Development of expert system for the process of high-speed diamond grinding of superhard materials based on macro- and microscale 3D models

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A feature of grinding of superhard materials is the absence of excess hardness of the tool material over the machined one. Hence there is no cutting process in the classical way, and the grinding process is a process of controlled mutual microdestruction of two equally hard materials (diamond grain and processed superhard material (SHM)) upon high-speed impact. The manufacturing and operation processes of the diamond-abrasive tool were investigated with the help of dynamic 3D modeling of the high-speed diamond grinding processes at macro and micro levels. This makes it possible to solve the following tasks: at the design stage, calculation of the tool design for certain processing modes; at the manufacturing stage, determination of rational conditions for sintering the diamond layer of the grinding wheel; at the application stage, the theoretical determination of processing productivity, especially the consumption of diamond grains. The solution of these problems by means of simulation allows processing efficiency to be significantly increased. The introduction into industry of the results of such modeling of high-speed diamond grinding processes can be effectively accomplished using expert systems that allow problematical situations to be solved based on optimizing the manufacturing conditions and operating modes of diamond wheels; the expert systems also increase the level of automation directly in production.

Keywords: algorithm, diamond wheel, finite element method, methodology, simulations, variables

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1. Introduction

Superhard polycrystalline materials and composite superhard materials (SHM) based on diamond are increasingly used both as tool material (especially in precision machining processes) and as structural materials. The complexity of their processing is comparable in terms of labour intensity with the processing of natural diamonds. Currently, the most technologically advanced SHM processing method is diamond grinding. However, the currently used processes of diamond grinding with wheels comprising organic and metal binders do not fully solve the problems of low productivity—a significant specific consumption of diamond grains—and a significant rejection rate due to the appearance of microcracks on the treated SHM surface. One of the most promising ways for improving the efficiency of grinding operations and expanding their technological capabilities is increasing the cutting speed, which is set by the wheel speed.[1,2] It has been established that by increasing the speed the thickness of the cut of the material by each grain decreases, and some other parameters of the process also change.[1]

Optimization of SHM processing involves choosing the best of all possible options for implementing high-speed grinding technology. A complete enumeration of all options may turn out to be inefficient or practically impossible; therefore, to solve such a problem, the fundamental mathematical results and numerical methods of optimization theory should be applied. Currently, there is no single integrated methodology for three-dimensional computer-aided design (3D-CAD) modeling of the processes of manufacturing the working layer of a wheel from a diamond-composite material (DCM), and carrying out diamond-abrasive machining with tools made from such material. The creation of such a methodology will significantly reduce the amount of experimental research to determine the rational design parameters of diamond-abrasive tools, and the optimal conditions for their manufacture and use. The idea of the research presented in this paper is to develop the theoretical foundations and means of implementing the methodology of computer 3D modeling of physical processes for the development of optimal resource-saving technologies for processing with tools made from SHM. Based on the developed methodology, it becomes possible to create an expert system for identifying rational characteristics of diamond-abrasive tools and devising processing modes. The reliability and quality of the SHM tool must be improved, without which it is impossible to use it in automated production.

The development of an expert system for the SHM diamond grinding process is based on the establishment of its physical and technological features and it will significantly reduce the amount of labour-intensive and expensive experimental studies in solving the problem of increasing the processing efficiency of diverse SHM grades, including newly created ones.

[1] J.F.G. Oliveira, E.J. Silva, C. Guo and F. Hashimoto. Industrial challenges in grinding. *Ann. CIRP* **58** (2009) 663–680.
[2] F. Klocke and T. Merbecks, Characterization of vitrified CBN grinding wheels, *Proc. 4th Intl Machining and Grinding Conf.*, SME, Michigan (2001).

2. Literature review

High speed grinding is a machining method with speeds exceeding 120 m/s,[2,3] which is designed to improve productivity, accuracy and surface quality. Under modern conditions, taking into account the use of high-strength diamond grains, the grinding speed can be increased 1.5–2 times, as revealed by theoretical and practical studies.[2,3]

Increasing the circumferential speed of the grinding wheel determines the reduction in wear of its working surface, as well as of the cutting forces that occur during grinding.[4,5] Such processing indicators open up certain prospects for the development of high-speed grinding for SHM processing, but require qualitative and quantitative confirmation. The recommendations given in ref. 1 allow us to conclude that there is an undeniable trend towards the need to significantly increase the grinding speed. At the same time, the high-speed processing régime requires suitable equipment, a diamond-abrasive tool with sufficient strength, and system rigidity. Recently, high-speed grinding régimes have begun to be studied at universities in developed countries. The cost of the tool, and the need of a better understanding and monitoring of the high-speed grinding process are major concerns, along with the need to research how to implement technology guidelines for high-speed grinding applications.[2] Principal factors restraining the wider application of high-speed diamond grinding are shown in Fig. 1.

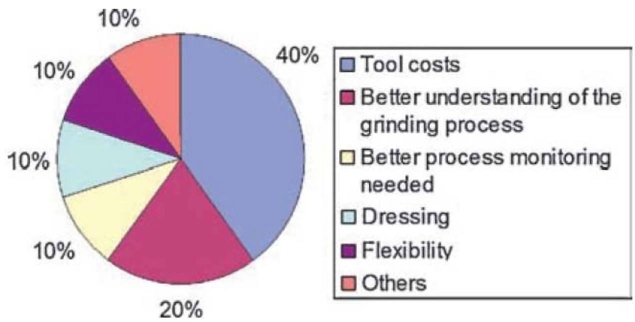

Figure 1. The main factors restraining the wider application of high-speed diamond grinding.[1]

A description from the point of view of tool manufacturers indicates a way to achieve a good understanding of the main limitations for expanding the use of diamond grinding. However, research into the reliability and effectiveness of high-speed diamond grinding is needed to justify the investment in the technology enhancements. An effective and inexpensive way to approach the research is via simulation of the grinding process, with which it is possible

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[3] E. Brinksmeier, J.C. Aurich, E. Govekar, C. Heinzel, H.-W. Hoffmeister, F. Klocke, J. Peters, R. Rentsch, D.J. Stephenson, E. Uhlmann, K. Weinert and M. Wittmann. Advances in modeling and simulation of grinding processes. *Ann. CIRP* **57** (2006) 667–696.

