Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science. 2024 vol. 26 no. 2 pp. 158–173
ISSN: 1994-6309 (print) / 2541-819X (online)
DOI: 10.17212/1994-6309-2024-26.2-158-173

NSTU NETI
Obrabotka metallov -
Metal Working and Material Science
Journal homepage: http://journals.nstu.ru/obrabotka_metallov

Design simulation of modular abrasive tool

Dmitry Lobanov [1, a], *Vadim Skeeba* [2, b], *Ivan Golyushov* [1, c], *Valentin Smirnov* [1, d], *Egor Zverev* [2, e]

[1] I. N. Ulianov Chuvash State University, 15 Moskovsky Prospekt, Cheboksary, 428015, Russian Federation
[2] Novosibirsk State Technical University, 20 Prospekt K. Marksa, Novosibirsk, 630073, Russian Federation

[a] https://orcid.org/0000-0002-4273-5107, lobanovdv@list.ru; [b] https://orcid.org/0000-0002-8242-2295, skeeba_vadim@mail.ru;
[b] https://orcid.org/0000-0001-9757-1368, ivan.golyushov.97@mail.ru; [d] https://orcid.org/0000-0003-2721-9849, vms53@inbox.ru;
[e] https://orcid.org/0000-0003-4405-6623, zverev@corp.nstu.ru

ARTICLE INFO

Article history:
Received: 07 March 2024
Revised: 21 March 2024
Accepted: 27 April 2024
Available online: 15 June 2024

Keywords:
Abrasive tools
Modular grinding wheel
Tool design
Simulation

Funding
This research was funded by Russian Science Foundation project N 23-29-00945, https://rscf.ru/en/project/23-29-00945/

Acknowledgements
The research was carried out at the equipment of the Engineering Center "Design and Production of High-Tech Equipment" and the shared research facility" Structure, mechanical and physical properties of materials".

ABSTRACT

Introduction. Grinding is one of the most common types of finishing. It allows the production of surfaces with the required quality parameters and is one of the most available and productive methods for machining high-strength and difficult-to-machine materials. Grinding wheels represent the most prevalent application of grinding technology in mechanical engineering. The use of this abrasive tool helps to increase processing productivity by ensuring the removal of a significant layer of material. In addition, grinding wheels have a longer service life and are widely used in the implementation of hybrid technologies based on the combination of mechanical (abrasive), electrical, chemical, and thermal effects in various combinations. A variety of tool body shapes and types of abrasives allow the use of wheels in a wide variety of production areas. One of the ways to analyze and design a new tool is numerical simulation. In this research, graphic modeling was selected as the most appropriate method for representing the future design of the tool. This approach allows for a more straightforward conceptualization process compared to other modeling techniques. **The purpose of the work** is to simulate a modular abrasive tool in order to analyze and synthesize structures to increase the efficiency of tool support for the manufacture of products made of high-strength and difficult-to-process materials using traditional or hybrid processing technologies. **Research methodology.** Theoretical studies are carried out using the basic principles of system analysis, geometric theory of surface formation, cutting tool design, graph theory, mathematical and computer simulation. To solve the problem, we have studied the available designs of modular grinding wheels. There has also been the analysis of the types of abrasive parts, methods of fastening of the abrasive cutting part on the wheel's body, the materials used for the manufacture of the body, the characteristics of the body of the wheel, and fastening schemes. **Results and discussions.** A simulation technique based on graphic modelling theory has been developed. A comprehensive investigation of the existing design of the grinding wheel has enabled the identification of the key structural elements that define its design. The data obtained has been used to create a generalized graphic simulation of a modular abrasive tool. This simulation integrates all the components and displays a conditional constructive relationship between them. The developed design methodology was tested on an example of two designs of modular grinding wheels. The theoretical studies established that the design efficiency of modular abrasive tools can be increased by 2–4 times by using the developed simulation technique.

For citation: Lobanov D.V., Skeeba V.Yu., Golyushov I.S., Smirnov V.M., Zverev E.A. Design simulation of modular abrasive tool. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2024, vol. 26, no. 2, pp. 158–173. DOI: 10.17212/1994-6309-2024-26.2-158-173. (In Russian).

Introduction

The quality requirements for products manufactured by machine-building enterprises are increasing every year. This, in turn, leads to the introduction of more traditional and hybrid finishing technologies as well as smoothing ones. Grinding is one of the most common types of finishing used in shaping processes to

*** Corresponding author**
Lobanov Dmitry V., D.Sc. (Engineering), Professor
I.N. Ulianov Chuvash State University,
15 Moskovsky Prospekt,
428015, Cheboksary, Russian Federation
Tel.: + 7 908 303-47-45, **e-mail:** lobanovdv@list.ru

form a surface with the required quality parameters. It is one of the most available and productive methods for machining high-strength and difficult-to-machine materials [1–6].

