Heat treatment effect on structural and elastic characteristics of a single-component abrasive tool

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Abstract. The article presents the results of a research of elastic properties of a bondless single-component abrasive tool (SCAT) after sintering. The method of determining the modulus of elongation and porosity based on theoretical and experimental data is used. The dependency between the modulus of elongation and porosity, as well as experimental formulas indicating these dependencies, are presented. Based on the experimental and calculated data on the magnitude of the modulus of elongation, depending on the sintering temperature and the size of the abrasive grains in the initial abrasive compound, empirical dependencies of the elastic characteristics are determined in order to predict the production of a bondless tool with predetermined properties.

1. Introduction
Obtaining a bondless single-component abrasive tool (hereinafter referred to as SCAT) from an abrasive compound of white fused alumina and boron carbide [7, 8], relates to powder metallurgy and consists in pressing and further sintering at high temperature. Only after sintering, the tool obtains the necessary strength, structural and elastic characteristics – porosity and modulus of elongation, which, being considered structurally insensitive, are deeply connected structurally insensitive, are deeply related to the nature of adhesion forces and other structural features of a porous brittle body (nature of bonds, crystalline structure, etc.).

Therefore, the study of the elastic zone of deformation is of great practical importance for brittle states of bodies under conditions of processing and operation.

The importance of the research of elastic deformation is conditioned upon the fact that it is the process of deformation and fracture that begins with it. [20]

The article presents the results of a research of the elastic properties of a bondless single-component abrasive tool (SCAT) after sintering.

2. Characterization of properties of single-component abrasive tool structure
The conducted analysis of scientific and technical sources on the manufacture, structure and properties of the modern abrasive tool [1-4] leads to the conclusion that to improve the efficiency of the abrasive processing, one of the directions is the improvement of the abrasive tool, to which researchers and manufacturers impose the following requirements:

1. high strength of cutting grains and the tool as a whole;
2. high retention forces of bonded abrasive grains in order to maximize the use of the cutting properties of the grains;
3. a large number of cutting edges on the working surface of the tool;
4. a sufficient number of pores in the body of the instrument.

The comparative study of domestically produced and foreign-made tools for \( \text{Al}_2\text{O}_3 \) honing were carried out according to indicators provided by the national standard [5]. The interest in such tools is conditioned by the fact that the efficiency of the honing process and the quality of the processed surface depend on them in many respects. The results of the research showed that the properties of abrasive particles and the density of the tool had a significant impact on the performance of the tool [6].

One way to create a highly porous wear-resistant durable tool is a bondless single-component abrasive tool (SCAT) [7, 8], which was created at the Engineering Technology Department of Volgograd State Technical University. In the complete absence of the bond in the volume of the instrument, the grains are bonded to each other along contact juvenile surfaces (bond bridges), formed as a result of approaching white fused alumina grains during compression by shock wave. Bond bridges acquire significant strength (like the entire tool) as a result of the consequent high-temperature sintering.

Figure 1 shows the grain size distribution curves of white fused alumina depending on the pressure in the shock front. The presence of breakpoints on all the curves (Fig. 1) can be explained as follows. When a shock wave passes through an abrasive powder, it crushes it and, with the relative movement of grains and their fragments, makes them come together and contact not at the points, but over newly exposed juvenile surfaces. Unexpectedly broken attractive forces with high activity interact with a new face of another grain to form bond bridges owing to cohesive forces. This is a short-term process, and cohesive interaction does not lead to the formation of sufficiently strong bonding forces between the grains, but the pressing already has a certain strength. Since an expansion wave follows its compression front when a shock wave moves, expansion pressure also increases with increasing pressure in the compression front. The expansion pressure, in turn, leads to a certain redistribution of pores in the pressing owing to the weakening of cohesive forces in some bond bridges and their strengthening in others. Pore redistribution takes place under certain pressing conditions, i.e. when the expansion forces are superior in their magnitude to the cohesion forces formed during abrasive powder compression.

![Figure 1. Grain size distribution in white fused alumina pressings – pressure in the shock wave front is as follows – 1 – 75 hPa; 2 – 50 hPa; 3 – 15 hPa](image)

3. Formation of properties of a single-component abrasive tool in its manufacture
In the manufacture of single-component abrasive tools [7, 8], the task of ensuring uniform distribution of abrasive grains and pores is one of the main ones in the formation of their structure at the stage of abrasive compound preparation. But if creating a molding compound for the manufacture of a standard abrasive tool, only thorough mixing of all the components is enough, then the manufacture of SCAT has a number of special features.
The pressing of the abrasive powders compound was carried out in accordance with the scheme shown in Fig. 2 using the equipment described in [9].