[4] B. Li, C. Dai, W. Ding, C. Yang, C. Li, O. Kulik and V. Shumyacher. Prediction of grinding force during grinding powder metallurgy nickel-based superalloy FGH96 with electroplated CBN abrasive wheel. *Chinese J. Aeronautics* (2020), doi: https://doi.org/10.1016/j.cja.2020.05.002

[5] U. Shirsat, B. Ahuja and M. Dhuttargaon. Effect of burnishing parameters on surface finish. *J. Instn Engrs (India)* **98** (2017) 431–436.

to predict the behaviour of the tool under given conditions and create methods for selecting the necessary materials and structures for the tool.[6]

Modern tendencies in the creation of science-intensive products are characterized by a sharp expansion of applications of mathematics, largely associated with the creation and development of computer technology,[7] which opens up prospects for the development of 3D methodology for a comprehensive study of interrelated processes for the manufacture and operation of DCM and tools made from them, increasing their reliability in high-speed processing modes. Use of computer information technologies (CIT) at the main stages of the DCM life cycle is considered as an approximation to the CALS (computer-aided logistics support) ideology[8,9] and relevant to the development of the fourth scientific and technological revolution—"Industrie 4.0".[10] Such an approach is especially necessary in the study of such new and previously not thoroughly studied processes such as high-speed grinding of superhard materials. The implementation of CALS technologies in practical terms involves the organization of a single information space (an integrated information environment), which combines automated systems designed for the effective solution of engineering tasks, and for planning and managing production and enterprise resources.

In this study, the main tool for implementing theoretical modeling of high-speed grinding is analytical computer-aided engineering (CAE) software based on the finite element method (FEM).[11] Once this is implemented, the industrial realization of the results of dynamic 3D modeling of high-speed diamond grinding of SHM processes can be effectively carried out using expert systems,[12] which allow solving problems by optimizing conditions for

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[6] A.G. Mamalis, A.I. Grabchenko, V.A. Fedorovich and J. Kundrak. Simulation of effects of metal phase in a diamond grain and bonding type on temperature in diamond grinding. *Intl J. Adv. Manufacturing Technol.* **58** (2012) 195–200.

[7] S. Agarwal, S.S. Dandge and S. Chakraborty. Parametric analysis of a grinding process using the rough sets theory. *Facta Universitatis Ser. Mech. Engng* **18** (2020) 91–106.

[8] M.J. Jackson, N. Barlow and K.K.B. Hon. Computer-aided design of high-performance grinding tools. *Proc. Instn Mech. Engrs B: J. Engng Manufacture* **215** (2001) 583–588.

[9] J.C. Aurich et al. Abrasive processes for micro parts and structures. *CIRP Ann. Manufacturing Technol.* **68** (2019) 653–676.

[10] K. Bondar. Challenges and opportunities of Industry 4.0 – Spanish experience. *Intl J. Innovation Management Technol.* **9** (2018) 202–208.

[11] CAE is a general name for programs or software systems designed for engineering calculations, analysis and simulation of physical processes.[12,13] The computational part of the programs is most often based on numerical methods for solving differential equations. These methods comprise the finite element method, the finite volume method, the finite difference method and others, which allow evaluation of how a computer model of the product behaves under real operating conditions and help to verify that the product is working without spending a lot of time and funds on a physical realization.[12,14]

[12] A.G. Mamalis et al. Development of an expert system of diamond grinding of superhard polycrystalline materials considering grinding wheel. *Intl J. Adv. Manufacturing Technol.* **17** (2001) 498–507.

[13] Thi-Hoa Pham, Duc -Toan Nguyen, Tien-Long Banh and Tong Van Canh. Experimental study on the chip morphology, tool–chip contact length, workpiece vibration, and surface roughness during high-speed face milling of A6061 aluminum alloy. *Proc. Instn Mech. Engrs B: J. Engng Manufacture* **234** (2019) 610–620.

[14] M.J. Jackson, C.J. Davis, M.P. Hitchiner and B. Mills. High-speed grinding with CBN grinding wheels—applications and future developments. *J. Mater. Processing Technol.* **110** (2001) 78-88.

manufacturing diamond wheels, and for grinding modes. An expert system is a computer program that uses expert knowledge to provide highly efficient problem-solving in a narrow subject area. The system uses both a database and a knowledge base—in our case in the area of diamond-abrasive machining. The database contains reference data on the characteristics of diamond wheels (binder, grain grades, concentration, grain size etc.), on the physical and mechanical properties of various grades of diamond grains, and about the processed SHM. The expert system is developed on the basis of a procedural knowledge base, which operates with such concepts as reliability of the SHM tool blade, defects during its sharpening and the relative statistical weights of various factors contributing to processing efficiency, and is built according to the proposed algorithm for determining the optimal conditions for microfracture of the elements of the SHM–grain–binder system, based on providing a load on a single grain. Our expert system includes the software packages Cosmos, LS-Dyna and Ansys, which uses FEM.

