushing is clamped in tool holder 8. One end of matrix 3 of the required profile is placed at the pre-machined surface of a workpiece; bushing 4 is pressed into matrix 3 with a slight pull. Bushing 4 has a centered hole at the other end, through which it is pressed by the cone of rotating center 5 against the machined workpiece. A change in the position of the tool holder

is enabled by the displacement of transversal support 7. The tool holder rotation in the direction of angle β ensures a fracture angle of the axis of the rotating center α relative to the rotation axis of the workpiece's hole. Fig. 5 shows the intentionally enlarged fracture angle α in order to elucidate the process. The value for fracture angle α reaches 2° .

A technique for making shaped holes in Fig. 5, *b* differs in that bushing 4, onto which matrix 3 is mounted with a pull, is also installed with a pull in rotating center 5, ensuring the alignment of matrix's rotation axis relative to the axis of center 6. The centering does not exist, which is why, prior to operation, it is required to fine-tune the match between the axis of matrix 3 and the axis of workpiece 2. Adjustment is performed by changing and adding spacers when the lug of bushing 6 is clamped in tool holder 7. It was established by comparing the structure of the broaching head, shown in Fig. 3, which consists of more than 40 parts and nodes, that the proposed technique for making profiled surfaces employs 8 parts and nodes.

It is proposed to use the socket heads of wrench spanners as the matrix. Socket heads are widely used in the repair and maintenance of many nodes and elements in machines. This type of tool is mostly required in the process of repairing a car. The main advantages of socket heads over other types of manual tools is the possibility to use them in hard-to-reach places, as well as the application of the maximum effort to connections.

The most common type of a profile is hexagonal. Also found are the twelve-point socket heads, which are characterized by a more comfortable arrangement on the mounting. Given the popularity of imported equipment, the caps with new types of profile have been popular. Certain types of the profile are shown in Fig. 6.

In addition, socket heads are divided into those for general purposes and the impact heads (Fig. 7). Those for general purposes are used for operations involving a mechanical tool. Such heads are made of chrome-vanadium steel, they have a mirror chrome plating and demonstrate optimal wear resistance. The impact heads are designed for use with motorized actuators and have enhanced mechanical strength. These heads are made of chrome-molybdenum phosphate steel, they are characterized by the presence of holes for a safety pin and a circular duct for the locking ring.

In our research, we shall use socket heads for general purposes since they are more common. Application of the impact heads will ensure a better result because the values for hardness of working surfaces of heads for general purposes, and the impact ones, are, respectively, HRC 38...42 and HRC 42...48.

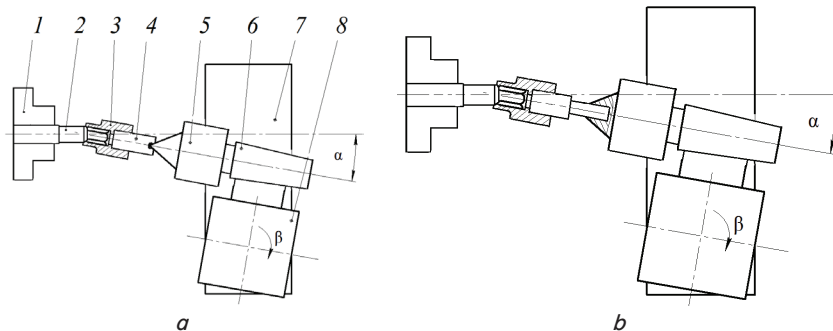


Fig. 5. Variants for making the shaped holes at machine tools of the turning group using rotary shape formation: *a* – a matrix is self-installed; *b* – a matrix is rigidly fixed in the rear center

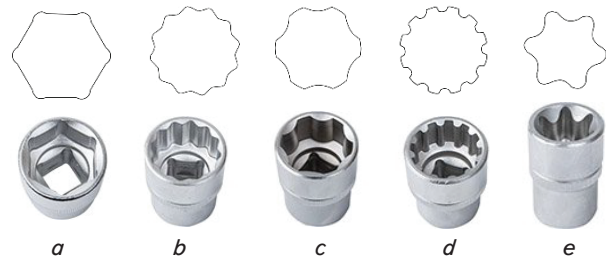


Fig. 6. Certain types of the profile of socket heads: *a* – hexagonal; *b* – twelve-point; *c* – SL (Superlock, Surface) for fractured edges; *d* – universal (for different types of profiles, including inch-based); *e* – TORX (E-heads)