![SCAT explosive pressing scheme](image)

**Figure 2.** SCAT explosive pressing scheme: 1 – plunger; 2 – cathode; 3, 5 – insulators; 4 – explosion (discharge) chamber body; 6 – water; 7 – plate; 8 – striker; 9 – support bar; 10 – mold body; 11 – pressed abrasive powder; 12 – matrix; 13 – press bed

The research was conducted with the help of the electro-hydraulic installation T-1226. After the accumulation of electric energy in capacitors with the capacity of 200 μF at the voltage of 10 kV using two electrodes 2 and 4 (discharge chamber body), an electric arc was formed in the water bath 6, which led to the instantaneous formation of a gas bubble, upon the disappearance of which a shock wave was formed. The latter acted on the plate 7, the plunger 1 and – through the striker 8 – to the pressed abrasive powder 11, consisting of alumina powder (Al$_2$O$_3$) (90%) and boron carbide (B$_4$C) (10%) and used in the manufacture of SCAT according to the method [7].

As far as is known, elasticity is the property of bodies to change shape and size under the loads and to spontaneously restore the original configuration upon termination of the influence of external loads. The elasticity of bodies depends on the forces of interaction of the atoms from which they are built.

Under the action of external stresses, atoms are displaced from their equilibrium positions together with an increase in the potential energy of the body by an amount equal to the work of external stresses on changing the shape of the body. After the removal of external stresses, the configuration of an elastically deformed body with non-equilibrium interatomic distances turns out to be unstable and spontaneously returns to the equilibrium state. The excess potential energy stored in the body is converted into the kinetic energy of the vibrating atoms, i.e. in heat energy.

This paper presents the results of a research of the structural and elastic characteristics of the SCAT, including the density, porosity, and modulus of elongation, depending on the porosity of the abrasive tool after pressing and sintering the test abrasive compound containing 90% of alumina (Al$_2$O$_3$) and 10% of carbide boron (B$_4$C) to obtain the SCAT in accordance with the patent [7]. A more detailed technique for choosing the boundary values of the parameters is described in the publication of the author [17].

4. Determination of elastic characteristics of a single-component abrasive tool

According to a number of scientists [4, 10, 19], the magnitude of the modulus of elongation can be considered as a characteristic of elastic resistance, or elastic hardenability, of a material, i.e. as a characteristic of the intensity of the increase in stress with the increase of elongation. The greater the modulus of elongation is, the stronger the stress increases with the increasing elastic deformation.
Ya.I. Frenkel considered the sintering stage as the fusion of droplets, where the gaps between the particles float so much that the remaining pores are disconnected. The subsequent stage of sintering reduces to closing, or so-called “crust formation,” of the residual pores that do not intercommunicate.

The existing explanations of the processes of the mix of materials in the solid phase are based either on the idea of the need to increase the energy of surface atoms involved in the interaction, or on the idea of the possibility of interaction only on juvenile surfaces formed after the removal of oxide films, or on the concepts of the decisive role of diffusion. All the ideas can be divided into two groups – the first one explains the formation of dissimilar materials compounds due to seizure resulted from the interatomic forces of interaction. Seizure is a diffusion-free process, after which diffusion processes are possible. If juvenile surfaces are formed in the contact zone during connection, then their activity is sufficient to provide the seizure. The bonding process is reduced to the “stitching” of contact surfaces, the formation of bonds among the atoms belonging to different surfaces [10, 21].

When studying the sintering process, the action of the following mechanisms is usually taken into account: a) without the transfer of material (by adhesion); b) with the transfer of material over considerable distances by moving lattice elements (surface and volume diffusion along defects, through the lattice and along grain boundaries, evaporation and condensation) or moving the entire lattice (plastic flow, sliding along the grain boundaries); c) with the transfer of material within the interatomic distances (return and recrystallization).

Due to plastic deformation, when the powders are pressed, the surfaces of the contacting grains close the range sufficiently, the surface films are repeatedly torn, and their insulating effect is largely eliminated. Therefore, the main factor is the geometric factor of binding.

The studies of R.A. Andriyevskiy [11] also prove that the self-diffusion mechanism is predominant during the alumina powders sintering. At the initial stage of sintering, the growth of contact zones is decisive; at the later stage, closed porosity is formed. G.S. Kuchinskiy extended the theory of volume diffusion also to the late stages of sintering.

