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ORIGINAL ARTICLE

# Evaluation of the characteristics of diamond grinding wheels at their production and operation stages

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**Abstract** The evaluation of important characteristics of the diamond-bearing layer of grinding wheels contributes to improving the effectiveness of diamond grinding of hard-to-work materials. This evaluation is carried out by applying 3D simulation methodology utilizing the finite element method. The whole life cycle of diamond composite materials, from development and production to operation, is considered. More specifically, the effect of the number of metal phase inclusions within the diamond grain during sintering is studied. Furthermore, a novel approach for investigating the influence of diamond grain wear during grinding, on the grain, is presented. Models exhibiting the impact of diamond grain orientation are also discussed. Finally, the value of grain embedment in bond is investigated. The proposed methodology makes it possible to determine the contribution of force and thermal factors in deflected mode of the diamond-bearing layer in the sintering of grinding wheel and in grinding operation. The role of such factors as grade of grain and wheel bond, relative orientation, and degree of wear of diamond grains can be evaluated during development, production, and operation of diamond composite materials.

**Keywords** Diamond grinding wheel · Finite element method · Metal phase inclusions · Sintering · Grain wear · Grain orientation

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## 1 Introduction

The effectiveness of diamond-abrasive processing is mainly determined by the rational choice of the structure, the physical and mechanical properties of the tool's diamond-bearing layer, and the modes of grinding. The problem of increasing production effectiveness and application of precision diamond grinding tools and single-point tools made of diamond composite material (DCM) is still a challenging one because of the unique physical and mechanical properties of diamond grains; however, it assists in improving the expert evaluation of innovative products [1–3]. Nevertheless, experimental solution of this problem is quite expensive and labor intensive. Current trends in the development of products make use of computer aids, with modeling and simulation being commonly employed [4–6]. The relevant literature reveals the tendency towards transition from two-dimensional (2D) to three-dimensional (3D) simulations to match the advancement in computational power available today [7–10].

More specifically and in regard to grinding, a review on the modeling work performed so far can be found in [11]. Grinding models can be classified into macro- and micro-scale models. Macro-scale models consider the overall wheel–workpiece interaction, while micro-scale models focus on the individual grain–workpiece interactions. Most of the available macro-scale models deal with thermal modeling of surface grinding, with many works dedicated to the distribution pattern of the heat source over the contact length between the grinding wheel and the workpiece. Wang et al. [12] and Jin and Stephenson [13] were among the first to present 3D models. Mao et al. [14] presented a 3D thermal simulation with a parabolic distribution for heat flux in the contact zone. Wang et al. [15] used the finite difference method in order to determine energy partition when grinding TC4 titanium alloy with CBN wheels. In micro-scale models, the modeling of a single grain acting as a cutting tool is usually described. Wang et al. [16] presented a 3D model of a cone-shaped grain interacting with the workpiece. Siebrecht et al. [17] studied the influence of individual grains on the topography of the ground surface.

The proposed methodology described in this paper is based on analysis via the finite element method (FEM) of the deflected mode (DM) of the sintering area of diamond-abrasive tools and grinding area, including the sharpening and finishing of precision diamond single-point tools. In this case, without extended, labor-intensive, and expensive experimental studies, a reasonable composition of the diamond-bearing layer and physical–mechanical properties of its components, i.e., bond of the wheel, graininess, concentration of diamond grains, as well as regular style design of grinding wheel, e.g., for high-speed grinding, can be determined by means of calculation. Indeed, one of the solutions to the problem under consideration is 3D simulation of the mentioned processes. The analysis aims at improving tool reliability at the stages of production, tool sharpening, and operation. Optimum grinding conditions can be determined prior to experiments, allowing drastic reduction of the experimental work volume needed to be performed.

The abovementioned methodology includes the following steps: (1) 3D computer-aided simulation of deflected mode during sintering of the diamond layer in order to determine the conditions under which the integrity of the diamond grains is kept intact; (2) 3D computer-aided simulation of the deflected mode of the grinding area in order to determine reasonable processing conditions; (3) 3D computer-aided simulation of deflected mode in the process of dressing of abrasive wheels with diamond tool; (4) 3D research of topography parameters of the wheel-working surface and machined surface by means of the laser scanning method; (5) 3D simulation of sharpening process of a single-point tool made of DCM for determining conditions for trouble-free operation; (6) 3D computer-aided simulation of the deflected mode of the area of precision diamond single-point processing for determining reasonable cutting conditions and tool geometry for tools made of DCM; (7) development of an expert system for the definition of reasonable characteristics of DCM and modes of their processing. Thus, the philosophy of comprehensive computer-aided automation of all processes' simulation, including production, machining, and operation of precision diamond tool, is realized. In this paper, the first two steps will be considered.