Fig. 7. Physical appearance of heads: *a* – for general purposes; *b* – impact

The process of profile formation, by analogy with work of the broaching heads manufactured by foreign producers, Slater Tools and Brighetti Meccanica, implies the use of a cutting tool with pointed cutting edges (Fig. 3, *a*) with a taper angle in the range of $60-70^\circ$. The specified taper angle can be implemented by using socket heads. Socket heads that are produced to standard have an angle of the profile's working plane edge within $110-120^\circ$ (Fig. 7, *a*). Machining a socket head at the lathe enables the sharpening of angle of the profile's working surface edge at any magnitude. In this research, we used a taper angle of 65° . Note that socket heads were sharpened exclusively by cutters with carbide inserts. We observed the enhanced hardness of heads' working surfaces in the specified range HRC 38...42. In addition, there remained burrs at the edges of working surfaces of a socket head, which required additional efforts for their elimination.

The process of forming the profiled surfaces, in addition, employed socket heads without post-machining the edge of a working surface. It is assumed that the edge of a socket head, which has an angle of the profile's working surface edge in the range of $110-120^\circ$, would form the required profile by cold plastic deformation rather than remove excessive metal by a sharp cutting edge. We shall consider this acceptable, at least in two aspects. First, the process of broaching the profiled surfaces with the removal of unnecessary material will be replaced by the process of plastic deformation, which is characterized by the improved mechanical properties with the result being an increase in the endurance limit for the metal of the produced profiled surface of a workpiece by 30%. Second,

socket heads with the required shaped profile prior to the shape-forming process will not require additional machining, which is difficult both due to a significant strength of heads themselves and the necessity of removing sags after turning, in order to re-sharpen cutting edges.

5. Results of research into shape-formation of outer profiled surfaces

We have tested two techniques for making profiled outer surfaces with self- installation and when the head is rigidly fixed in the rear center (Fig. 8). The tests were carried out at the lathe 1I611P, the end twelve-point head 10 is manufactured by STANLEY. The socket head was initially used without preliminary sharpening at the angle of the profile's working plane edge within 110–120°, and afterwards – at a taper angle of 65°. The following parameters were applied in the course of research: a fracture angle of the rotation axis $\alpha=1.5^\circ$; rotation frequency, 800 rpm; feed, 0.1 mm/rev. The force of longitudinal feed was not enough, which is why we pressed using the rear center of the lathe.

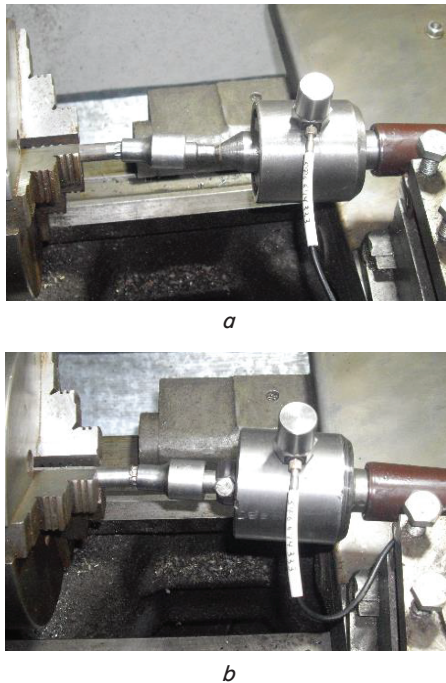


Fig. 8. Technique for obtaining outer profiled surfaces using a socket head, which is: *a* – freely installed between a workpiece and the sharpening of the rotating center; *b* – rigidly fixed in the rotating center

Testing a socket head without modification, with a working edge angle in the range of 110–120°, yielded a good result for both techniques (Fig. 8). The second technique required a more precise adjustment, while the obtained result was close to that from the first technique.

Testing a socket head after its additional modification to a taper angle of 65° did not work out for the first technique at all. The second technique confirmed the efficiency of the design only after precise adjustment. It required both the alignment of a workpiece rotation axis with the profile center of the socket head's cutting edges and the absence of a backlash throughout the entire structure. Application of

the socket head with a taper angle of 65° proved to be impractical during further tests.

In order to identify causes of the process of rotational shape-formation in line with the first and second techniques, we recorded a series of vibrograms. We used the vibrosensor DN-3-M1, which was attached via pin M4 to the oiling hole of the rotating center. A signal from the vibrosensor was converted by the vibrometer VVM-201, it was then registered by the USB oscillograph IRIS.