The main purpose of the expert system is to predict the level of output indicators when grinding various grades of SHM, including newly created ones, and to optimize the processing.[12] At certain stages of work, the expert system provides for the participation of a human expert, who has knowledge of the process and how to influence its effectiveness. Creating and using expert systems is one of the conceptual stages of technology development. Intelligent problem-solving in a certain subject area is based on the principle of reproducing the knowledge of experienced specialists—experts. Based on his own experience (held in his memory), the expert analyses the situation and recognizes the most useful information, whereby he optimizes decision-making, cutting off dead-end paths. The expert system achieves high efficiency by sorting through a large number of alternatives when choosing a solution, additionally relying on the high-quality experience of a group of human specialists; the system can analyse the influence of a large number of new factors, evaluating them when building strategies, and adding forecasting capabilities.

The developed expert system is a set of computer programs and modules that transform the experience of experts (in this paper, within the field of high-speed diamond machining) into the form of heuristic rules, which allow, within a certain range, the determination (eventually prediction) of the possible results of a high-speed grinding operation. The rules can also increase the efficiency of production of diamond wheels at the stage of their design and sintering. The main difference between expert systems and other software products is the use of not only a database, but also knowledge, as well as a special mechanism for deriving solutions and new knowledge based on existing solutions and knowledge. It is almost self-evident that the knowledge that might be said to reside in an expert system is available in a form that can be easily processed by a digital computer.

3. Research methodology

Based on the features of synthetic diamond (SD) as a tool material, as well as the processes of shaping tools based on SD, a methodological approach to research was determined based on the widespread use of 3D modeling of the processing process in connexion with the experimental data obtained to assess the adequacy of the models. All essential features of the studied systems (diamond grain, metal phase, binder, coating of diamond grains, ground SHM) and processing conditions are considered in interaction with each other. Dynamic 3D modeling is used to determine the performance parameters and consider the processes of destruction of diamond grains and a binder during high-speed grinding. The concept is shown in Fig. 2.

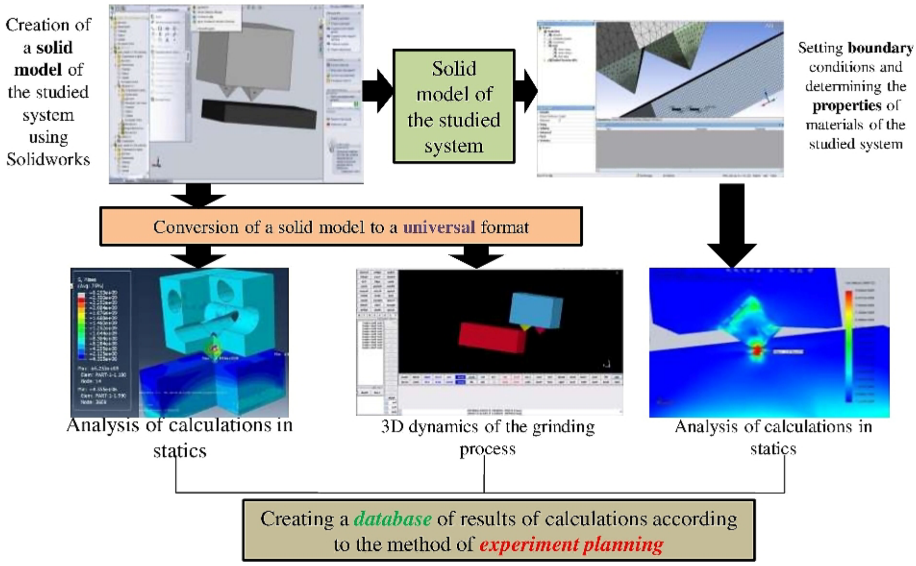

Figure 2. The general concept of research for improving the efficiency of diamond-abrasive tools in the processing of SHM.

To implement studying the stress–strain state in the grinding zone, ANSYS, LS-DYNA, CosmosWorks and Abaqus calculation systems were used. The construction of 3D models was realized by SolidWorks—a CAD system of automation of design in 3D.

Since quantitative analysis of high-speed grinding of SHM tools requires an assessment of the intensity of wear of diamond grains and the volume of material removed from the machined surface of synthetic diamond, a modern laser scanning method was used to determine the parameters of the 3D topography of the working surface of the wheel (WSW) and the machined surface of the SHM. The study of the 3D topography of the WSW and the surface of the SHM was carried out on a Perthometer S8P laser scanning device with a FOCODYN laser sensor.

Calculations using FEM quantified the principal and reduced stresses, strain energy, and strain energy density in the sintered elements and in the grinding zone, depending on their size, physical and mechanical properties, sintering conditions (temperature, pressure) and grinding modes. Volumes of materials were considered destroyed if the reduced stresses or strain energy density (or both) in them exceeded the limit values. Model experiments were carried out in accordance with the theory of experiment planning.[15] Factor values were encoded by linear transformation of the factor space coördinates with the origin transferred to the zero point and the choice of scales along the axes in units of factor variation intervals. These model experiments are a component for obtaining a common database that contains all the necessary information to optimize the properties of the elements of the diamond layer during sintering of

[15] P.G. Katsev. *Statistical Research Methods for Cutting Tools* (2nd edn). Moscow: Engineering (1974).

wheels for high-speed grinding (elastic modulus of the binder and coating, thermal expansion coefficient (CTE) of the metal phase, sintering modes etc.).

Optimization consists in choosing the best of all possible options for implementing SHM high-speed grinding technology. A complete enumeration of all options may turn out to be inefficient or practically impossible. Therefore, the mathematical apparatus and numerical methods of optimization theory should be used, which allow choosing the best option without directly checking all possible solutions. Such a choice is realized by means of calculations carried out using special algorithms and is practically impossible without the use of computer technology.[3,16]

When considering the problems of optimization, the boundary of the object under study can be delineated by the spatial area of the cutting tool when solving the problems of choosing the optimal characteristics of diamond wheels at the stages of their design and manufacture. The independent variables are a set of parameters that characterize the state of the object under consideration within the selected boundary:

$$\{x\} = \{x_1, x_2, \ldots x_n\}^T, \tag{1}$$

where $\{x\}$ is a vector of the independent variables, n the number of independent object variables, x_1, x_2,…x_n the individual independent variables and superscript T denotes the operation of transposition.