The solution of the considered tasks may be undertaken by commercial software packages for FEM simulations; in this study, *COSMOSWorks* is used. Finite element analysis is carried out using eight nodded SOLID elements. Selective refinement in the area of the inclusion of metallic phases is carried out when constructing the finite element mesh of the model. The elements of the Hex Dominant type are used when creating a mesh for metallic phases. Such an approach makes it possible to simulate the deformation of model fragments accurately enough, while taking into account the remoteness of edge effect areas.

The following characteristics of the system elements are put in the calculation model according to the reference data: elastic modulus ($E$), bulk modulus ($G$), coefficient of linear thermal expansion ($\alpha$), Poisson's ratio ($\mu$), yield strength ($\sigma_0$), and the coefficient of heat conductivity ($\lambda$). The methodology of simulation is explained in greater detail in other works of the authors [1, 2, 18–23]. In the present work, an extension of relevant works performed earlier by the authors, the influence of the quantitative composition of metallic phase in diamond grain and of the temperature on the deflected mode of the diamond layer during diamond wheel sintering is considered. Furthermore, the influence of diamond grain wear, grain orientation, and grain embedment in bond are investigated and discussed. The estimated simulation models are verified and validated by data from a wide range of experimental investigations carried out by the authors [23].

## 2 Influence of the quantitative composition of metallic phase in diamond grain on the deflected mode of the sintering zone

Diamond crystals are synthesized under high pressure and temperature in the presence of iron–nickel alloy catalyst [24]. Impurities, in the form of metal phase inclusions, are identified in the synthetic diamond crystals [25]. Furthermore, heating of the synthetic diamonds above the temperature of 850 °C can lead to a decrease in strength [27]. It is the authors' opinion that the reason for this is a significant difference in the values of the coefficients of thermal expansion of metallic phase and diamond grains [1]. As a rule, thermal expansion coefficient of the metal catalyst is much greater than that of synthetic diamond; therefore, diamond grain is damaged from within when heating.

In order to investigate the influence of the quantity of metallic phase in a grain, models with different percentages of metallic phase are developed. In the reference model, the diamond grain of AC6 brand (graininess 160/125) is considered. In Table 1, the physical properties of the grain-metallic phase-bond system, which were used in the analysis, are shown [28].

The metallic phase in the diamond grains can reach 10% of the grain volume [28]. In order to analyze the influence of the quantitative composition of metallic phase in grain, models were developed with various percentages of metallic phases, as well as with random orientation of metallic phases. Figure 1 shows the estimated model containing one metal catalyst inclusion (3% metallic phase), two (6%), and three (9%).

In Fig. 2, the effect of the quantitative content of metallic phase in grain to changing equivalent stresses generated in the

**Table 1** Physical properties of the grain-metallic phase-bond system

| | Grain | Metallic phase | Bond |
|---|---|---|---|
| Modulus of elasticity (GPa) | 1060 | 273 | 110 |
| Compression modulus (GPa) | 360 | 40 | 40 |
| Poisson's ratio | 0.1 | 0.2 | 0.37 |
| Coefficient of thermal expansion (1/K) | $0.95 \times 10^{-6}$ | $1.3 \times 10^{-5}$ | $24 \times 10^{-6}$ |
| Thermal conductivity (W/mK) | 2400 | 78 | 390 |
| Specific heat capacity (J/KgK) | 1400 | 39 | 390 |

sintering zone of the diamond layer is shown. Stress diagrams show that the maximum stresses when heating up to the temperature 850 °C are concentrated in the field of metallic phase and it is the metal phase that plays a key role in the destruction of the diamond grains in the sintering process of diamond-abrasive tools. With the locations of the metallic phase inclusions close to each other, one can see the growth of stress fields spreading to 40% of the grain volume. With all three inclusions of metallic phase placed at the bottom of the grain, as can be seen in Fig. 2c, stress superposition is observed; this leads to the destruction of a significant amount of diamond grains.