An analysis of the vibrograms (Fig. 9, *a, b*) reveals that the first technique results in a stable process of profiling the outer surfaces while the second, in addition to the specified, proceeds with separate dynamic jerks. Numerical values for vibro-accelerations amounted to, respectively, 2.4 and 3.3 m/s², indicating that the first technique is more stable than the second. It was determined that separate dynamic jerks were triggered by the console technique for fixing the equipment and a possible presence of gaps in some sections. The repeated observation of links' components in the technique implying rigid fixation pointed to the presence of significant radial efforts in connections, which led to the weakening of the previous pull. Thus, the variant for a rigid fixation is suitable for application, but happens to be impractical in comparison with the first technique.

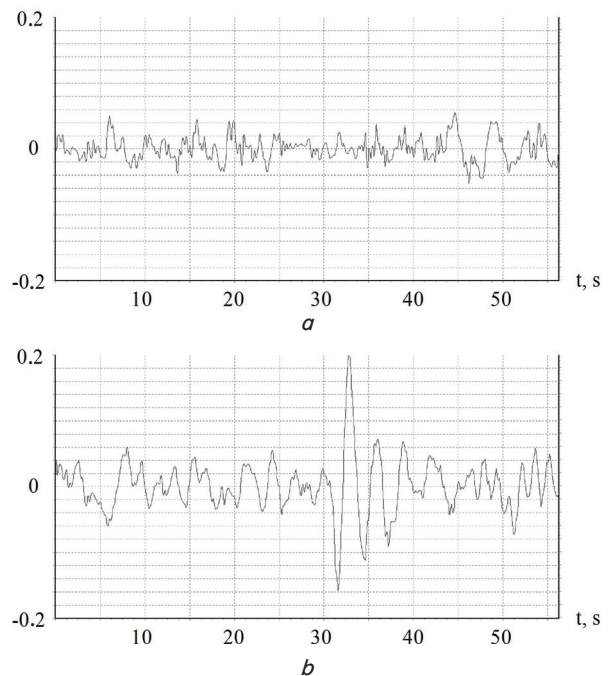


Fig. 9. Vibrograms of the process of shape-formation of outer profiled surfaces using a socket head, which is: *a* – freely installed between a workpiece and the sharpening of the rotating center; *b* – rigidly fixed in the rotating center

Fig. 10, *a* shows the received profiled twelve-point surface S10. We have used a technique when a socket head is freely installed between a workpiece and the sharpening of the rotating center. Upon fabrication, the resulting profiled surface is smaller in size than the dimensions of the socket head, which was involved in the production. This is caused by a fracture angle between the axis of the received profiled surface and the axis of the socket head. At a fracture angle of 1.5° the radial gap is 0.2 mm. That makes it possible to freely, without a pull, to mount a wrench on the surface. The state of the socket head after a series of production cycles testifies

to the lack of destruction traces, especially when the lubrication of conjugated surfaces was used.

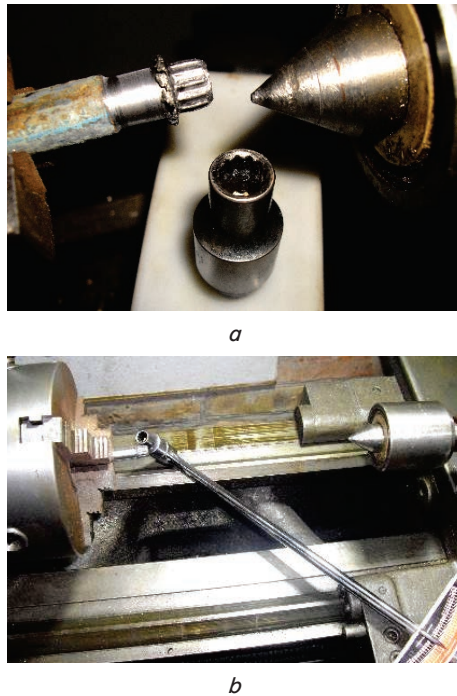


Fig. 10. The result of shape-formation of the twelve-point outer profiled surface S10: *a* – obtained surface and state of the socket head; *b* – test for strength using a torque indicating wrench

Fig. 10, *b* shows the test of the received surface S10 for destruction. The destruction occurred in a place where the core contacts a socket head in the form of twisting the core itself at a torque of 32.2 N·m. Despite the presence of a small radial gap between the wrench and the resulting surface, the circular backlash of the wrench was negligible, the faces were not damaged.

