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INCREASING THE RESOURCE OF MILLING CUTTERS USED TO PROCESS THE LOCOMOTIVE WHEELSETS. PART 2: STUDY OF STRESSED-DEFORMED STATE

Summary. The article deals with the stress-strain state of the cutters used in the mills of a new design for the restoration of the working surfaces of locomotive wheels. A comparative analysis of stresses in the cutters was carried out using the finite element method, which showed a significant advantage of the new technical solution, the novelty of which is confirmed by the patent.

1. INTRODUCTION. EXISTING TECHNOLOGIES FOR RECONSTRUCTIVE REPAIR OF LOCOMOTIVE WHEELSETS

During the operation of the locomotives of the main and industrial railway transport, the need to restore the worn profile of the wheels without wheelsets dismantling periodically arises. The latter operation is very time consuming and can only be used during scheduled major repairs. At the same time, current repairs, which often include the operation of wheelsets processing, are made quite often. It depends on the operating conditions of the locomotives. Their work in areas with a large number of curves, for example, in mountainous terrain, increases the wear of the wheels, especially in the flange area. Another factor that may lead to the need for immediate restoration work is emergency braking, which leads to the formation of flats on the working surfaces of the wheels and should be immediately eliminated. There are also a number of other defects that require repair of wheelsets.

Currently, there are two main technologies for the restoration of locomotive wheelsets - these are wheel-turning and wheel-milling. In most European countries, underground wheel-turning machines are used for this operation. Examples of such equipment are U2000-150D and U2000-400 machines from Hegenscheidt-MFD (Germany) [1] or UGE 180 N, UGE 300 N, and UGE 400 N from RAFAMET S.A. (Poland) [2]. The difference between these machines is primarily in the axial load of the processed locomotives. It is quite obvious that for the efficient operation of locomotives, it is necessary that the time of forced downtime associated with their repair should be as short as possible. It is not surprising, therefore, that the aforementioned companies offer new technical solutions that allow you to simultaneously process two wheelsets that are not mechanically connected to each other, for example, the design of machines like Tandem 2 UGE 300 N, 2 UGE 400 N (RAFAMET), or U2000-400D (Hegenscheidt). The latter company even developed a version of the machine that allows you to process simultaneously 2 biaxial bogies U2000-400Q.

Wheel milling is an alternative solution that was developed in the USA, and currently machines from Simmons Machine Tool Corporation, for example, TN-84C [3], are widely used. Nevertheless, this technology was most widely used in the countries of the former USSR owing to the products of

the KZTS plant (Kramatorsk, Ukraine) [4]. This plant was a monopolist and for many years produced machines of the KJ20 type and their modifications KJ20B, KJ20MKh, KJ20M, KJ20vf1, KJ20tf1, and KJ20tf3. The production of this equipment continues at present, despite the fact that other manufacturers are trying to organize the production of similar products or to carry out its overhaul, for example, the company LLC “SLAVERS” (St. Petersburg, Russia) [5] or LLC “TSS–TyazhStankoServis” (Kramatorsk, Ukraine) [6].

Comparison of the aforementioned technological processes for locomotive wheelsets processing shows that, unfortunately, there are no fundamental changes in wheel milling technology yet. In contrast to the wheel-turning technology, which already allows to process several wheelsets at the same time, which can significantly speed up the process of restoration repair, there are no wheel-milling machines that process several wheelsets at the same time. In this case, each new technical solution, which is aimed at improving the latest technology, should be highly appreciated. For example, in the article by Kushner et al. [7], it was proposed to change the design of the cutter, replacing cylindrical cutters with standard cutting inserts with six straight cutting edges. Such a cutting element of the mill should be used in principle for machining the rolling surface and chamfering the working surface of the wheel. Unfortunately, so far this idea has not found its wide application, and, as before, mills with 10 tool holders (knives) are used everywhere in the countries of the former USSR, in which about 130 cylindrical cutters are installed. The exact number of cutters depends on the purpose of the cutter, i.e. for processing on which profile of the working surface this or that mill is designed.

2. STATEMENT OF THE PROBLEM OF DETERMINING THE STRESSED STATE OF HARD-ALLOY CUTTERS

Traditionally, the bottleneck of wheel-milling technology is the main tool with which the working surfaces of the wheels are processed, i.e. profile mills. The first part of the article by Śładkowski et al. [8] described the problems that arise during the operation of this equipment. It is especially difficult to process wheelsets that have defects such as flats or hardening. This leads to the formation of irregular very hard sections of the working surface, the cutting of which can lead to chips of hard-alloy cutters. In Fig. 1 shows a cutter practically destroyed.



Fig. 1. Defective hard-alloy cutter rejected during operation of the mill to the KJ20 machine

The danger of such defects of cutters lies in the fact that their destruction can also lead to damage to toolholders (knives), which after that may either not be repaired, or their repair can be unreasonably expensive. Thus, the mills during operation must be constantly monitored, replace defective cutters,

periodically rotate them in the seat, and regularly adjust the mills itself so that deviations from the given profile of the working surface of the wheels are within tolerance.

Thus, it is obvious that in order to increase the overall performance and operational reliability of mills for the KZh20 machine of various modifications, it is necessary to reduce the cutting force acting on each hard-alloy cutter. In the article by Śładkowski et al. [8], as a possible solution, the use of a new design of the mill was proposed, where instead of 10 toolholders, 14 are used. As a result, the number of cutters increases from 130 to 182, and the load on each cutter decreases. At the same time, the thickness of the metal layer cut by each cutter decreases. This design has been patented [9]. The forces acting on a single cutter during the processing of wheelsets are experimentally determined.

Note that in the modeling the technological process of metal cutting was made by different authors. As an example, a dissertation can be cited [10]. Moreover, the size of the cutting surface depends on the depth of deepening by mill into the machined wheel. This depth is limited by the design of the toolholder, as if the insertion is erroneously excessively deep, contact occurs between the machined surface of the wheel and the base metal of the toolholder with its subsequent damage. Accordingly, the wheels should not be machined at a depth of incision of the cutters on the main surface of the profile, which exceeds 0.7 mm, in order to protect the toolholders from enveloping the metal and their further damage. The size of the cutting surface also depends on the distance between successively working cutters. The higher the frequency of arrangement of such cutters, the less the surface will be under consideration. Due to the fact that for different profiles of the working surfaces of the wheels in their different sections, the frequency of installation of the cutters is significantly different, respectively, the surface of the cut metal in the flange fillet area or in the central part of the profile will be different.