Experimental investigations of the parameters of working surface of diamond wheels by laser scanning convincingly confirmed the results of theoretical calculations [23]. A prototype batch of grinding wheels on metal bond with diamond grains AC6 (metallic phase percentage 9%), AC15 (metallic phase percentage 6%), and AC32 (metallic phase percentage 3%) with 200/160 grain size was produced in order to corroborate the theoretical calculations of the influence of quantitative composition of metallic phase in the grain on the DM of the sintering area of diamond-abrasive tools. After sintering, the metal bond of the grinding wheel was electrochemically dissolved and the sizes of extracted diamond grains were compared with sizes of grains in their initial condition using a microscope. It turned out that 80% of the grains of AC6 brand were fractured, 38% of the grains of AC15 brand were fractured, and only 13% of grains of AC32 brand were fractured. The experiment validates the conclusion that the greater the percentage of metallic phase in diamond grains, the greater the probability of their fracture when sintering a grinding wheel.

## 3 Influence of diamond grain wear degree on deflected mode of grinding area

Regarding the process of grinding, a novel approach is suggested for the study of the influence of diamond grain wear degree on deflected mode of grinding area. This approach makes it possible to select the optimum characteristics of the diamond-bearing layer of a grinding wheel in a more reasonable manner. Cases with varying degrees of diamond grain wear ($U$), namely 10, 25, and 40% of the value of grain protrusion from the bond, are simulated. The finite element model setup of this approach is shown in Fig. 3.

The results of the analysis of the influence of grain wear on the deflected mode of grinding area are presented in Fig. 4. Since the material being processed is synthetic diamond, the friction coefficient of diamond on diamond is low, so the temperature in contact area is not high, and in consequence, stresses are not visually fixed in the area of metallic phase arrangement. The results show that growth of stress is observed in contact area, even at temperatures of about 400–500 °C, due to the increased contact area of grain with the workpiece.

In a non-elastic scheme of grinding, the growth of stresses is observed in the contact area because of the increased contact area of grain with the material being machined. Tensile stresses exceeding their limiting values for the bond appear in embedment locations of grains in the diamond matrix [23]. Thus, growth of the worn place of a grain contributes to intensification of the process of self-sharpening of the diamond wheel when grinding. Optimal conditions for self-sharpening of a