Fig. 11 shows the obtained outer profiled surface and the state of socket heads after making other profiled surfaces, specifically the hexagonal surface S10 and the surface TORX E14.

The profiled surfaces, shown in Fig. 11, indicate the assigned geometrical shape without defects and drawbacks. Working edges of the socket heads show no wear or jamming after repeated tests. The test results confirm the possibility of making the outer profiled surface applying the proposed technique.

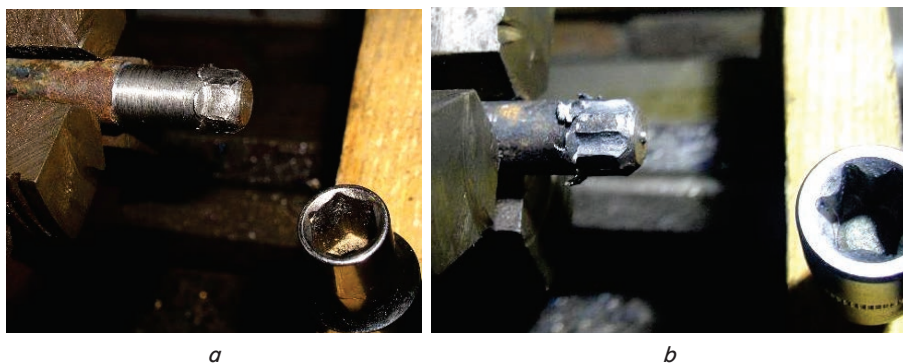


Fig. 11. The obtained outer profiled surfaces and the state of socket heads after production: *a* – hexagonal S10; *b* – TORX E14

6. Discussion of results of the shape-formation of outer profiled surfaces

The strengths of this work worth noting include the possibility to implement a technology for manufacturing outer profiled surfaces at any enterprise that has a lathe. All other equipment is always present at the workplace of a turner: a rotating center and reducing bushings for Morse cones. The shape-forming matrix to be used is a socket head of the required profile, which is also common. The proposed technique should be used in small-scale manufacturing, where the acquisition of specialized equipment, a rotary head and a broach, which are expensive, is not economically feasible. In addition, the technique to form the shape of a profiled surface is accompanied by the plastic deformation of a workpiece's metal, which improves its mechanical properties.

A weakness of the study performed is that the proposed technology is suitable for the manufacture of a small number of articles, up to 30–50 workpieces. It is not possible to produce a large number of profiled surfaces using the same tool, because the hardness of working edges of socket heads does not make it possible.

A promising direction in the improvement of quality of the profiled surface, obtained when applying the proposed technique, is to undertake a research using, as a shape-forming matrix, the impact socket heads together with a lubricating-cooling liquid. Such a comprehensive application of the specified measures would make it possible to considerably increase both the resistance of the matrix's edges and the performance efficiency of the process.

Difficulties in the implementation of the proposed technology are due to the wear of existing CNC machine tools, namely the presence of a radial run-out at a cam holder, which affects the quality of operation for the shape-formation of profiled surfaces. Application of the more precise metal-cutting equipment implies a substantial increase in costs, as it would involve the modernization of existing equipment.

7. Conclusions

1. It has been proven that it is advisable to use, as a matrix for the external production of profiled surfaces, the wrench socket heads, whose profile coincides with the required profile for production. We conducted this study applying socket heads for general purposes, whose working surfaces' hardness is HRC 38...42. Application of impact socket heads ensures the best result; hardness is HRC 42...48.

2. Socket heads were not additionally modified prior to the process of shape-formation; their working edges were not sharpened, it ensured the process of cold plastic deformation of the surface and made it possible to improve mechanical properties of the obtained workpiece. The resulting profiled surface S10 was destroyed in a place where the core contacts a socket head in the form of twisting the core itself at a torque of 32.2 N·m.

3. An analysis of working edges of socket heads following the

process of making the profiled surfaces has revealed the absence of wear, dents, and damage. It is mandatory that working edges of socket heads should be lubricated in the process of shape-formation.

4. By conducting experimental tests using the recording of vibrograms in the process of profile formation of outer surfaces, we have substantiated a technique that ensures the

required surface quality. Numerical values for vibro-accelerations when using this technique were 2.4 m/s^2 in contrast to another one, 3.3 m/s^2 , indicating that a given technique is more balanced and less energy-intensive than another one. Our technique is characterized by minimal previous adjustment of equipment without changing the design of the rotating center.