Thus, to answer the question of how the design will affect the performance and operational reliability of mills, which is the subject of this article, it is necessary to determine the stress-strain state of individual cutters during operation for mills of various designs.

3. GEOMETRIC MODELING

Creating a solid model of a cylindrical cutter does not cause any additional difficulties. It is created using standard operations of rotation and drawing out flat figures with subsequent logical subtraction operations to create a profile hole. Fig. 2 shows two solid-state cutters that are used in mills of a generally accepted design (with 10 tool holders) and a reduced height cutter for a mill of the proposed design.

A much more difficult task is the geometric modeling of the cutting process. For this purpose, a solid model of the entire mill, as well as a locomotive bandage, must be created. This was done using AutoCAD software. In particular, Fig. 3 shows the modeling of bandage processing with a standard profile according to GOST 11018 with a flange 33-mm thick for locomotives (Fig. 13 of the instruction [11]) when machining on the DMetI LR profile (Fig. 20 of the instruction [11] or Fig. 6.20 of the instruction [12]). Obviously, this “processing” is hypothetical, as it makes no sense to process a wheel with a flange thickness of 33 mm, turning it on a repair profile with a thickness of 30 mm. However, for geometric modeling, this is quite important.

The previous conclusion is supported by the following figure (Fig. 4). Shown here is the machining of the working surface of the above wheel in a slope of 1:7. For a better understanding of the processing of this section, it shows only the initial contour of the wheel. Multi-colored cylinders are hard-alloy cutters mounted on sequentially working toolholders at the moment of their highest position during one revolution of the mill. It is obvious that each cutter removes its own layer of metal, while the cutters mutually overlap each other.

The higher the repetition rate of the cutters, the better the surface finish of the wheel. However, this is an additional, secondary effect. The main one is achieved due to the fact that the thickness of the metal being cut for a new cutter is significantly less, which ultimately affects the reduction of the cutting force acting on one cutter.

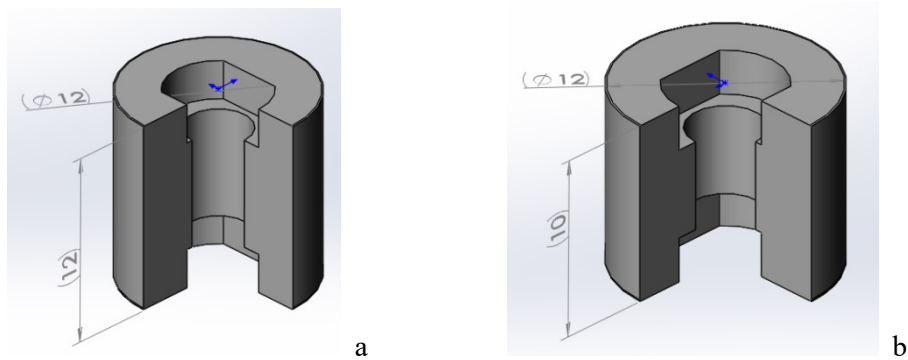


Fig. 2. Cylindrical cutter. a) $\text{Ø}12$ mm, $h=12$ mm; b) $\text{Ø}12$ mm, $h=10$ mm

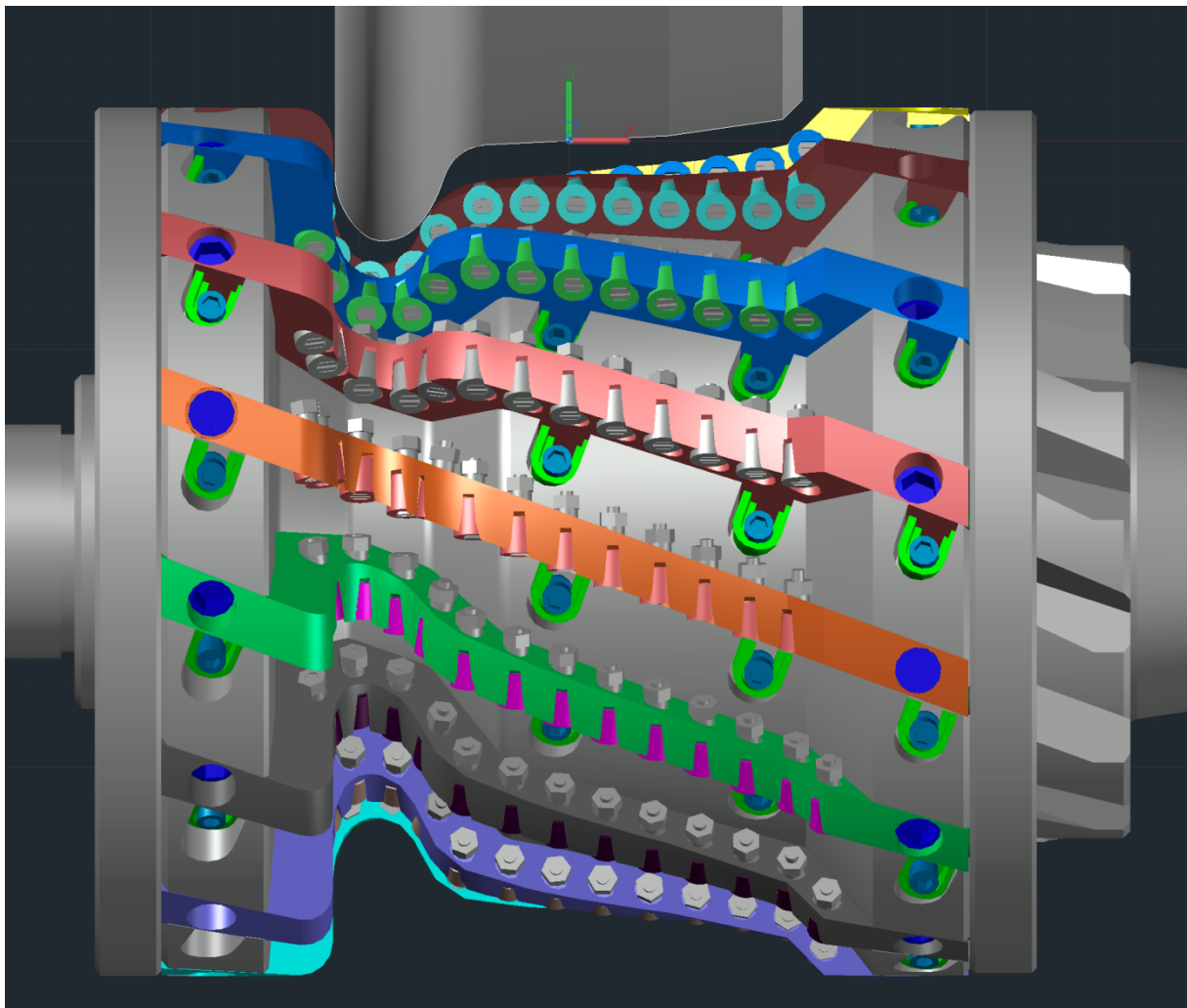


Fig. 3. Geometric modeling of processing a locomotive bandage with a mill of a new design with a repair profile of the working surface of DMet1 LR (30 mm)