The fundamental range of abrasive tools used in manufacturing processes encompasses grinding and cutting wheels, in addition to heads and bars and other types of cutting equipment. Furthermore, there are also less common types of tool designs [7].

In mechanical engineering, grinding wheels are one of the most popular tools for machining parts due to its high efficiency. The use of this type of tools enables the removal of a significant layer of material. Additionally, grinding wheels have a longer service life and are widely used in modern hybrid technologies [8–17]. These technologies provide mechanical (abrasive), electrical, chemical, and thermal treatment in various combinations [18–31] to achieve unique results in processing. The variety of shapes and types of abrasive materials allows grinding wheels to be adapted to a wide range of production applications, ensuring its use in multiple manufacturing areas.

The choice of modular grinding wheels as an object of research is due to a series of strategic advantages that make its use a profitable and effective solution in various industrial sectors:

1. ***Abrasive material saving***. In modular grinding wheels, the main part is the body, which can be made of steel or aluminum alloys. This means that the abrasive material is used only in the part that is immediately involved in the grinding process. The use of more expensive and high-quality abrasive materials where really needed without increasing the total cost of the wheel helps to reduce costs.

2. ***The possibility of the wheel body reuse***. Since the body of the modular grinding wheel does not wear out during use (it is not in immediate contact with the surface), it can be reused. When the abrasive part wears out, the body can be fitted with a new one, reducing the need to replace the entire wheel and helping to save resources and costs.

3. ***The flexibility of replacing the abrasive part***. Another significant advantage of modular wheels is that only the abrasive part of the wheel can be replaced. The designer can select a material with a different abrasive type or grit size depending on the current application while retaining the wheel body. This flexibility of modular wheels allows creating highly efficient tools for a variety of machining operations while minimizing the need to own a large number of specialized devices [32–35].

For this reason, modular grinding wheels are the preferred choice for many production applications. Its economic and technological efficiency make it the ideal solution for ever-increasing demands for machining quality, reduced production costs, and longer tool life.

One of the promising methods for improving the performance of modular grinding wheels is to develop designs that reduce heat generation in the machining area during grinding. Wheel designs with an interrupted working part are capable of reducing the temperature in the machining area to an acceptable level, below which structural and phase changes in the machined material do not occur [36–41].

The choice of abrasive wheel plays an important role in the machining process [42–44]. After all, many parameters depend on the correct wheel choice, such as productivity, the quality of the machined surface, the cost of the tool, and, consequently, the finished part and the life of the abrasive wheel.

However, the range of grinding wheels has expanded to such an extent that it has become challenging to select the optimal tool for a given task. Solving this problem requires careful analysis and verification of a large amount of collected information. Sometimes, the only possible solution is the development of a new and unique tool design that will contribute to the realization of the given task.

Numerical simulation plays a major role in the analysis and design of new tools, integrating a multitude of techniques [45], each of which has its own distinctive advantages and applications. In our study, we selected graph modeling [46] as the optimal methodology because this simulation not only enables us to effectively analyze and visualize the relationships and dependencies between the various components of the designed abrasive tool but also simplifies the process of identifying the key elements and its functional purpose.

The purpose of the study is to simulate a modular abrasive tool in order to analyze and synthesize structures and increase the efficiency of tool support for the manufacture of products made of high-strength and difficult-to-process materials using traditional or hybrid processing technologies.

Research methodology

Theoretical studies are carried out using the basic principles of system analysis, geometric theory of surface formation, cutting tool design, graph theory, mathematical and computer simulation.

The selection of wheels for a manufacturing process takes place in several stages:

selection of the abrasive material according to the task;

search for the required type of wheel profile, taking into account its industrial purpose;

development of a new design of modular grinding wheel.

Achieving the required surface quality and productivity in the grinding process depends largely on the wheel used and its characteristics: the combination of machining and abrasive materials, dimensions, wheel design features, as well as the machining conditions and modes. Each of the characteristics described above is important in its own way and has an impact on the machining process.

The choice of abrasive material and the determination of the optimum grit size also have an important influence on the grinding process and the achievement of the required product quality parameters. At the same time, it is important to maintain the high productivity of the grinding process [47–49].

The use of simulation in the design solution provides an opportunity to perform tool selection and analysis at various stages of design, as well as process and tool preparation in production. We have developed a simulation technique based on graphic modeling theory in order to effectively solve the tasks set.