References

1. Broaching of Ti-6-4 – Detection of Workpiece Surface Anomalies on Dovetail Slots through Process Monitoring / Axinte D., Boud F., Penny J., Gindy N., Williams D. J. // *CIRP Annals*. 2005. Vol. 54, Issue 1. P. 87–90. doi: [https://doi.org/10.1016/S0007-8506\(07\)60056-0](https://doi.org/10.1016/S0007-8506(07)60056-0)
2. Broaching Performance of Superalloy GH4169 Based on FEM / Kong X., Li B., Jin Z., Geng W. // *Journal of Materials Science & Technology*. 2011. Vol. 27, Issue 12. P. 1178–1184. doi: [https://doi.org/10.1016/S1005-0302\(12\)60015-2](https://doi.org/10.1016/S1005-0302(12)60015-2)
3. Vasylyev A. V. Popov S. V., Datsenko V. D. Development of the construction of the cut-off blade from circular saws // *Technology audit and production reserves*. 2015. Vol. 3, Issue 1 (23). P. 60–64. doi: <https://doi.org/10.15587/2312-8372.2015.44396>
4. Klocke F., Döbbeler B., Seimann M. Dry Broaching Using Carbon Free Steel as Tool Material // *Procedia CIRP*. 2016. Vol. 46. P. 496–499. doi: <https://doi.org/10.1016/j.procir.2016.04.076>
5. Hard Broaching of Case Hardened SAE 5120 / Meier H., Ninomiya K., Dornfeld D., Schulze V. // *Procedia CIRP*. 2014. Vol. 14. P. 60–65. doi: <https://doi.org/10.1016/j.procir.2014.03.074>
6. Instrument i tekhnologicheskaya osnastka dlya slesarey / Albanskiy P. P., Kolominov B. V., Kuz'min V. A., Murav'ev V. I., Rodin I. I., Sysoev A. M., Harchenko K. S. Moscow: Mashinostroenie, 1969. 200 p.
7. Improving the method of rotational broaching in the production of profile openings on the lathes of turning group / Vasilyev A., Popov S., Vasilyev E., Pavelieva A. // *Eastern-European Journal of Enterprise Technologies*. 2017. Vol. 1, Issue 1 (85). P. 4–9. doi: <https://doi.org/10.15587/1729-4061.2017.92256>
8. Hiegemann L., Weddeling C., Tekkaya A. E. Analytical contact pressure model for predicting roughness of ball burnished surfaces // *Journal of Materials Processing Technology*. 2016. Vol. 232. P. 63–77. doi: <https://doi.org/10.1016/j.jmatprotec.2016.01.024>
9. Kuznetsov V. P., Tarasov S. Y., Dmitriev A. I. Nanostructuring burnishing and subsurface shear instability // *Journal of Materials Processing Technology*. 2015. Vol. 217. P. 327–335. doi: <https://doi.org/10.1016/j.jmatprotec.2014.11.023>
10. Simulation Approach for the Prediction of Surface Deviations Caused by Process-Machine-Interaction During Broaching / Schulze V., Zanger F., Krauß M., Boev N. // *Procedia CIRP*. 2013. Vol. 8. P. 252–257. doi: <https://doi.org/10.1016/j.procir.2013.06.098>
11. Korzynski M., Zarski T. Slide diamond burnishing influence on of surface stereometric structure of an AZ91 alloy // *Surface and Coatings Technology*. 2016. Vol. 307. P. 590–595. doi: <https://doi.org/10.1016/j.surfcoat.2016.09.045>
12. Rotary broach tooling. URL: <http://www.slatertools.com/>
13. Complete broaching solutions. URL: <http://www.brighttbroaching.com/>
14. Proshivnaya golovka BR-G16L KM4. URL: <https://dp.prom.ua/p599335846-proshivnaya-golovka-g16l;all.html>
15. Proshivka GL 16-E-8. URL: <https://dp.prom.ua/p599348099-proshivka;all.html>
16. Schroeter R. B., Bastos C. M., Crichigno Filho J. M. Simulation of the main cutting force in Crankshaft turn broaching // *International Journal of Machine Tools and Manufacture*. 2007. Vol. 47, Issue 12-13. P. 1884–1892. doi: <https://doi.org/10.1016/j.ijmactools.2007.03.008>