Fig. 5 shows a simulation of processing of the aforementioned section of the working surface of the wheel with a cut depth of each cutter of 0.7 mm. Obviously, the distances between subsequent cutters for real structures may differ slightly, but here, when modeling, the ideal case was adopted when all the cutters are at the same center-to-center distance. In the first case (Fig. 5a), 10 consecutive cutters are considered, each reinforced in its own toolholder. It is accepted that the indicated center-to-center

distance is 1.23 mm. Each cutter in the figure is indicated by its color. The cutting zone of the last cutter, i.e. the one that is processing the wheel surface in the current moment is highlighted in red. According to a measurement made using AutoCAD, the chip cross-sectional area is 0.8489 mm^2 .

Fig. 5b presents a similar simulation for a new mill design with 14 toolholders. Depth of cut is taken of the same, but 14 consecutive working cutters are already being considered. In this case, the center-to-center distance is less than in the previous case, and is 0.88 mm. Then the cross-sectional area of the chip (the zone highlighted in red in the figure) also decreases and amounts to 0.6119 mm^2 .

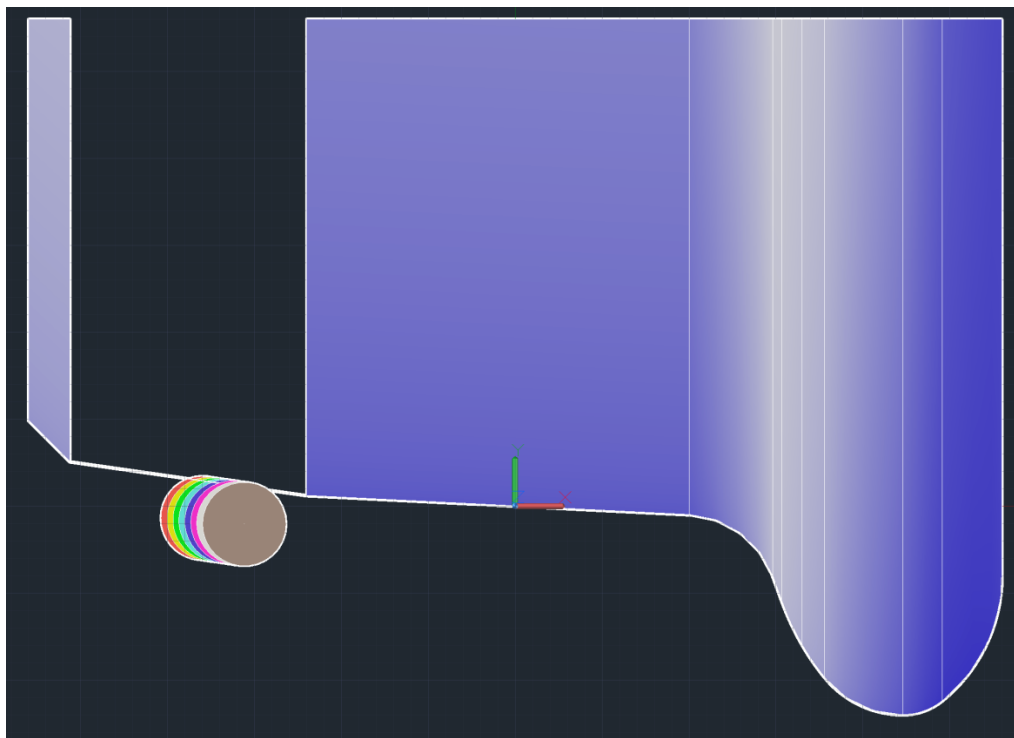


Fig. 4. Geometric modeling of processing the working surface of a locomotive wheel

The obtained results of geometric modeling are very important for setting the conditions for applying the cutting force when calculating the knife using the finite element method (FEM). It should be noted that the FEM is effectively used to analyze the stress-strain state of the machined parts and tools for various types of machining [13]. Particular attention can be paid to the work devoted to the calculation of hard-alloy cutters in the processing of working surfaces of wheelsets [14].

The preparatory phase of geometric modeling is also associated with the selection of a specific calculation object. The fact is that the locomotive mill as a whole is not subjected to significant loading. At each particular moment of processing, only individual cutters are loaded. The nearby area of their toolholders, to which the load from the cutter is transferred, is also important. For example, in the first part of article [8] possible defects of cutters due to a similar effect were shown. Including in one of the images (Fig. 2b) it can be seen that the seat itself in which the cutter was fixed was subjected to destruction. This is possible not only due to the destruction of the cutter itself, but in case of improper manufacture of the toolholder or incorrect installation of the cutter when setting the mill.

Thus, in the future we will not consider the mill as a whole according to Fig. 3, but first we select one tool holder, which is shown in Fig. 6, and in it we cut out the area with one cutter (shown by a white dashed line). In addition, in this way, we act both with a standard design mill and with a new design mill. For the purity of setting up a numerical experiment, we cut out the regions under consideration in the same zone of the mills. In particular, a zone was selected which is intended for machining wheels in the slope zone of 1:7, which is shown in Fig. 4. In the future, the fastening and

adjusting elements of the installation of the cutters are not considered, as they do not play a significant role for the stress state of the cutters. Thus, each geometric object will consist of two bodies: a hard-alloy cylindrical cutter and the adjacent part of the toolholder.

A very significant point for conducting numerical modeling is also the specification of the loading region of the cutters. Fig. 5 shows the cutting areas for each of the considered mill designs. Accordingly, the load should act on the cutter in the area shown in Fig. 5 in red. Obviously, this load cannot be distributed evenly over the specified area. Nevertheless, if such an area is modeled using a rigid flat surface of a certain shape and the total cutting force defined in Sładkowski et al. [8] is applied to it; this will be a fairly accurate approximation by which it will be possible to simulate real conditions of cutting of the wheel metal using a single cutter.