When solving optimization problems, each independent variable x_k, $k = 1,2,\ldots n$ represents some numerical technological characteristic. In relation to the problems of optimizing the processes of manufacturing diamond wheels and high-speed grinding, the following independent variables were taken: technological modes of sintering wheels, physical and mechanical properties of the diamond-bearing layer, processing modes, and physical and mechanical properties of the material being processed. Each of the independent variables is expressed in units of the value it represents and can vary within certain limits:

$$x_k^{\min} \le x_k \le x_k^{\max}, k = 1, 2, \ldots n, \tag{2}$$

where $x_k^{\min}$ and $x_k^{\max}$ are the maximum and minimum possible values of the independent variable x_k. Our preliminary results show that a mathematical model of the studied processes can be quite accurately represented by a quadratic function, which in the general case of n independent variables (factors) is written as:[15]

$$Y = b_0 + \sum_{i=1}^{n} b_i X_i + \sum_{i=1}^{n-1} \sum_{j-i+1} b_{ij} X_i X_j + \sum_{i=1}^{n} b_{ii} X_i^2 \tag{3}$$

where Y is the optimized value of the output indicator (e.g., grinding performance, stresses in

[16] LAZARUS is an open and free-to-use integrated development environment built on the FreePascal compiler. This environment is almost a complete analogue of the well-known commercial system Delphi. With the use of the LAZARUS system, many software projects for various purposes have been developed.[17] The Lazarus program, on the basis of which the system was developed, is an object-oriented visual programming environment. Therefore, it includes object-oriented visual programming tools; in particular, a large number of visual components. The Lazarus Visual Component Library (LCL) is compatible with Delphi's Visual Component Library (VCL) and includes most of the components found in the VCL, such as forms, buttons, text fields, and the like. Visual programming technology and the presence of a library of visual components provide the ability to reuse components when creating new programs.

[17] M. Weisfeld. *The Object-Oriented Thought Process (*4th edn). Addison-Wesley (2013).

the sintering zone) at given values of factors X_i. Quadratic functions (eqn 3) of independent variables (eqn 1) can be represented in matrix–vector form as:

$$Y = \frac{1}{2}\{X\}^T [A]\{X\} + \{B\}^T \{X\} + B_0, \tag{4}$$

where $[A]$ is a specified matrix of numerical coefficients, $\{B\}$ is a specified vector of numerical coefficients and B_0 is a specified numerical factor:

$$[A] = \begin{bmatrix} 2b_{11} & b_{12} & b_{13} & \cdots & b_{1n} \\ b_{12} & 2b_{22} & b_{23} & \cdots & b_{2n} \\ b_{13} & b_{23} & 2b_{33} & \cdots & b_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ b_{1n} & b_{2n} & b_{3n} & \cdots & 2b_{nn} \end{bmatrix}, \{B\} = \begin{Bmatrix} b_1 \\ b_2 \\ b_3 \\ \vdots \\ b_n \end{Bmatrix}, B_0 = b_0. \tag{5}$$

The solution of the optimization problem for the case of a quadratic function (eqn 3) was reduced to solving a system of linear algebraic equations, using the most universal LU decomposition method, implemented in LAZARUS.[16] Thus, using the finite element method, it is possible to carry out a full cycle of modeling the manufacturing process and the operation process of diamond wheels for high-speed SHM grinding. Using the developed expert models of the processes under study and the results of modeling, it is possible to determine ways to improve their efficiency.

4. Results

The concept of macro–micro transition in studying the sintering process is shown in Fig. 3.

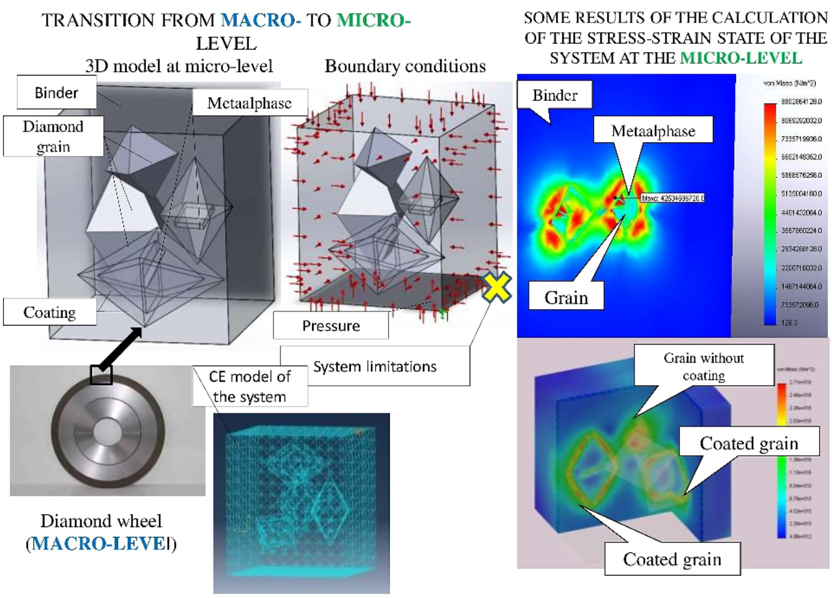

Figure 3. Simulation of the sintering process of the diamond layer from the macrolevel to the microlevel, as well as some intermediate results of calculating the stress–strain state in the sintering zone.