We have studied the existing designs of modular grinding wheels to solve the problem described above. The types of the abrasive part, the methods of fastening the abrasive cutting part on the body of the wheel, the materials used to manufacture the body, the characteristics of the body of the wheel and the fastening schemes were analyzed [50]. As a result of the analysis of existing wheel designs, the key structural elements are identified that make it possible to describe the design of the grinding wheel.

The description of the abrasive part of the grinding wheel is based on the following elements: the design of the abrasive part (solid or segmented); the dimensional characteristics of the abrasive part, which determine the size and accuracy of the production of grinding elements; the abrasive material; the hardness of the wheel; the grit size; the bond; the shape of the elements and its quantity.

The body part is defined by the type of its profile; dimensional parameters; material composition (such as steel or aluminum alloys); the presence or absence of coating.

The fastening part is characterized by the method of fastening, which encompasses the type of connection of the abrasive part with the body part; the presence or absence of adjusting and fastening screws; its quantity and dimensional parameters.

Furthermore, the model contains data about the intended purpose of the wheel; unbalance class; accuracy class; maximum speed; manufacturer information.

The data analyzed has been used to construct a generalized graph-based model of modular grinding tool designs. This model contains all the constituent components that are included in the designs of various modular grinding wheels and displays the conditional constructive relationship.

The grinding wheel design is a system of separate parts of the wheel design, or interconnected components, and is represented as an oriented graph.

$$G = (X, E),$$

where X are vertices; E is an illustration of the set X in X or the relationship between the vertices of the graph (represented by connection lines).

The relationship between the wheel elements and its characteristics is shown by vertex-edge connections $\{X_1, l_{x1}\}$, $\{X_2, l_{x2}\}$, ... etc. Each edge of a connected graph is a set of vertices, which is described by a subset of vertices and a subset of edges.

An edge of a graph l_i is a set of vertices of a graph $l_i\ X_i$ and simultaneously consists of elements X_1, X_2,...X_n, which can also be sets (Fig. 1). Thus $l_i = \bigcup_{i=1}^{n} X_i$.

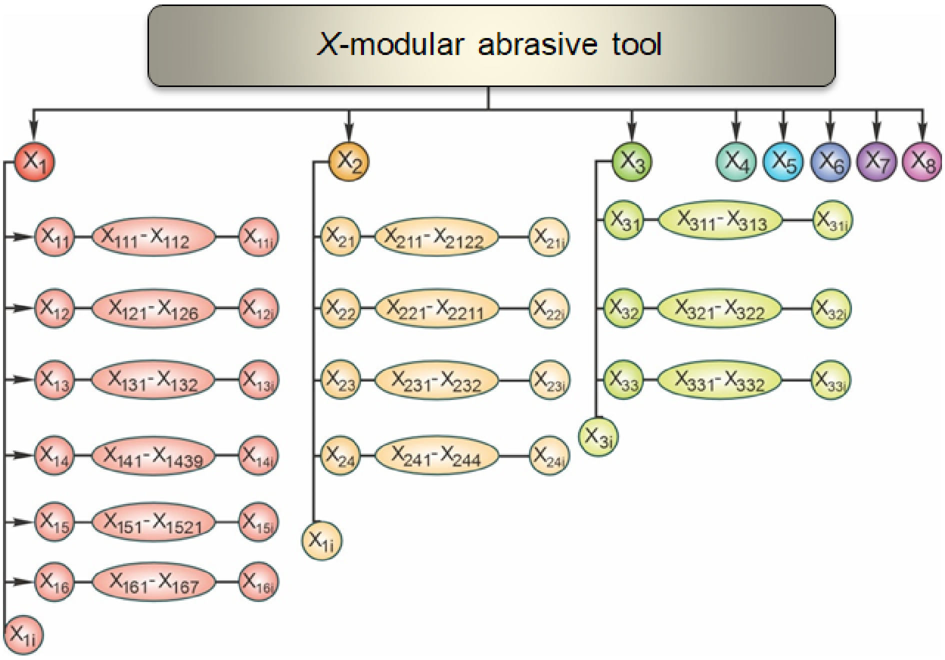

Fig. 1. Graph-based model of a modular wheel

Let us consider the orientation of the edges and vertices of the graph $G = (X, E)$.