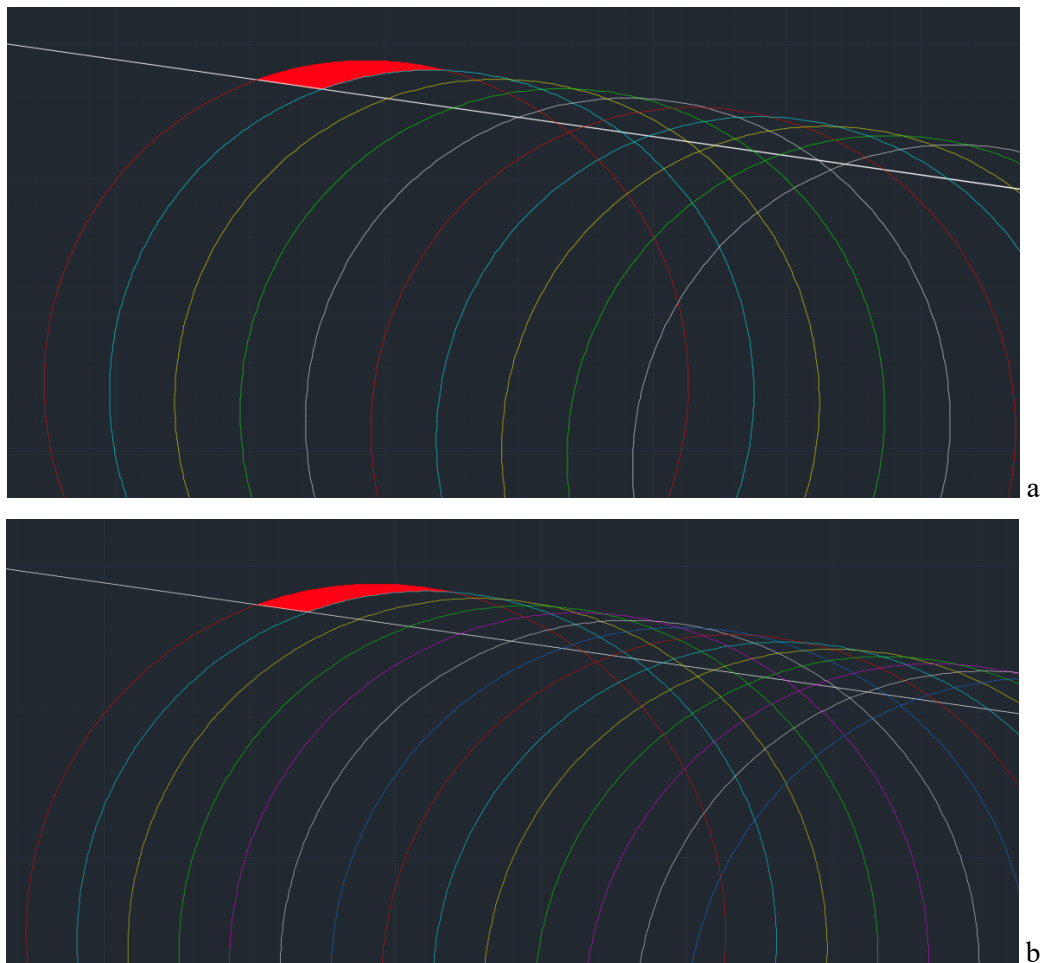


Fig. 5. Modeling of cutting the machined surface of the wheels with sequentially working cutters for mills of two designs: a) the standard mill with 10 toolholders; b) the mill of a new design with 14 toolholders

Fig. 7 shows a comparison of the selected parts of the mill (cutter + adjacent area of the toolholder) for the mills of the two designs under consideration. That is, each of the regions under consideration consists of two solid bodies, as well as a solid flat surface, where the cutting force will act, and which in Fig. 7 is drawn in red. In this figure, it can be noted that the mill of the new design is equipped with cutters, which are 2 mm lower in comparison with standard cutters. This allows to place the cutter a little deeper in height.

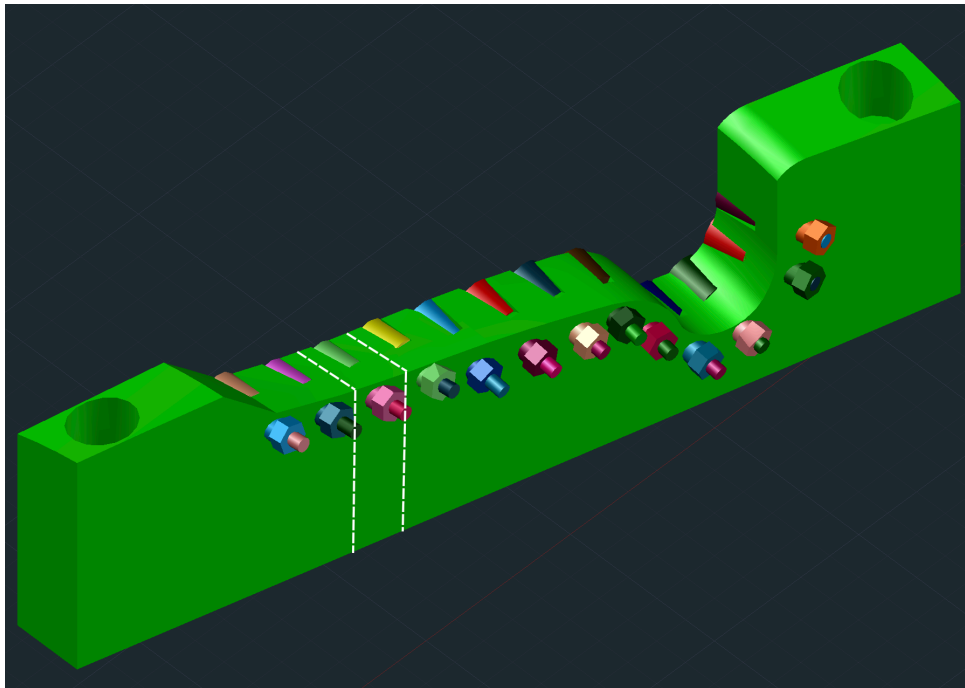


Fig. 6. Cutting of the considered area of the toolholder

4. CREATION OF A FINITE ELEMENT MODEL AND BOUNDARY CONDITIONS DEFINITION

Currently, there is a large selection of software that uses FEM as the main calculation tool. In this paper, the advantage was given to the MSC.Marc application software package. In the monograph [15], the advantages of this package are considered. For a specific task, one of the most valuable advantages is a fairly simple simulation of the complex contact interaction of individual parts, of which there are many in the mill. In addition, this software is designed to solve complex physical problems. The cutting process is just such a task. There are still a number of advantages of the MSC.Marc package, for example, such as the ability to write additional custom modules in Fortran or perform parallel calculations using partitioning the FE mesh into separate clusters. These advantages will be used in further calculations.