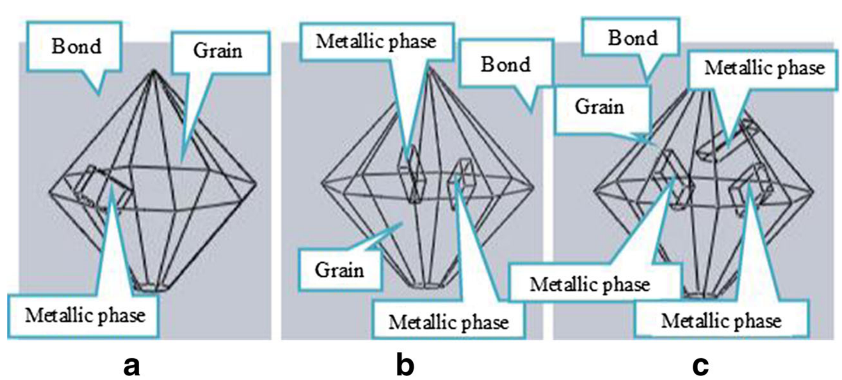


**Fig. 1** 3D models of diamond grains containing **a** one, **b** two, and **c** three inclusions of metal catalyst

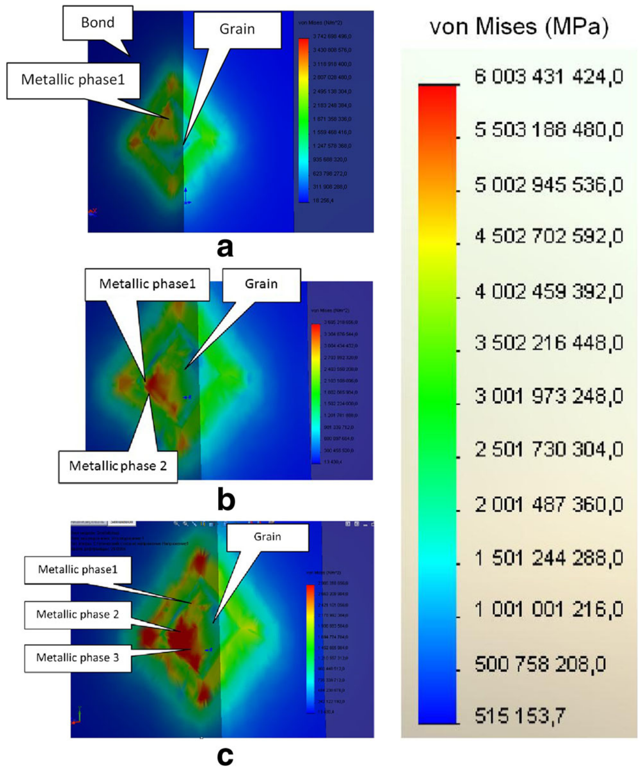


**Fig. 2** Influence of the number of inclusions of metal phase in grain on equivalent stress occurring in sintering zone of diamond-bearing layer for **a** one inclusion, **b** two inclusions, and **c** three inclusions

diamond wheel in the processing of certain groups of workpiece materials can be achieved by a qualitative selection of composition properties [29].

## 4 Influence of diamond grain orientation in the composite on DM of grinding area

One way to reduce the cost of machine component manufacturing is to increase tool life and cutting ability; these

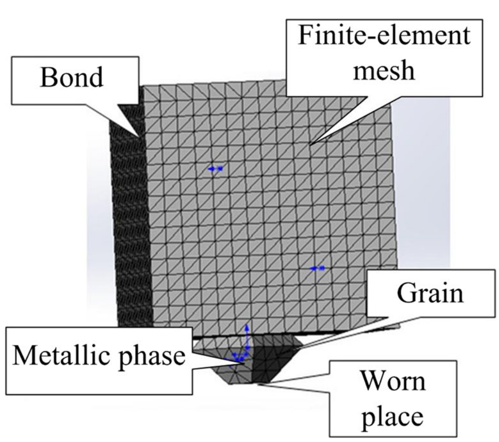


**Fig. 3** Finite element model that simulates wear of diamond grains in grinding

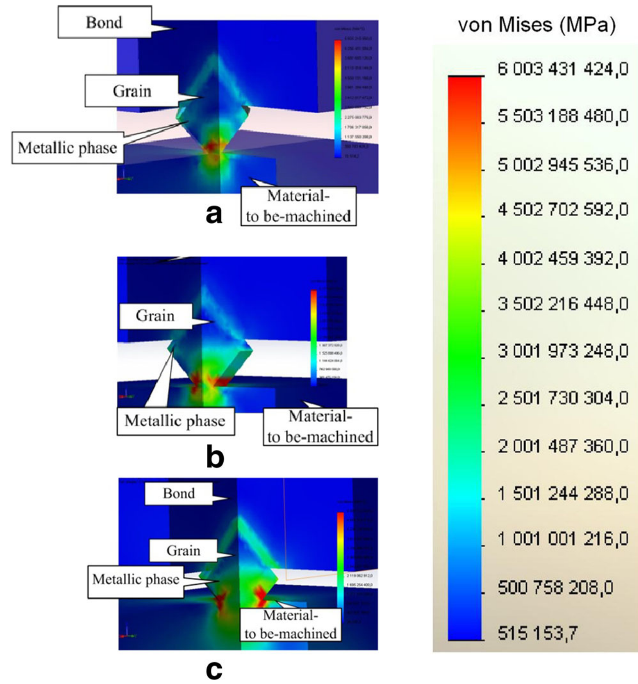


**Fig. 4** Stress distribution contours for various degrees of diamond grain wear. **a** $U = 10\%$. **b** $U = 25\%$. **c** $U = 40\%$

attributes can be achieved by using abrasive diamond wheels with oriented grains [26]. In ordinary grinding wheels, the abrasive grains are placed chaotically. During processing, the cutting edges of non-oriented abrasive grains come into contact with the surface being machined at various angles, which frequently differ from the theoretical rational cutting angles. This imposes considerable cutting forces and therefore thermal impact, which leads to structural changes in the surface layer, e.g., occurrence of burns.