At the production stage, most manufacturers of professional diamond abrasive tools use the technology of sintering diamond grains and a binder. However, this technology has disadvantages that are not only limited by the shape of the tool. It has been established that the granulometric analysis of grains of synthetic diamonds AC50 400/315, recovered from sintered samples by recuperation, showed that only about 10–20% of grains remains intact during sintering.[18] The formation of cracks in the crystals of diamond grains after heating is associated with a sharp increase in the volume of inclusions of the metal phase.[6] Consequently, the initial temperature of the appearance of cracks in crystals will depend on the value of the thermal expansion coefficient of the metal phase. The initial crack initiation temperature will also depend on the volume of inclusions and on the nature and location of inclusions. Therefore, at the first stage, using 3D modeling, it is the process of sintering of the diamond-bearing layer at the microlevel that is considered.

To obtain a mathematical model of the sintering process of the diamond wheel, we used the method of planning an experiment with a B4 type plan (see ref. 15, eqn 3). Table 1 (cols 1–5) presents the ranges of independent variables (factors) $X_1 \ldots X_4$ considered in this study for the sintering of a diamond layer at the microlevel (mathematical model described by eqn 6).

Table 1. Ranges and meaning of factors $X_1 \ldots X_4$ for the sintering process of a diamond layer (the column on the extreme right is for the mathematical models described by eqns 7–10).

Level of factor	X_1 CTE of metal phase /K^{-1}	X_2 Elastic modulus of binder /mN m^{-2}	X_3 Elastic modulus of grain coating /mN m^{-2}	X_4 Temperature /°C	X_4 Processing speed /m s^{-1}
Upper level	1.7×10^{-5}	6.9×10^{11}	9.01×10^{11}	800	300
Main level	1.1×10^{-5}	4.4×10^{11}	5.01×10^{11}	600	195
Lower level	0.5×10^{-5}	1.9×10^{11}	1.01×10^{11}	400	90

Processing the results of the experiment on the basis of finite-element calculations made it possible to obtain a mathematical model in the form of eqn (3) that describes the process of sintering of diamond wheels for high-speed grinding in the presented range of variation of independent factors. In coded form, the model appears as:

$$Y = 31.09 - 0.39X_1 - 0.17X_2 - 2.29X_3 + 3.64X_4 + 0.85X_1X_2 + 0.85X_1X_3 + 0.85X_1X_4 + \\ +0.61X_2X_3 + 1.6X_2X_4 + 0.38X_3X_4 - 12.89X_1^2 - 8.6X_2^2 + 14.5X_3^2 - 10.04X_4^2, \quad (6)$$

where Y denotes equivalent stresses/GPa in the sintering zone of the diamond layer.

When designing a modern tool for high-speed grinding, it is necessary to take into account the need to conserve scarce high-strength materials and the creation of *lightweight* disk structures while ensuring their reliable operation at high processing speeds.[19,20] In

[18] N.V. Novikov et al. *Resistance to Destruction of Superhard Composite Materials*. Kiev: Dumka (1993).
[19] Wei Li, Mingjia Liu, Yinghui Ren and Qidi Chen. A high-speed precision micro-spindle use for mechanical micro-machining. *Intl J. Adv. Manufacturing Technol.* **102** (2019) 9–12.
[20] Wei Li, Yinghui Ren, Chenfang Li and Zhipeng Li: Investigation of machining and wear performance of various diamond micro-grinding tools. *Intl J. Adv. Manufacturing Technol.* **106** (2020) 10–15.

practice, the designer and analyst have to repeatedly modify the design and carry out verification calculations for strength until the final design is obtained. Automation of this iterative process via mathematical formulation of the optimal design problem allows speeding it up.[21] Obtaining a general method for the optimal design of the body of the wheel, allowing all possible loads and operating conditions, various strength criteria and restrictions to be considered, is practicable only when using mathematical programming methods.

As a result of the calculation the hyperbolic shape of the wheel body was obtained; the finite element method was used to calculate stresses and deformations (deviations from the original shape) from the action of centrifugal forces during high-speed grinding (Fig. 4). Calculations show that further optimization will reduce the deformation of the diamond wheel due to the action of centrifugal forces by 10–15%.

Figure 4. FE analysis of the optimized shape of the grinding wheel body. at a circumferential speed of 300 m/s; the wheel body material is a light alloy based on aluminum.

Turning to the study of the stage of using an SHM tool, it should be noted that one of the most important output indicators of the grinding process is its productivity, especially the specific consumption of diamond grains, assuming that processing quality requirements are satisfied.[1,2] Establishment and use for practical purposes of the functional dependence of the main output indicators of grinding is an actual scientific and production problem.[21,22] This is especially true for the new and not fully understood high-speed machining processes in SHM diamond grinding. It is extremely difficult to reveal such mathematical regularities as may exist with the help of physical experiments, which are likely to incur significant material costs; therefore the global trend is to study such processes through modeling.[3] Unsurprisingly, one of the main tasks that arise in solving this problem is the development and debugging of dynamic models of the process and their analysis; calculation of the grinding process requires significant computational resources. A dynamic 3D model and calculation results are shown in Fig. 5. Table 1 (cols 1–3, 5 & 6) presents the ranges of independent variables (factors) considered in this study for planning model experiments of the high-speed grinding process at the microlevel.

[21] Cong Mao, Fangjian Zhou, Yongle Hu and Peihao Cai. Tribological behavior of CBN-WC-10Co composites for dry reciprocating sliding wear. *Ceramics Intl* **45** (2018) 6447–6458.

[22] Xinying Lia, Yufei Gao, Runtao Liu and Wei Zhou. Experiment and theoretical prediction for subsurface microcracks and damage depth of multi-crystalline silicon wafer in diamond wire sawing. *Engng Fracture Mechanics* **266** (2022) 108391.