Calculations using the MSC.Marc package will be performed using previously prepared geometry in millimeters. For this purpose, in AutoCAD, we export the ones shown in Fig. 7 solid objects in ACIS (SAT) format, and in the MSC.Marc package, we import them. As a result, for each case, we have 3 solid objects: two objects of the Solid Bodies type (cutter and cut out part of the toolholder), as well as Solid Sheet Body (the cutting area modeled in Fig. 5).

Next, we are going to generate FE meshes for the first two objects. Owing to the loading conditions of the FE, the meshes do not have to be regular, uniformly broken. It is obvious that the greatest density of the FE mesh should be created on the upper surface of the cutter. This can be done by preparing a partition of surfaces into elements of a given size using Solid Mesh Seeds, an object - solid entity Face - the specified surface of the cutter, the Target Length - 0.2 mm specified in our case. The subsequent Automesh Volumes procedure, using the remaining mesh generation parameters set automatically, allows generating the FE mesh of the considered cutter (Fig. 8a). In particular, for the model of a hard-alloy cutter of 12-mm high, the created mesh contains 6217 nodes and 26321 tetraidal finite simplex elements. For the convenience of further work, we set the specified FE mesh of the cutter model as the first contact body.

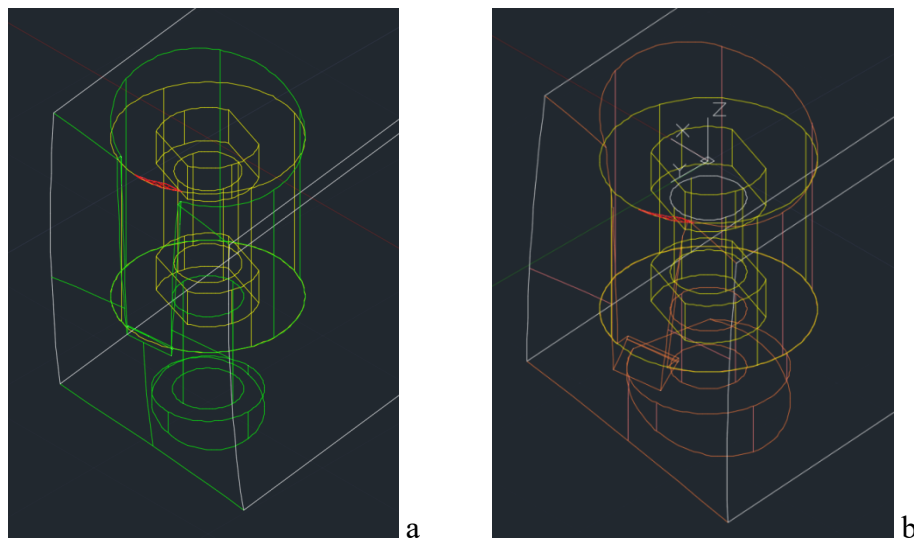


Fig. 7. Modeling of the area under consideration - “solids” - the cutter, part of the toolholder and a solid flat cutting surface (red zone): a) a standard mill with 10 toolholders and b) mill of a new design with 14 toolholders

When creating the FE mesh of the part of the toolholder, we use a similar approach, with the difference that at the stage of preparing the mesh generation, a regular fine mesh will be created on the edge of the landing slot, i.e. solid entity Edge - the specified toolholder line. Since in our case it consists of two halves, we choose the size 2 times larger than the previous one, i.e. Target Length 0.4 mm. Then, similarly, a FE mesh is shown, as shown in Fig. 8b. For the toolholder of a standard mill, the generated FE mesh contains 1538 nodes and 5609 tetraidal finite elements. This FE mesh will be used when defining the second contact body. Similarly, FE mesh are created for the considered region of a new design mill.

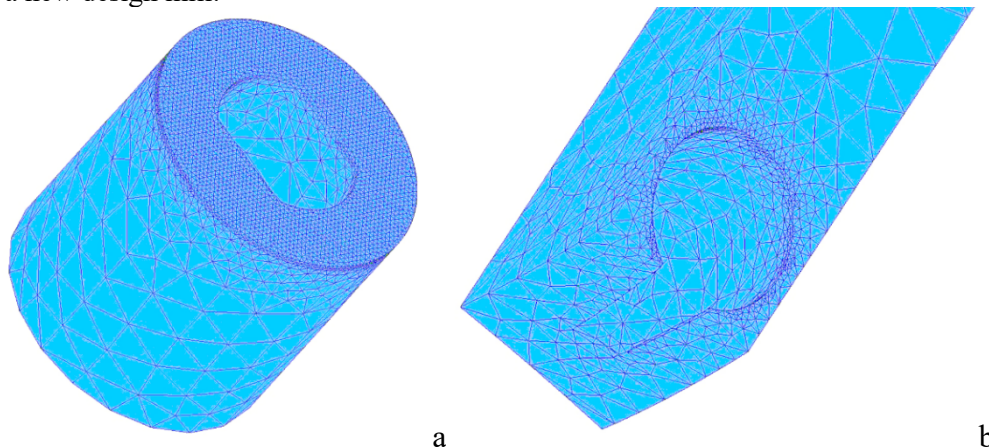


Fig. 8. Generation of FE meshes of the objects under consideration: a) hard-alloy cutter of 12 mm high; b) cut-out area of the toolholder for a typical mill

The next important issue is the specification of the materials of the bodies in question. In an article [16], it is indicated that hard-alloy cutters are currently made from alloys SM30, PT20, T14K8. The most common is the latter alloy. In the article by Pamfilov et al. [17], it is indicated that titanium tungsten hard alloys, and, in particular, T14K8, work quite well on compression. At the same time, the compressive strength of this alloy is 2940 MPa, whereas in tension, it is only 588 MPa. This fact should be taken into account when strength analysis of products from this alloy. We also note here that for this material is fragile, it is not necessary to talk about some plastic properties. However, to specify

the elastic material in the MSC.Marc program, one should also specify the Young's modulus E and Poisson's ratio ν . These data for the T14K8 alloy can be obtained from sources [18, 19]. They are somewhat contradictory, for example, in "Hard alloys" [18], it is indicated that $E = 520$ GPa, whereas in "Groups of hard alloys and their properties" [19], $E = 550$ GPa. As the technology for the production of parts from this material is quite complicated (sintering under high pressure), this spread of mechanical properties is explainable. In our calculation, we will use the average value, i.e. $E = 5.35 \cdot 10^5$ N/mm² (we use the indicated dimension since the geometry of the object is given in millimeters according to the drawing). Based on the data of [19], we take $\nu = 0.21$.