The grinding wheel in this case is shown in the form of the following parts: abrasive part (vertex $\boldsymbol{X_1}$), body (vertex $\boldsymbol{X_2}$), fastening (vertex $\boldsymbol{X_3}$), unbalance class (vertex $\boldsymbol{X_4}$), accuracy class (vertex $\boldsymbol{X_5}$), maximum speed (vertex $\boldsymbol{X_6}$), wheel manufacturer (vertex $\boldsymbol{X_7}$) other parameters (additions or notes vertex $\boldsymbol{X_8}$) and other elements (vertices $\boldsymbol{X_9}...\boldsymbol{X_n}$) represented by the set $\boldsymbol{l_X}$:

$$l_X = \bigcup_{i=1}^{n} X_i.$$

The abrasive part (vertex $\boldsymbol{X_1}$) is represented by the parameters $\boldsymbol{l_{X1}}$, which are the vertices of the edge; $\boldsymbol{X_{11}}$ is the design of the abrasive part; $\boldsymbol{X_{12}}$ is geometric dimensions; $\boldsymbol{X_{13}}$ is abrasive material; $\boldsymbol{X_{14}}$ is grit size; and $\boldsymbol{X_{ln}X_1}$ is other parameters described by the set $\boldsymbol{l_{X1}}$:

$$l_{X_1} = \bigcup_{i=1}^{n} X_{1i}.$$

The abrasive part (vertex $\boldsymbol{X_{11}}$) is described by the parameters that are the vertices of the edge $\boldsymbol{l_{X11}}$; $\boldsymbol{X_{111}}$ is a solid cutting part; $\boldsymbol{X_{112}}$ is the interrupted (segmented) part; and $\boldsymbol{X_{nl}\,X_{11}}$ is other versions presented as a set $\boldsymbol{l_{X11}}$

$$l_{X_{11}} = \bigcup_{i=1}^{n} X_{11i}\ .$$

The dimensions of the abrasive part (vertex $\boldsymbol{X_{12}}$) are described by different parameters, which are the vertices of the graph $\boldsymbol{l_{X12}}$:$\boldsymbol{X_{121}}$ is the shape of the insert; $\boldsymbol{X_{122}}$ is the dimensions of the insert; $\boldsymbol{X_{123}}$ is the height of the abrasive layer; $\boldsymbol{X_{124}}$ is the width of the abrasive layer; and $\boldsymbol{X_{125}}$ is the concavity of the abrasive layer. $\boldsymbol{X_{126}}$ is the design of the insert; $\boldsymbol{X_{nl}\,X_{12}}$ are other parameters represented as a set $\boldsymbol{l_{X12}}$:

$$l_{X_{12}} = \bigcup_{i=1}^{n} X_{12i}\ .$$

The abrasive material (vertex X_{13}) is better presented in the form of the following variants, which are the vertices of graph l_{X13}: X_{131} is natural abrasives; X_{1311} is diamond; X_{1312} is corundum; X_{1313} is emery; X_{1314} is pumice stone; X_{1315} is quartz; X_{132} is artificial (synthetic) abrasives; X_{1321} is synthetic diamond; X_{1322} is silicon carbide (carborundum); X_{1323} is boron carbide; X_{1324} is borazon; X_{1325} is cubic boron nitride; X_{1326} is electrocorundum; X_{1327} is normal electrocorundum; X_{1328} is white electrocorundum; X_{1329} is monocorundum; X_{13210} is zirconium electrocorundum; X_{13211} is alloyed electrocorundum, represented as a set l_{X13}:

$$l_{X_{13}} = \bigcup_{i=1}^{n} X_{13i} .$$

The grit size (vertex X_{14}) is expressed by various versions represented by the vertices of the graph l_{X14}: X_{141} – *F4*; X_{142} – *F5*; X_{143} – *F6*; X_{144} – *F7*; X_{145} – *F8*; X_{146} – *F10*; X_{147} – *F12*; X_{148} – *F14*; X_{149} – *F16*; X_{1410} – *F20*; X_{1411} – *F22*; X_{1412} – *F24*; X_{1413} – *F30*; X_{1414} – *F36*; X_{1415} – *F40*; X_{1416} – *F46*; X_{1417} – *F54*; X_{1418} – *F60*; X_{1419} – *F70*; X_{1420} – *F80*; X_{1421} – *F90*; X_{1422} – *F100*; X_{1423} – *F120*; X_{1424} – *F150*; X_{1425} – *F180*; X_{1426} – *F220*; X_{1427} – *F230*; X_{1428} – *F240*; X_{1429} – *F280*; X_{1430} – *F320*; X_{1431} – *F360*; X_{1432} – *F400*; X_{1433} – *F500*; X_{1434} – *F600*; X_{1435} – *F800*; X_{1436} – *F1000*; X_{1437} – *F1200*; X_{1438} – *F1500*; X_{1439} – *F2000*; $X_{nl}X_{14}$ is other variants presented as a set l_{X14}:

$$l_{X_{14}} = \bigcup_{i=1}^{n} X_{14i} .$$

The hardness of the wheel (vertex X_{15}) according to *DIN ISO 525* standard is represented by the following parameters, which serve as the vertices of the edge l_{X15}: X_{151} – *F*; X_{152} – *G*; X_{153} – *H*; X_{154} – *I*; X_{155} – *J*; X_{156} – *K*; X_{157} – *L*; X_{158} – *M*; X_{159} – *N*; X_{1510} – *O*; X_{1511} – *P*; X_{1512} – *Q*; X_{1513} – *R*; X_{1514} – *S*; X_{1515} – *T*; X_{1516} – *U*; X_{1517} – *X*; X_{1518} –*Y*; X_{1519} – *Z*; X_{1520} – *V*; X_{1521} – *W*; $X_{nl}X_{15}$ is other options presented as a set l_{X15}:

$$l_{X_{15}} = \bigcup_{i=1}^{n} X_{15i} .$$

Type of bond (vertex X_{16}): X_{161} is metal, X_{1611}...X_{161n} is marking; X_{162} is ceramic, X_{1621}...X_{162n} is marking; X_{163} is silicate, X_{1631}...X_{163n} is marking; X_{164} is magnesian, X_{1641}...X_{164n} is marking; X_{165} is bakelite, X_{1651}...X_{165n} is marking; X_{166} is vulcanite, X_{1661}...X_{166n} is marking; X_{167} is griphthalic, X_{1671}...X_{167n} is marking, represented in the set l_{X16}:

$$l_{X_{16}} = \bigcup_{i=1}^{n} X_{16i} .$$

For the wheels with diamond abrasive material (synthetic or natural), the following parameters are also taken into account:

Diamond concentration (vertex X_{13111} and X_{13211}), with these parameters forming the vertex of the graph l_{X13111}: X_{131111} – 25 %; X_{131112} – 50 %; X_{131113} – 75 %; X_{131114} – 100 %; X_{131115} – 150 %; $X_{nl}X_{13111}$ is other options.

The body of modular grinding wheels *GOST R 52781-2007* (vertex X_2) is described by the following parameters forming the vertices of the edge l_{X2}: X_{21} is profile type; X_{22} is dimensional parameters of the body; X_{23} is body material; X_{24} is wear-resistant coating and hardening; $X_{nl}\,X_{21}$ is other parameters described by the set l_{X2}:

$$l_{X_2} = \bigcup_{i=1}^{n} X_i .$$

X_{21} is the profile type, where X_{211} is type **1**; X_{212} is type **2**; X_{213} is type **3**; X_{214} is type **4**; X_{215} is type **5**; X_{216} is type **6**; X_{217} is type **7**; X_{218} is type **10**; X_{219} is type **11**; X_{21101} is type **12**; X_{21102} is type **14**; X_{2111}

is type **20**; X_{2112} is type **21**; X_{2113} is type **22**; X_{2114} is type **23**; X_{2115} is type **24**; X_{2116} is type **25**; X_{2117} is type **26**; X_{2118} is type **35**; X_{2119} is type **36**; X_{2120} is type **37**; X_{2121} is type **38**; X_{2122} is type **39**; described by the set l_{X21}:

$$l_{X_{21}} = \bigcup_{i=1}^{n} X_{21i} .$$

X_{22} is dimensional parameters of the body: X_{221} is outer diameter of the wheel; X_{222} is the diameter of the landing hole; X_{223} is the diameter of the support end; X_{224} is the thickness of the base part of the body; X_{225} is the diameter of the undercut; X_{226} is the radius; X_{227} is the outer corner of the body cone; X_{228} is the wheel's height; X_{229} is the height of the working part; X_{2210} is the width of the working part; X_{2211} is the working angle, represented as a set l_{X22}:

$$l_{X_{22}} = \bigcup_{i=1}^{n} X_{22i} .$$

X_{23} is the body material: X_{231} is structural steel, X_{2311} is *steel 3*; X_{2312} is *steel 20*; X_{2313} is steel 25; X_{2314} is *steel 30*; X_{2315}**is** *steel 35*; X_{2316} is *steel 45*; X_{2317} is steel *U8A*; X_{2318} is steel *0.9 C-Cr-V*; X_{232} is aluminum alloys, X_{2321} is alloy *AK6*; X_{2322} is alloy ***D16***, represented as a set l_{X23}:

$$l_{X_{23}} = \bigcup_{i=1}^{n} X_{23i} .$$

X_{24} is wear-resistant coating and hardening: X_{241} is type of hardening; X_{242} is depth of hardening; X_{243} is coating material; X_{244} is coating thickness; $X_{nl}\,X_{24}$ is other options; presented as a set l_{X24}:

$$l_{X_{24}} = \bigcup_{i=1}^{n} X_{24i} .$$

The fastening of the abrasive part of the prefabricated grinding wheels (vertex X_3) is described by the parameters forming the vertex of the graph l_{X3}: X_{31} is the type of connection of the abrasive part to the body, X_{32} is adjusting screws, X_{33} is fixing screws. The fastening part is represented as a set of l_{X3}:

$$l_{X_3} = \bigcup_{i=1}^{n} X_{3i} .$$

X_{31} is the type of connection of the abrasive part to the body: X_{311} is mechanical; X_{3111} is fastening with a radial screw; X_{3112} is fastening with an axial nut; X_{3113} is fastening with an axial bolt; X_{3114} is fastening with a radial nut; X_{312} is soldered; X_{3121} is solder *PSr 40* (*Ag*); X_{3122} is solder *PSr 50* (*Ag*); X_{313} is adhesive; X_{3131} is phenolic rubber adhesive (*VK-32-20*); X_{3132} is epoxy resin (*ED-6*); these connection methods are presented in the form of a set l_{X31}:

$$l_{X_{31}} = \bigcup_{i=1}^{n} X_{31i} .$$

X_{32} is adjusting screws: X_{321} is the amount of screws; X_{322} is the thread parameters described by the set l_{X32}:

$$l_{X_{32}} = \bigcup_{i=1}^{n} X_{32i} .$$

X_{33} is mounting screws: X_{331} is the number of screws; X_{332} is the thread parameters; $X_{nl\,X33}$ is the other components described by the set l_{X33}:

$$l_{X_{33}} = \bigcup_{i=1}^{n} X_{33i} .$$

The unbalance class (**1**, **2**, **3**, **4**) is indicated by the vertex X_4.

The accuracy class (***AA***, ***A***, ***B***) is indicated by the vertex X_5.

The maximum allowed processing speed is indicated by the vertex X_6.

The manufacturer is indicated by the vertex X_7.

Additional parameters (notes, additions) are represented by the vertex X_8.

The graph structure proposed for the description of grinding wheel design options allows for the decomposition of any design into its components for providing a comprehensive representation of the wheel.

As previously stated, the precise definition of the vertices of the graph allows for the construction of a wheel to be represented as a matrix ***B***, which corresponds to the graph-based model.

$$B = \begin{vmatrix} b_{11} & b_{12} & \cdots & b_{1j} \\ b_{21} & b_{22} & \cdots & b_{2j} \\ \cdots & \cdots & \cdots & \cdots \\ b_{i1} & b_{i2} & \cdots & b_{ij} \end{vmatrix},$$

where $_{ij} \begin{cases} 1, \mathit{if}\ \iota_{ij} \in \iota \\ 0, \mathit{if}\ \iota_{ij} \notin \iota_n \end{cases}$

In this instance, the matrix ***B*** is employed to illustrate the interrelationship between the design process of the grinding wheel and the selection of optimal parameters for specific tasks.

The conversion of the graphic model into a matrix form will result in the creation of a single database of grinding wheel designs, which, in turn, will facilitate the systematization of grinding wheels available at enterprises. In addition, this model can be expanded to accommodate the incorporation of novel components in the structural design.

Results and Discussion

Using the methodology described above, two designs of modular grinding wheels with different sizes, methods of fastening the abrasive part, and other design features were simulated.

The first modular grinding wheel design is represented by a *6A2* diamond surface grinding wheel shown in Figure 2.

This wheel has a solid ring-shaped abrasive section that is fastened to the body by phenolic rubber adhesive. The abrasive part is made of *Bakelite B2-01* bond and synthetic diamond. The body is made

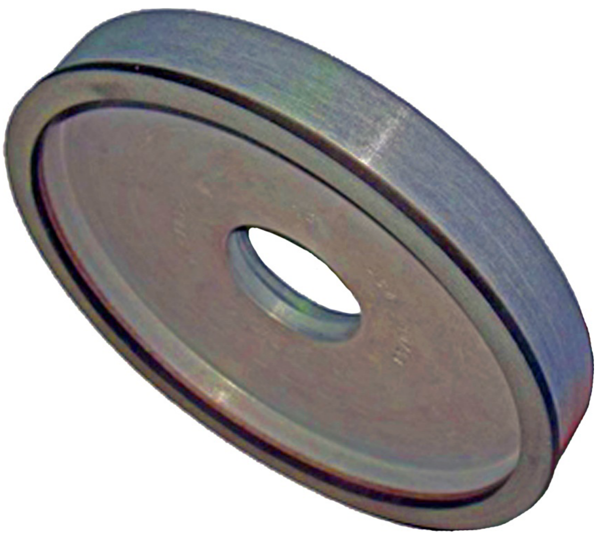

Fig. 2. Surface diamond grinding wheel type *6A2*

of *D16* aluminum alloy and is type **6**, with body dimensions of 200×20×4×29×76 mm. This wheel has a maximum permitted cutting speed of 50 m/s.