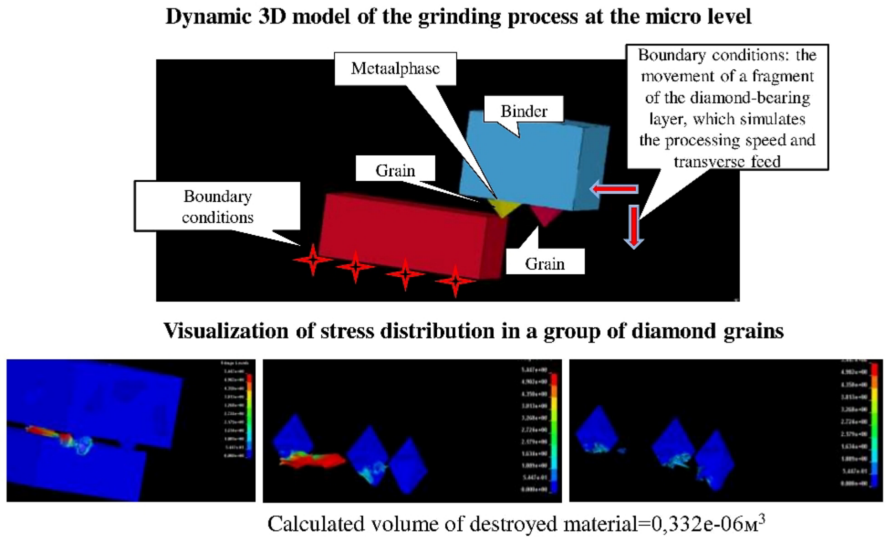

Figure 5. Dynamic model of the grinding process at the microlevel, which makes it possible to calculate the volumes of the destroyed material of diamond grains and the material being processed during processing.

With this approach, it is possible to determine the cutting conditions that ensure the maximum efficiency of the process at minimum cost. A large series of model experiments made it possible to establish trends and mathematical dependencies during high-speed diamond sharpening of blade tools from SHM.

Based on the results of the model experiments, a mathematical model of the process of high-speed diamond sharpening of an SHM tool was constructed, in which the output indicator Y_m is the volume of the destroyed processed material:

$$Y_m = 33.4 + 0.08X_1 - 0.04X_2 + 5.64X_3 + 4.51X_4 + 0.01X_1X_2 + 0.04X_1X_3 - 0.071X_1X_4 - \\ -0.2X_2X_3 + 0.06X_2X_4 + 1.42X_3X_4 - 4.13X_1^2 - 2.51X_2^2 - 11.04X_3^2 - 10.52X_4^2. \quad (7)$$

Using a similar model, we obtain the dependence for the output indicator Y_A—the volume of destroyed diamond grains:

$$Y_A = 37.7 + 0.07X_1 - 0.04X_2 + 4.68X_3 + 3.588X_4 + 0.05X_1X_2 + 0.08X_1X_3 - 0.09X_1X_4 - \\ -0.21X_2X_3 + 0.06X_2X_4 + 2.44X_3X_4 - 3.17X_1^2 - 1.41X_2^2 - 10.04X_3^2 - 7.28X_4^2. \quad (8)$$

Approximating the results of calculations to 0.5 s, we obtain a mathematical model that describes the process of high-speed diamond sharpening of an SHM tool in which the output indicator Y_{Pr} is the performance of the grinding process (i.e., the volume of destroyed processed SHM per unit of time):

$$Y_{\text{Pr}} = 55.91 + 0.02X_1 - 0.07X_2 + 6.79X_3 + 0.51X_4 - 0.001X_1X_2 + 0.01X_1X_3 - 0.001X_1X_4 - \\ -0.02X_2X_3 + 0.06X_2X_4 + 0.32X_3X_4 - 3.83X_1^2 - 3.25X_2^2 - 12.05X_3^2 - 9.52X_4^2. \quad (9)$$

In the same way, a mathematical model of the process of ultrahigh-speed diamond sharpening of an STM tool was obtained in which the output index Y_{SC} is the specific consumption of diamond grains during high-speed grinding (i.e., the ratio of the mass of destroyed working diamond grains to the volume of the destroyed processed SHM):

$$Y_{SC} = 23.12 + 0.04X_1 - 0.17X_2 + 3.66X_3 + 0.56X_4 - 0.001X_1X_2 + 0.006X_1X_3 - 0.023X_1X_4 - \\ -0.03X_2X_3 + 0.014X_2X_4 + 0.031X_3X_4 + 1.28X_1^2 + 1.50X_2^2 + 1.25X_3^2 - 2.36X_4^2. \quad (10)$$

The optimal *Y* value is the best value of the output indicator (for example, the *minimum* value of the specific consumption of diamond grains or the *maximum* productivity value that can be obtained by varying all four factors. This approximation has been repeatedly verified in our studies and has shown good convergence with the experimental results.[6,12]

The results form the knowledge base of the expert system. We recall that the main idea of using expert systems is to capture expert human knowledge, load it into the computer memory and use it whenever the need arises. Consider the conceptual algorithm of the high-speed grinding expert system "HSGES" presented in Fig. 6, which includes the operation of the subroutines and cycles described earlier, as well as the connexion between modules and subroutines into one common system that has a user interface, control panels, input, output and data analysis.