According to "Mills KZh-20 / Mill KZh20 for turning wheel sets of traction rolling stock, motor car rolling stock" [20], the material of toolholders at the present time, as before, is steel St45. In the database of materials used in the MSC.Marc program, there is a European and American analogue of this rather common steel (C45), correspondingly; the task of the material of the part of the toolholder under consideration is not a problem.

The next step is to set the boundary conditions. If we turn to Fig. 6, then on the surfaces of the section, which are shown by white dashed lines, for all nodes, a restriction of movement in the direction perpendicular to the surface of the section is set. There are also surfaces of the cut out part of the toolholder, in which for nodes belonging to these surfaces, all nodal movements are limited. These are the surfaces on which the toolholder contacts the groove of the mill body. Such a specification of the boundary conditions is explained by the fact that, in comparison, in the most loaded region, i.e. the cutter + the nearby area of the toolholder, the mill body is quite rigid and practically does not deform. For the toolholder, according to the conditions of its attachment to the mill body, any axial, radial, or longitudinal movements are excluded. Thus, for the FE nodes of the mesh that are in contact with the mill body, any displacements can be considered excluded. Fig. 9 shows the definition of the aforementioned boundary conditions.

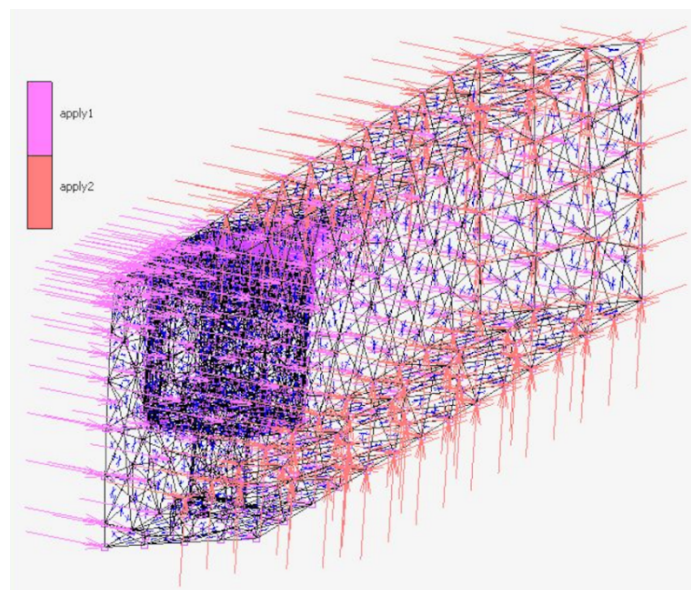


Fig. 9. Setting the boundary conditions in the displacements: a) pink color - limitation of normal displacements on the surfaces of the section; b) orange color - restriction of all nodal displacements in the contact areas of the toolholder with the mill body

We also set the last boundary conditions that simulate the force action on the cutter in the cutting zone. To determine the nodes that belong to this area, the third imported body is used, which was described above and shown in Figs. 5 and 7. When defining nodal forces that act perpendicular to the upper surface of the cutter, all nodes that fall into this zone are first determined. Then the total force, determined earlier in the article [8], is divided equally between all nodes in this area. Obviously, this approach is not entirely accurate, since in real conditions it would be necessary to solve the problem of

contact interaction between the cutter and the machined surface of the locomotive wheel. However, as a first approximation, this approach can be used.

Thus, for a cutter of a standard mill, 36 nodes fall into the indicated cutting zone, which is larger in area, to which a total force of 2039 N is applied. For mill of a new design, 29 nodes fall into the specified cutting zone, where act a total force equal 1436 N.

5. SOLUTION OF THE PROBLEM AND ANALYSIS OF RESULTS

To further solve the problem, it was also necessary to specify a contact table and conditions for contact interaction. In the case under consideration, this question is quite simple, as only 2 contact bodies (cutter and toolholder) are considered. The coefficient of friction between them was not of fundamental importance and was chosen equal to 0.3.

Of much greater importance is the control of the accuracy of the solution and the choice of the solution algorithm. These parameters are set at the stage of setting the Loadcase conditions. In particular, the method of solving the Full Newton-Raphson equation system is chosen. The iterative procedure involves the use of one-time step, with the possibility of continuing the solution even in the case of a non-positive definite matrix of the system.

At the stage of choosing Job Properties, we take into account that non-linear analysis is considered owing to the solution of the contact problem. Moreover, solution vectors are selected that will be calculated and analyzed further at the postprocessing stage. In particular, we will be interested in the stress tensor, the vectors of nodal displacements, as well as the vector of maximum principal stresses. The latter is due to the fact that for hard alloys, which are mainly under the influence of compressive stresses, the most significant criterion is not to exceed the main compressive stresses in the object under consideration (in our case, in the cutter) of the permissible compressive strength.

As a result of solving the problem, the stresses and strains in the considered models of milling elements for the KJ20 machines were analyzed. The most significant information is the fields of maximum compressive stresses (the principal stresses, the word “maximum” is used here evaluating their absolute value). In particular, in Fig. 10, such stresses are considered in the FE model of a standard mill.

As can be seen from the aforementioned stress distributions, the maximum compressive stresses occur on the cutting edge of the hard-alloy cutter. Some non-uniformity of the field under consideration is due to the fact that the automatic FE mesh generator creates it using standard procedures, in this case, based on the MSC.Patran program. Nevertheless, the created mesh is irregular, which leads to some unevenness of the obtained solution. In the future, it is supposed to refine the solutions using semi-automatic generation of FE meshes. The maximum value of compressive stresses that occur in the cutter is equal to -1323 MPa. This value is significantly less than allowed for the material of the T14K8 alloy under consideration. Nevertheless, given that the machining conditions for the wheelsets are very uneven, and in particular, locomotive wheels during operation can have various kinds of defects on the working surfaces, for example, hardenings, flats, etc. All this can lead to local fluctuations in the hardness of the processed surface layer, which in turn can lead to a dynamic increase in stresses in the cutters and, most often, to chipping of the cutting edge.