A model with grains randomly inclined relative to the vertical axis is developed in order to study the DM in grinding area. The proposed model, showing the influence of randomness of diamond grain distribution on DM in grinding area, is shown in Fig. 5 and the results of the calculations are presented in Fig. 6.

Figure 7 shows the stress distribution at the location of the grain at a 90° angle to the longitudinal axis; processing is carried out with the blunt edge of a larger area of contact with the workpiece.

Computations show that in the case of grain inclination relative to the vertical axis of more than 45°, stresses along the contour of grain embedment in the bond are increased. Besides, stress in the neighborhood of the inclusion of metallic phase increases by 5–10% compared with the grain oriented perpendicularly. In the case of orientation of the grain by blunt edge to the workpiece, growth in the amount of stress fields in the microcutting area is observed, indicating an increase in cutting forces in this situation.

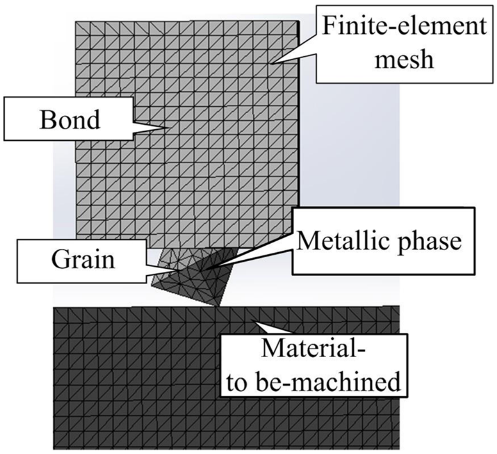


**Fig. 5** Finite element model that simulates randomness of grain distribution in composite

## 5 Influence of grain embedment value in bond on DM of grinding area

Because of the different height of grains over the bond, the efficiency of their application is very low. Due to the different height of grains, only 10–17% of grains are considered to actually cut [28], while the rest plastically deform metal or are not in contact at all with the workpiece. The force pulling the grain depends essentially on its protrusion over the bond surface, and the grains are not held in the bond in case of embedment less than $h_{emb}$ = 12–30% of its nominal size [28]. In order to study this problem, a model was developed for the determination of reasonable structure and properties of diamond composite materials. In this model, different values of grain embedment in the bond are taken into account.

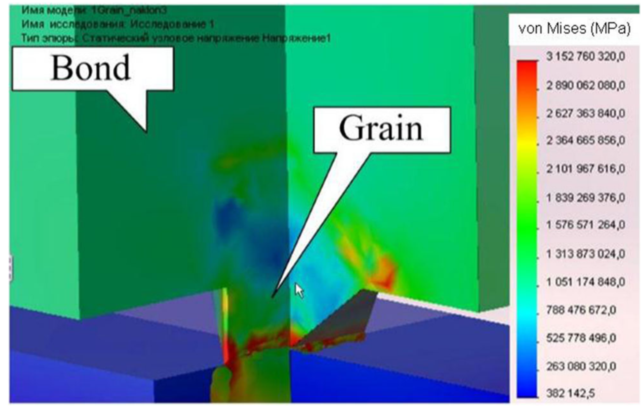


**Fig. 7** Stress distribution on grain at 90° angle to longitudinal axis

Figure 8 shows the results of calculation of diamond grains with dimensions of 250/200 μm embedded in metal bond at the value of 20, 50, and 65%.

The obtained results show that with increase of grain protrusion over the bond from 35 to 80%, pulling force decreases by 1.3–1.7 times. With increase of grinding temperature, the role of thermal stresses increases significantly. In case of embedding the grain in the metal bond to a value not less than 65% of total grain size, clogging of the grinding wheel can take place, because the stresses occurring are not sufficient to pull the grain out of the bond.