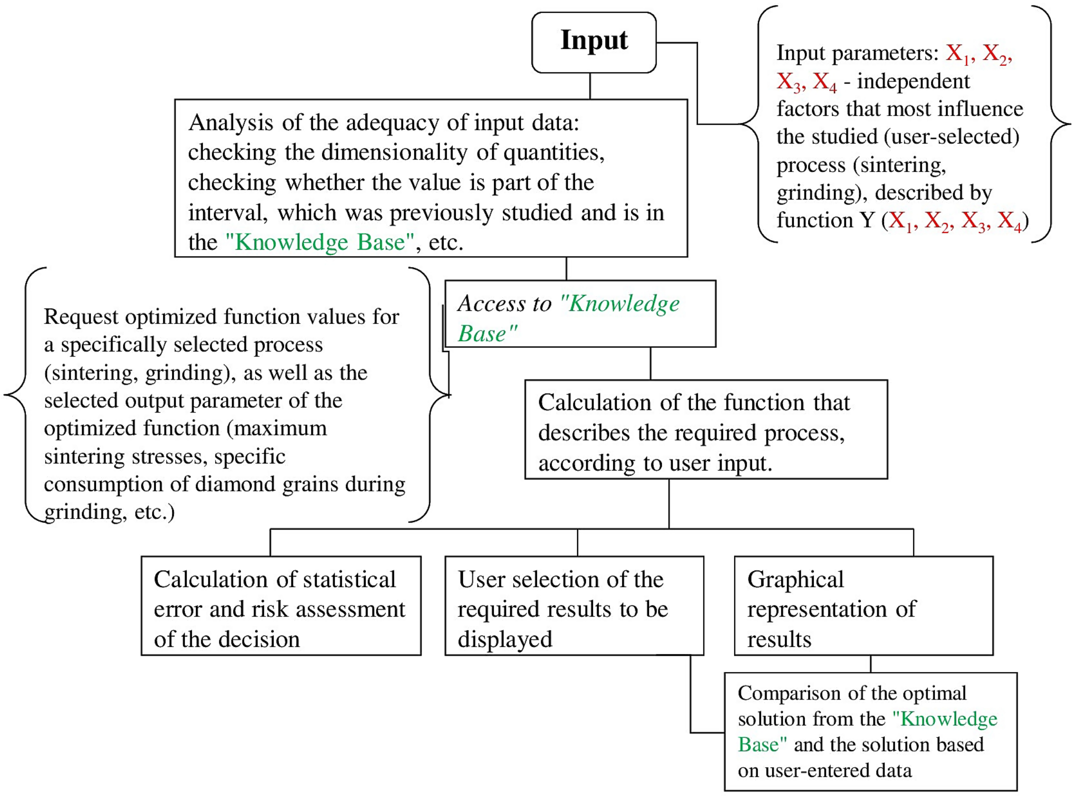

Figure 6. Conceptual algorithm of the "HSGES" expert system for high-speed grinding of SHM.

According to the concept, the expert system should integrate and store the accumulated databases ("knowledge base") of the model and calculate and store results; optimize the mathematical models described above; calculate statistical errors and assess decision-making risks; and update the databases and mathematical models as required. At the same time, it is necessary to give the user the opportunity to access the acquired knowledge and use it to solve any necessary production or scientific problem. To realize this possibility, it was necessary to develop a special computer application that includes a graphical interface through which the user could operate all the functions of the system. Such an application was developed, tested and debugged and Fig. 7 shows the input data tab of the interface.

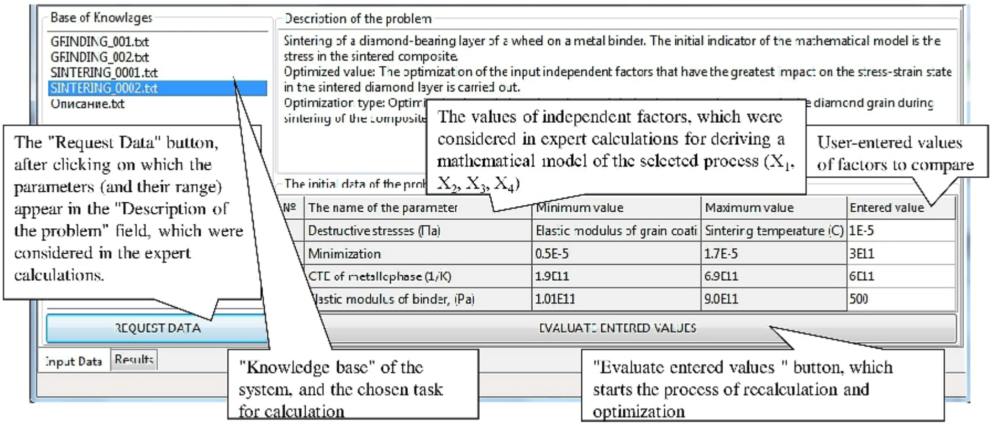

Figure 7. Input data tab of the user interface of the HSGES system.

The idea is that the user sets the input from the proposed set of parameters in the range covered by the system. The parameters are independent variables (factors from eqn 1) that, according to the expert, have the greatest influence on the output parameter (optimized value) of the mathematical model of the selected problem (e.g., for the process of sintering the diamond layer, the optimized value is that of the maximum destructive stresses).

Of course, the results of the calculations used in the knowledge base may contain some errors acquired due to: faulty hypotheses and assumptions made in the modeling; errors in the original data and their inconsistency with the actual parameters; errors in the use of numerical methods; and other factors that are difficult to take into account. Accordingly, it is necessary to propose an approach to justify the error of the results obtained. The definitive criterion is verification via the results of specially designed laboratory experiments and field tests. Such experiments involve significant material costs and require high-tech equipment that provides control measurements with reliable accuracy, especially because the optimality criteria use some physical parameters that cannot be measured directly (e.g., stresses). It should be remembered that the results of field experiments and tests also have errors and their use is possible only after properly estimating such errors. In our present case application of the methods of mathematical statistics may be more practical, whereby the results are considered as one of many possible implementations (i.e., one estimates the probability that the obtained result has a predetermined error).