Similar calculations were carried out for mills of a new design. In particular, Fig. 11 shows the distribution of maximum compressive stresses.

The distribution of the indicated stresses is similar to the previously considered case, but somewhat less in its maximum. In particular, in this case, the maximum value reached -901 MPa, i.e., was 32% less than with a standard mill. It should be noted here that a lower cutter height (10 mm compared with the base 12 mm) leads to the fact that the cutter is installed a little deeper in the landing slot. This is not always positive, since in this case the toolholder has a greater effect, as can be seen in Fig. 11. However, excessive cutter height may also be unsafe. Thus, the rational height of the cutter in the landing slot is determined by the correct execution of the design of the toolholder during its

manufacture, as well as by the correct tune of the cutter with the appropriate selection of compensation washers, which were not taken into account in the aforementioned calculation.

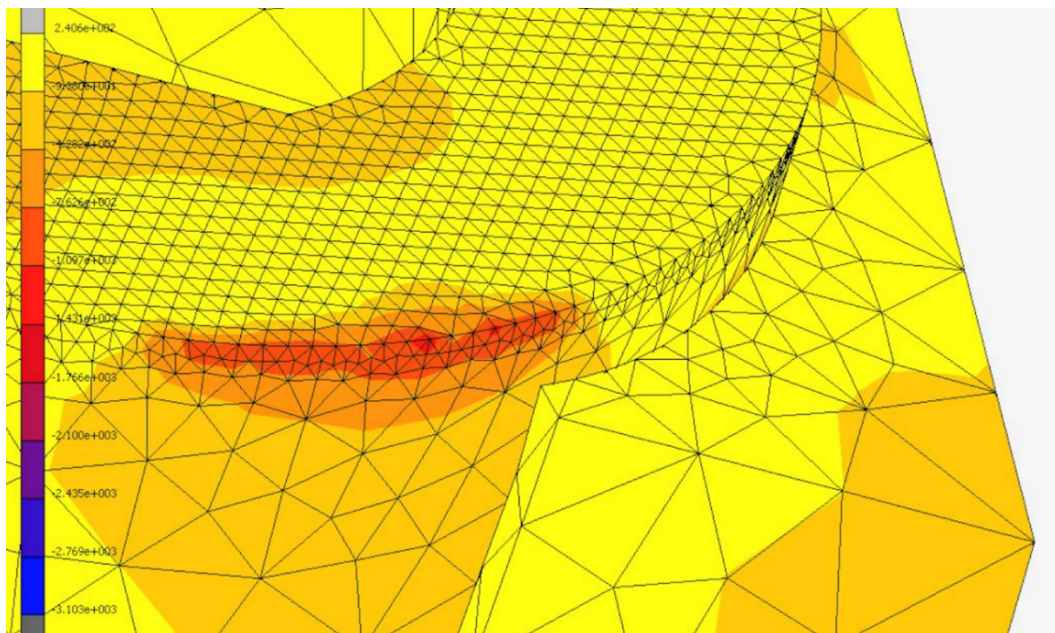


Fig. 10. Distribution of maximum compressive stresses in the considered FE model of a standard mill to the KJ20 machine

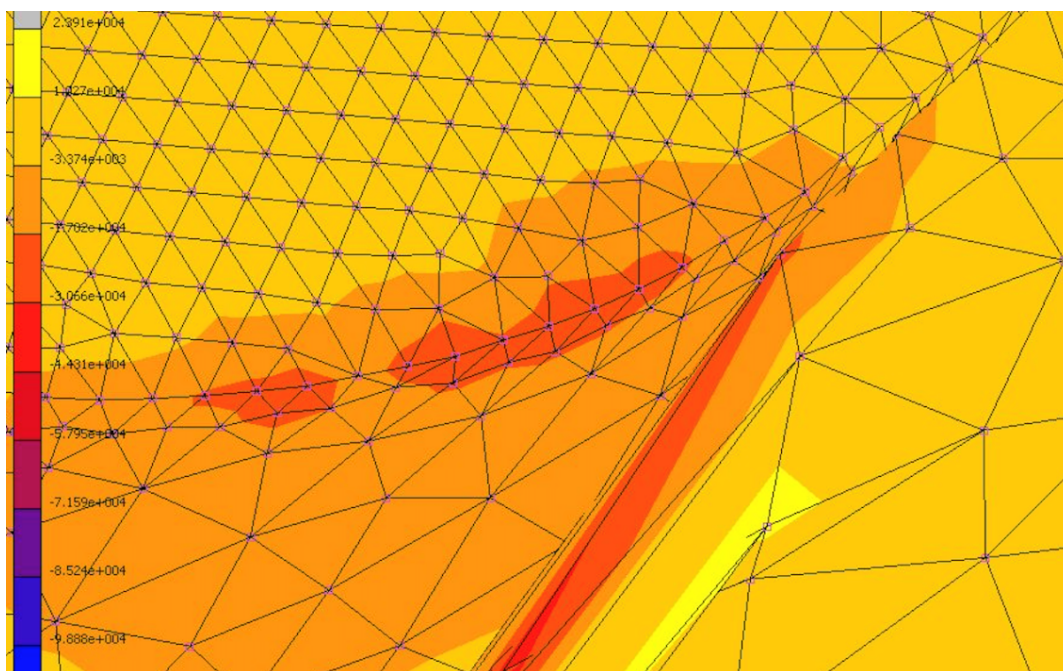


Fig. 11. Distribution of maximum compressive stresses in the considered FE model of a new design mill

6. CONCLUSIONS AND DIRECTIONS FOR FURTHER RESEARCH

As a result of the research, the following conclusions can be drawn. The proposed design of mills for the KJ20 machine, in addition to better surface treatment of locomotive wheels due to the larger number of cutters and the corresponding increased purity of processing, will also reduce the load on

individual cutters. This will ultimately contribute to a significant reduction in the stress state of the cutters and increase their durability.

It should be noted that the calculation of the stress state of the cutters presented in the article is primary. It did not take into account the uneven distribution of contact pressure in the cutting zone. The conditions of contact interaction with the machined surface of locomotive wheels were also not taken into account.