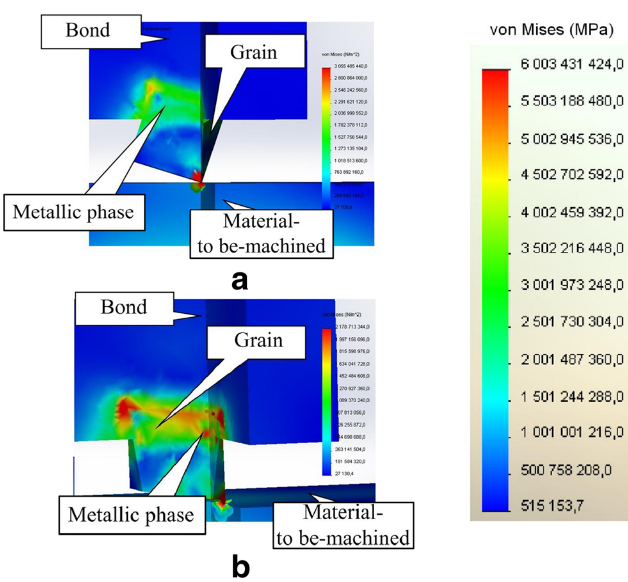


**Fig. 6** Stress distribution of "diamond grain–metallic phase–bond–material-to be-machined" system in DM for various grain orientations. **a** Grain is inclined to vertical axis at 30°. **b** Grain is inclined to vertical axis at 60°

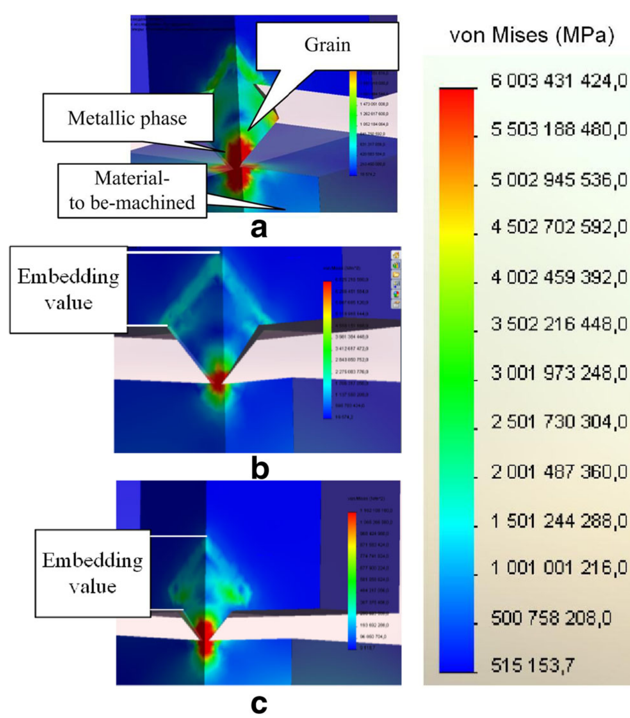


**Fig. 8** Visualization of stress fields in system under study in accordance with embedment of grain in bond. **a** $h_{emb}$ = 20%. **b** $h_{emb}$ = 50%. **c** $h_{emb}$ = 65%

## 6 Conclusions

From the performed analysis, several useful conclusions can be drawn:

- The decrease in strength of the synthetic diamonds above the temperature of 850 °C is attributed to the significant difference in the values of the coefficients of thermal expansion of metallic phase and diamond grains. Stress diagrams of the presented analysis show that the maximum stresses when heating are concentrated in the vicinity of the metallic phase; this plays a key role in the destruction of the diamond grains in sintering process of diamond-abrasive tool.
- The analysis indicates the influence of diamond grain wear on the behavior of the grain and bond material in grinding. An increased contact area due to grain wear intensifies the process of self-sharpening of the wheel.
- Grain orientation plays a significant role in tool life and cutting ability of the grinding wheel. Analysis shows that grain inclination of more than 45° relative to the vertical axis increases stresses along the contour of grain embedment in the bond.
- Grain embedment value in bond controls the efficiency of the grinding wheel. An increase of grain protrusion over the bond from 35 to 80% decreases pulling force by 1.3–1.7 times.

Application of the proposed models makes it possible to improve the process of scientifically based selection of wheel characteristics, manufacturing, and operation conditions. The results of the research make it possible to select the brand of diamond grain, in accordance with the content of metallic phase and grain shape, and the optimal parameters of the working surface of grinding wheel, i.e., the height of grain protrusion over the bond and allowable degree of wheel wear, without lengthy experimentation.

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