After clicking on the "Evaluate entered values" button, the "Results" tab opens (Fig. 8). At this moment, the system accesses the knowledge base and displays the optimal characteristics for the selected process and, using user data, determines the characteristic function (3) that describes the selected process. Having received data on the optimal and calculated values of the characteristic function, the system compares the results, displaying the difference between them as a percentage. At the same time, it is possible to graphically present the results, as well as visualize the probability and mathematical expectation. That is, it is possible to predict how the output indicators of SHM diamond grinding will behave with a certain degree of probability, or to obtain predictable information about the quality of a tool made from various superhard tool materials in comparison with the optimal ones. This makes it possible to assess the feasibility of using certain materials and processing modes. Thus, the expert system makes it possible to implement the concept of optimal design and manufacture of diamond wheels for high-speed grinding; enables optimal selection of processing modes to increase the productivity of the SHM high-speed diamond processing and reduce the specific consumption of diamond grains; and finds optimal conditions for sintering the diamond layer in order to reduce the stresses that cause the destruction of diamond grains even at the stage of tool manufacture (i.e., to increase the utilization rate of diamond grains).

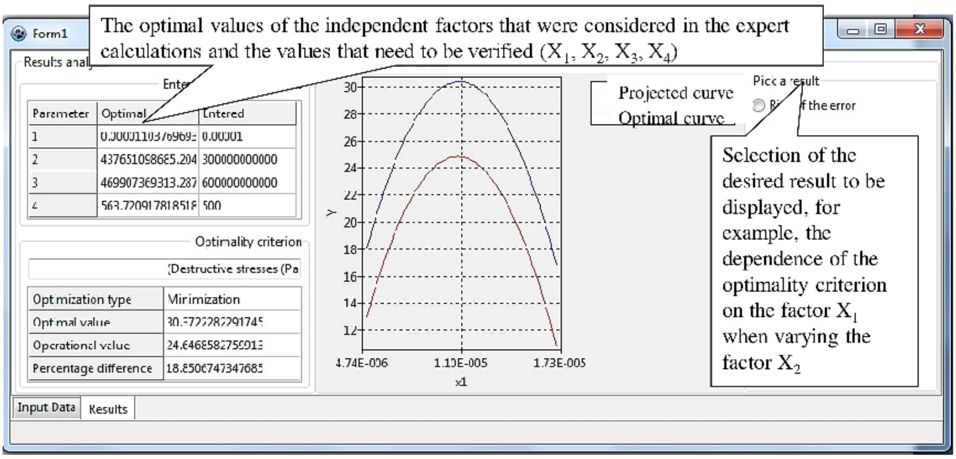

Figure 8. "Results" tab of the user interface of the HSGES system.

This all allows us to consider the presently developed expert system as a component of Industrie 4.0 (Fig. 9), which embodies the transition to fully automated digital production controlled by intelligent systems in real time in constant interaction with the external environment, and which goes beyond one enterprise, with the prospect of integrating en entire economy.[10,23] Many individual elements of Industrie 4.0 have long been successfully applied in practice, but combining them into one integrated system will greatly develop the concept of Industrie 4.0 and provide a new level of production efficiency and likely additional profit through the use of digital technologies.

[23] Some of these integrating features were already apparent in Project Cybersyn.[24]
[24] R. Espejo. Cybersyn, big data, variety engineering and governance. *AI Soc.* **37** (2022) 1163–1177.

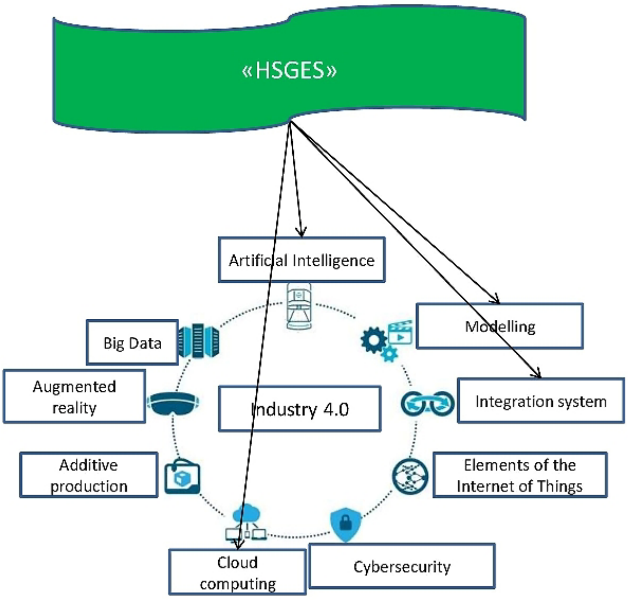

Figure 9. The place of the present work in the modern conditions of application of Industrie 4.0.

The developed software product is flexible and "learnable" (i.e., its further improvement and application to other machining processes is inherent in the product). Modernization of the HSGES system can be achieved by developing new models based on FEM, as well as other modeling methods available to the expert. Subsequent analysis of modeling results and the construction of mathematical models will expand the knowledge base of the HSGES system and, accordingly, increase its efficiency, as well as the degree of applicability in implementation in production processes and research.

5. Summary and conclusions

Theoretical bases and means of realization of the methodology of computer 3D modeling of physical phenomena for the definition of optimum resource-saving processes of high-speed diamond grinding of SHM are developed.

A scientifically based method of designing a diamond-abrasive tool is proposed, taking into account the peculiarities of its manufacture and the conditions of diamond grinding at high speeds.

To estimate the error in the results, methods of mathematical statistics are applied, considering the results as one of many possible implementations (i.e., the probability that the obtained result has a predetermined error is estimated).

Special software was developed that combines all the results of modeling into an expert system that allows the main indicators of the grinding process to be predicted with a certain probability and error, depending on the different properties of the tool and machining modes; the expert system can optimize the conditions of sintering of the diamond-bearing layer in order to reduce the stresses that cause the destruction of the diamond grains at the stage of tool manufacturing.