In the future, it is supposed to improve the calculation method using FEM, for which some modernizations of the considered FE mesh should be used. For example, the creation of regular FE meshes in the area of the cutter, which is adjacent to the cutting zone. It is also planned to take into account the interaction between the cutter and the workpiece. The loading conditions of the mill as a whole will also be taken into account.

References

1. *Hegenscheidt-MFD. Machines used in wheelset machining.* Available at: <https://www.hegenscheidt-mfd.com/en/railway-technology/machines-used-in-wheelset-machining/>.
2. *RAFAMET. Products. Machines for Railways.* Available at: <https://www.rafamet.com/en/products/machines-for-railways>.
3. *Stanray TN-84C Underfloor Wheel Truing Machine.* Available at: <http://smtgroup.com/railway-wheel-shop-equipment/underfloor-technology/underfloor-wheel-truing-machine-stanray>.
4. *KZTS. Railway Transport.* Available at: <http://www.kzts.com/en/products.html#product4>.
5. *ООО "СЛАВЕРС". Колесотокарные станки изготовление и модернизация под ЧПУ.* Available at: https://b2bspb.ucoz.ru/index/o_kompanii/0-101.
6. *Номенклатурный ряд оборудования, ремонтируемого ООО "ТСС-ТЯЖСТАНКОСЕРВИС".* Available at: https://tcc.at.ua/index/remont_i_modernizacija_tjazhelykh_metallorezhushhikh_stankov/0-5.
7. Кушнер, В.С. & Бургонова, О.Ю. & Иванов, И.А. & Терехов, П.М. Рациональные параметры фрезы и режимы резания при ремонте бандажных колесных пар повышенной твердости. *Бюллетень результатов научных исследований.* 2012. No. 5. P. 34-46. [In Russian: Kushner, V.S. & Burgonova, O.Yu. & Ivanov, I.A. & Terekhov, P.M. Rational parameters of the cutter and cutting conditions during the repair of bandage wheel pairs of high hardness. *Research Results Bulletin*].
8. Śladkowski, A. & Proydak, Yu. & Ruban, V. Increasing the resource of milling cutters used to process the locomotive wheelsets. Part 1: Determination of cutting forces. *Transport Problems.* 2018. Vol. 13. No. 3. P. 119-130.
9. UA 119973. *Збірна фасонна фреза для ремонтного відновлення профілю поверхні кочення колеса рухомого складу машин рейкового транспорту.* Національна металургійна академія України, Дніпропетровськ. (Сладковскі, А. & Хміленко, В.С. & Рубан, В.М.) а 2015 07376 22.07.2015. Publ. 25.10.2017. 5 p. [In Ukrainian: Sladkowski, A. & Hmilenko, V. & Ruban, V. Complex shaped milling cutter for repairing of the rolling surface profile of rolling stock wheels of railway vehicles].
10. Терехов, П.М. *Совершенствование восстановления бандажей колесных пар повышенной твердости.* Автореферат дисс. ... канд. техн. наук. Санкт-Петербург: Петербургский государственный университет путей сообщения. 2013. 16 p. [In Russian: Terekhov, P.M. *Improving the restoration of bandages of wheelsets of increased hardness.* Abstract of diss. ... cand. tech. sciences. St. Petersburg: Petersburg State University of Railway Engineering].
11. *Инструкция по осмотру, освидетельствованию, ремонту и формированию колесных пар локомотивов и моторвагонного подвижного состава железных дорог колеи 1520 мм.* Москва: ЦЕНТРАМГ. 2020. 126 p. [In Russian: *Instructions for the inspection, survey, repair and formation of wheelsets of locomotives and motor-car rolling stock of 1520 mm gauge railways.* Moscow: TSENTRMAG].

12. Інструкція з формування, ремонту та утримання колісних пар тягового рухомого складу залізниць України колії 1520 мм. ВНД 32.0.07.001-2001 (Нова редакція). Київ: Укрзалізниця. 2011. 171 р. [In Ukrainian: *Instruction on formation, repair and maintenance of wheelsets of traction rolling stock of the railways of Ukraine of 1520 mm gauge*. GNI 32.0.07.001-2001 (New edition). Kyiv: Ukrzaliznytsia].
13. Markopoulos, A.P. *Finite Element Method in Machining Processes*. Springer. 2013. 92 p.
14. Аверков, К.В. & Бунькова, Т.Г. & Бисерикан, М.И. & Петровиченко, С.В. Оптимизация технологического процесса ремонта колесных пар. *Омский научный вестник*. 2018. No. 1(157). P. 19-22 [In Russian: Averkov, K.V. & Bunkova, T.G. & Bicamerican, M.I. & Petrochenko, S.V. Optimization of the technological process of repairing wheelsets. *Omsk Scientific Bulletin*].
15. Javanbakht, Z. & Öchsner, A. *Advanced Finite Element Simulation with MSC Marc: Application of User Subroutines*. Springer. 2017. 352 p.
16. Обработка колесных пар на станках КЖ-20. Available at: http://www.efsispb.ru/obrabotka_kolesnyh_par_kzh20.htm [In Russian: *Processing wheelsets on the KZh-20 machines*].
17. Памфилов, Е.А. & Буглаев, А.М. & Толстяков, А.Н. К вопросу импортозамещения твердых сплавов для изготовления режущего инструмента. 2017. Available at: http://www.science-bsea.bgita.ru/2017/mashin_2017_26/pamfilov_vopros.htm [In Russian: Pamfilov, E.A. & Bugaev, A.M. & Tolstyakov, A.N. *To the question of import substitution of hard alloys for the manufacture of cutting tools*].
18. Твёрдые сплавы. Available at: https://ru.wikipedia.org/wiki/Твёрдые_сплавы [In Russian: *Hard alloys*].
19. Группы твердых сплавов и их свойства. Available at: <https://arxipedia.ru/materialy-i-svoystva/instrumentalnye-materialy/gruppy-tverdyx-splavov-i-ix-svoystva.html> [In Russian: *Groups of hard alloys and their properties*].
20. Фрезы КЖ-20 / Фреза КЖ20 для обточки колесных пар ТПС, МВПС. Available at: <https://drive.google.com/file/d/1Z6EB6vynvjW7U1AUUJpLrxgo79RdXsTF/view> [In Russian: Mills KZh-20 / Mill KZh20 for turning wheel sets of traction rolling stock, motor car rolling stock].