This wheel is proposed as a graphic model and shown in Figure 3.

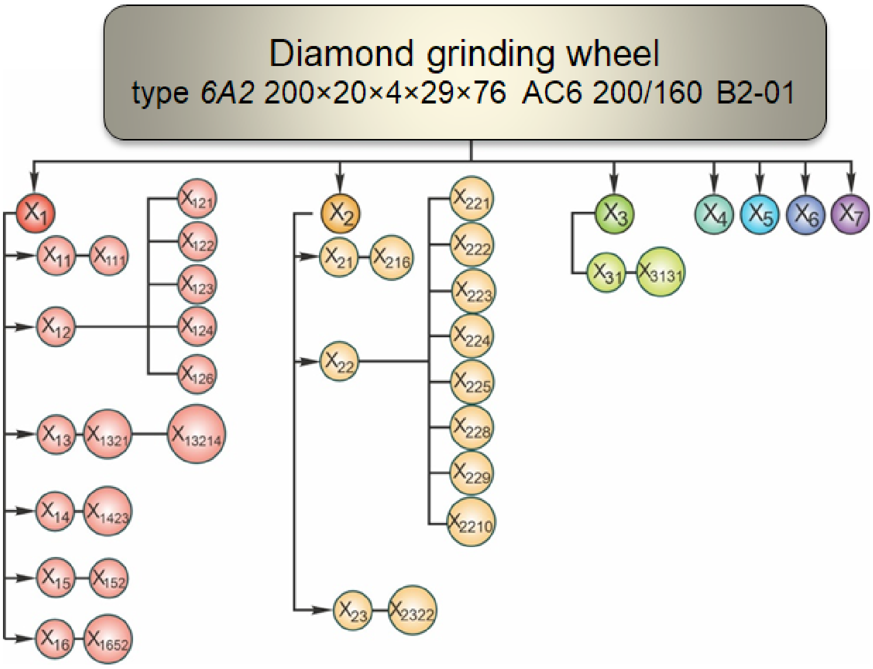

Fig. 3. Graph-based model of the wheel type *6A2* 200×20×4×29×76 AC6 200/160 B2-01

The present model is a simplified matrix $\boldsymbol{B_1}$, which contains only those elements present in the specific model of the wheel. The components not included in the design are not considered, which reduces the size of the matrix:

$$\mathbf{B}_1 = \begin{array}{c|ccccccccccc} & X_{111} & X_{121} & X_{122} & X_{123} & X_{124} & X_{126} & X_{1321} & X_{13214} & X_{1423} & X_{152} & X_{1652} \\ \mathrm{X}_1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ X_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ X_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array}$$

$$\begin{array}{ccccccccccc|} X_{216} & X_{221} & X_{222} & X_{223} & X_{224} & X_{225} & X_{228} & X_{229} & X_{2210} & X_{2322} & X_{3131} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{array}.$$

In order to gain further insight, we may now consider another design of a modular abrasive tool. This wheel has been specifically developed for diamond-abrasive machining [8, 51–52] and is presented in Figure 4.

This wheel has an interrupted (segmental) abrasive part in the form of cylindrical heads fastened in the body by radial screws. The abrasive part is made of *Bakelite B2-01* bond and synthetic diamond. The body is made of steel and is type **36** with body dimensions 250×10×7×34×51 mm. This wheel has a maximum permitted machining speed of 270 m/s.

This wheel is represented by a graphic model and is shown in Figure 5:

Now, by analogy, we construct the matrix $\boldsymbol{B_2}$ describing this wheel construction:

$$B_2 = \begin{array}{c|ccccccccccc} & X_{112} & X_{121} & X_{122} & X_{123} & X_{124} & X_{126} & X_{1321} & X_{13214} & X_{1423} & X_{152} & X_{1652} \\ \mathrm{X}_1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ X_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ X_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array}$$

X_{216}	X_{221}	X_{222}	X_{223}	X_{224}	X_{225}	X_{228}	X_{229}	X_{2210}	X_{2322}	X_{3111}	X_{321}	X_{322}
0	0	0	0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	1	1	0	0	0
0	0	0	0	0	0	0	0	0	0	1	1	1