In his work [11], he examined the effect of grain boundaries on the process of sintering, especially at the final stage of the disappearance of pores. By doing so, he estimates the rate of disappearance of pores from a polycrystalline sintered body based on two mechanisms – only diffusion along grain boundaries and volume diffusion of vacancies (upon reaching the grain boundaries, vacancies are removed from the body on its surface). The limiting link here is volume diffusion as the slowest one. The pore is considered as a place of accumulation of vacancies; the mechanism becomes apparent when considering vacancies as diffusing units replaced by atoms, taking into account the gradient of hole concentrations from the pore deep into the material [10].

Figure 3 shows the dependence of the density of the SCAT on sintering temperature.

Figure 3. Effect of the temperature of sintering (T, °C) on the density (ρ, kg/m³) of the SCAT for the initial size of Al₂O₃: 1 – 100 μm; 2 – 200 μm; 3 – 320 μm; 4 – 400 μm; 5 – 500 μm.
The dependences obtained using [15, 16] are as follows:

initial grain size of Al$_2$O$_3$ – 100 μm:

\[ \rho = 46.1 \cdot T^{0.564} \]  

(1)

initial grain size of Al$_2$O$_3$ – 200 μm:

\[ \rho = 180.8 \cdot T^{0.376} \]  

(2)

initial grain size of Al$_2$O$_3$ – 320 μm:

\[ \rho = 217.4 \cdot T^{0.346} \]  

(3)

initial grain size of Al$_2$O$_3$ – 400 μm:

\[ \rho = 547.6 \cdot T^{0.218} \]  

(4)

initial grain size of Al$_2$O$_3$ – 500 μm:

\[ \rho = 716.6 \cdot T^{0.18} \]  

(5)

As a result of sintering, boron carbide burns out already at a temperature of 700-800 °C [7], leaving small pores in the abrasive body, which become “healed” with an increase in sintering temperature, or close.

As a result, the porous body becomes solid sporadically.

The next stage of the research is to determine the porosity of sintered abrasive bodies. This value is determined by [12], using the dependence (6):

\[ \Pi = \frac{\rho_{p.s.} - \rho_{p.b.}}{\rho_{p.s.}} \]  

(6)

where \( \rho_{p.s.} \) is density of pure substance of Al$_2$O$_3$, kg/m$^3$; \( \rho_{p.s.} = 3900 \) kg/m$^3$;

\( \rho_{p.b.} \) is density of the porous body, kg/m$^3$.

Using the formula presented in [13], it is possible to determine the value of the modulus of elongation from the values of porosity:

\[ \frac{E}{E_p} = 1 - \frac{15(1-\mu)P}{(7-5\mu)+2(4-5\mu)P} \]  

(7)

where \( E_p \) is the modulus of elongation of the porous body, GPa;

\( P \) is porosity;

\( E \) is the modulus of elongation of the pure substance, GPa;

\( \mu \) is Poisson’s ratio (\( \mu = 0.23 \)).

Figure 4. shows the dependences of the modulus of elongation on the porosity of the SCAT, which are not rejected by the data of the issue [14].

![Figure 4](image-url)
After processing the calculated graphs, the following analytical dependencies were obtained:
for the grain size of $\text{Al}_2\text{O}_3$ 100 $\mu$m:
$$E_p = 1166 \cdot P^{0.412}$$ (8)
for the grain size of $\text{Al}_2\text{O}_3$ 200 $\mu$m:
$$E_p = 1256 \cdot P^{0.462}$$ (9)
for the grain size of $\text{Al}_2\text{O}_3$ 320 $\mu$m:
$$E_p = 1383 \cdot P^{0.534}$$ (10)
for the grain size of $\text{Al}_2\text{O}_3$ 400 $\mu$m:
$$E_p = 1465 \cdot P^{0.577}$$ (11)
for the grain size of $\text{Al}_2\text{O}_3$ 500 $\mu$m:
$$E_p = 1164 \cdot P^{0.41}$$ (12)

5. Conclusion

Based on the results of the research, it is possible to draw the following conclusions.
The formation of a porous abrasive body during sintering leads to ‘healing’, i.e. laminating of very small pores and the formation of a large number of bond bridges among abrasive grains $\text{Al}_2\text{O}_3$, which helps to increase the elastic properties of the porous body.
The practical significance of the elastic properties of materials is great [18, 22]. To prevent loss of stability, it is necessary to strive to use materials with a high value of the modulus of elongation. Materials with its reduced value at the expense of the accumulation (during operation) of a large supply of elastic energy have a high rate of microcracks development, which is their drawback.
The pressing has insignificant strength owing to the adhesive and cohesive forces of interatomic interaction and, therefore, at the stage of sintering, the tool acquires its final elastic characteristics.

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