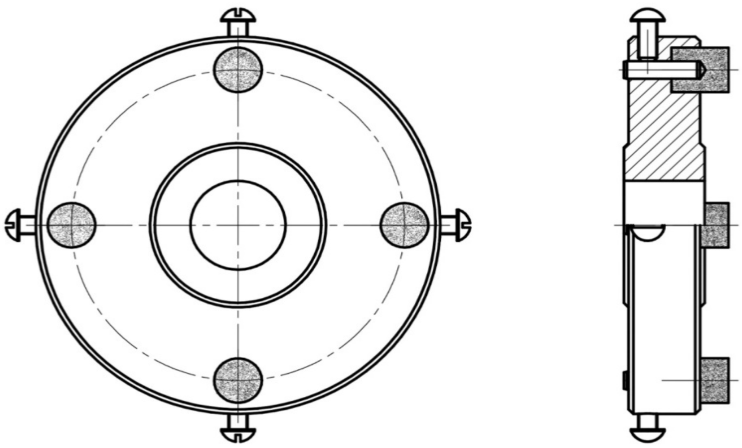

Fig. 4. Grinding wheel for diamond abrasive machining

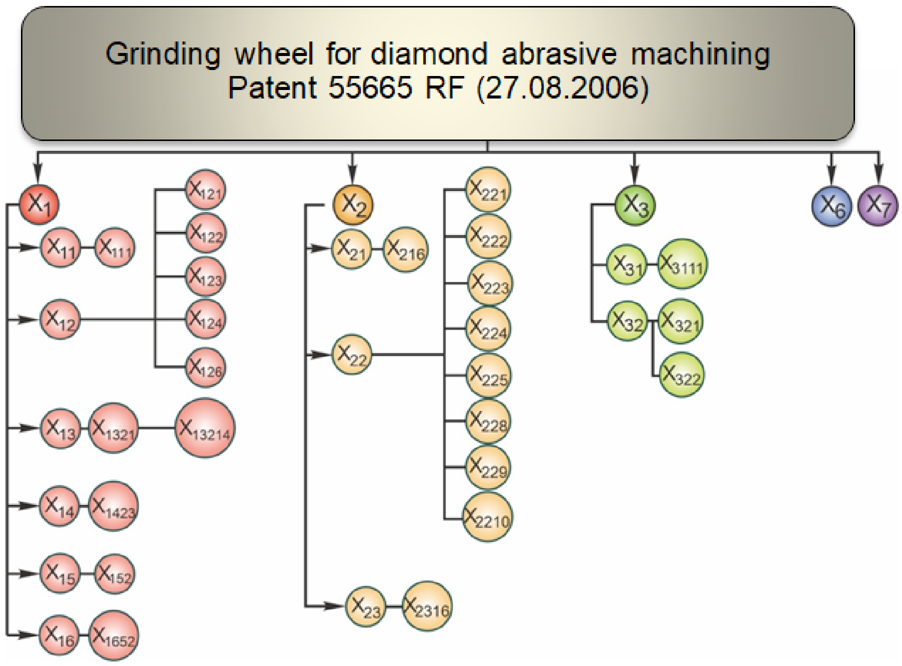

Fig. 5. Graph-based model of the wheel for diamond abrasive machining

When comparing these models, the constructional difference can be clearly seen. In the considered case, the branches X_3 (Fig. 3 and Fig. 5), which describe the fastening part, vary on the model because the fastening of the abrasive part is radically different. This can be seen both in the graphs and in the matrices B_1 and B_2 that describe these models. It can be demonstrated that each wheel design is unique and that when at least one design element is altered, the wheel model also undergoes a corresponding change.

Conclusion

The study proposes a novel methodology for simulating modular abrasive tools based on graph modeling theory and matrix analysis. This approach allows for comprehensive analysis and synthesis of design solutions, thus enhancing the effectiveness of tool support for the manufacture of products made of high-strength and difficult-to-process materials via conventional or hybrid manufacturing techniques.

The generalized graphic model is an innovative approach to the design and analysis of a modular abrasive tool that includes all the key structural elements and characteristics that can be used in such tools. The principal advantage of the model is its flexibility and extensibility, which enables it to be readily updated or augmented with new components to meet current or future abrasive tool requirements. This simulation allows for the visualization of existing abrasive tool designs and the experimentation with the creation of new designs by adding, modifying, or removing certain elements. Such a graphical approach facilitates comprehension of the interactions between the various tool components and its impact on the overall performance and efficiency of the tool. One of the most crucial attributes of a generalized graphic model is its capacity to be represented in a matrix form. Such representation not only enables the systematization and structuring abrasive tools data but also facilitates the process of analysis, synthesis, and the selection of optimal tools. The matrix form of information representation allows for the consideration of the specific characteristics of each tool, thereby providing an effective means for the management of the tooling assortment at the enterprise. This is critical to optimizing production processes and increasing efficiency through more informed tool selection.

The developed design methodology was tested on an example of model realization on two designs of modular grinding wheels. The theoretical studies established that the design efficiency of modular abrasive tools can be increased by 2–4 times (depending on the complexity of the tool design) by using the developed simulation technique.

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Conflicts of Interest

The authors declare no conflict of interest.