Sintering and properties of materials based on nanosized silicon nitride powder

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Abstract. A high-density material (ρ = 3.28 g / cm³, porosity 1.4% by volume) based on nanosized silicon nitride powder was obtained by the method of liquid-phase sintering. The effect of compacting pressure on the density of sintered silicon nitride materials is shown. The process of material structure formation during sintering has been studied. The main physical and mechanical characteristics were determined: density, porosity and grain size of the solid phase, elastic modulus, flexural and compressive strength, crack resistance coefficient, Vickers hardness.

1. Introduction

Silicon nitride is widely used in industry due to the unique combination of properties, such as high hardness and mechanical strength, low thermal conductivity and good erosion properties, which makes it possible to use silicon nitride products as wear-resistant, heat-resistant and acid-resistant materials operating in extreme conditions of high temperatures and aggressive environments [1–7]. Silicon nitride materials can be obtained by various methods: reaction sintering, activated sintering, chemical vapor deposition, and hot, hot isostatic pressing [8–11]. High properties are achieved in materials obtained by the last two methods, however, the high energy consumption and the impossibility of obtaining workpieces of complex shapes, as well as the use of high-density and expensive graphite as a press tooling, makes the production of materials by this method limited. It is impossible to obtain dense materials with a porosity of less than 5% by volume by the method of reaction sintering [12–19]. The use of the method of chemical vapor deposition leads to the production of materials with a practically theoretical density, but due to technological difficulties, their serial production is difficult. The most optimal method in terms of labor intensity is liquid-phase sintering with oxide additives. The method leads to the production of a material with high mechanical properties with less energy consumption and technological costs [20]. To obtain materials with a high level of mechanical properties, it is necessary to use finely dispersed powders, which is feasible with an additional technological grinding operation. The use of nanosized powders (NSP) as a starting material leads to the best mechanical characteristics, but complicates the intermediate stages of product preparation.

The aim of this work is to study sintering and analyze the properties of ceramic materials by liquid-phase sintering using nanosized silicon nitride powders.

2. Materials and methods of research

We used a Si₃N₄ plasma-chemical powder (NEOMAT Co, Latvia) with a specific surface area of ~ 40 m²/g and an average particle size of 20–40 nm and a powder obtained by furnace synthesis of the LC-
12 brand (Sandvik Materials Technology, Germany) with an average particle size \( d_{0.5} \sim 1 \mu m \). The compositions of the materials studied in the work are given in table 1.

**Table 1. Compositions of ceramic materials from silicon nitride.**

| № | composition | 5Al\(_2\)O\(_3\)\(\cdot\)3Y\(_2\)O\(_3\) content, % | Content of nanosized Si\(_3\)N\(_4\), % | Content of micron Si\(_3\)N\(_4\), % |
|---|-------------|-----------------------------------------------|--------------------------------|---------------------------------|
| 1 | 15          | 0                                             | 85                             |
| 2 | 15          | 5                                             | 80                             |
| 3 | 15          | 10                                            | 75                             |
| 4 | 15          | 15                                            | 70                             |
| 5 | 15          | 20                                            | 65                             |
| 6 | 15          | 25                                            | 60                             |
| 7 | 15          | 40                                            | 45                             |
| 8 | 15          | 60                                            | 25                             |
| 9 | 15          | 75                                            | 10                             |
| 10| 15          | 85                                            | 0                              |

To increase the bulk density of nanosized silicon nitride, the powder was repeatedly briquetted and granulated. The initial powders in a given ratio were mixed in a drum mixer. A 2% aqueous solution of polyethylene glycol was used as a temporary technological binder.

The resulting compositions with different mass content of micron and nanosized powder were poured into grinding drums with corundum grinding bodies in a material:grinding bodies:alcohol ratio of 1:6:1.2 and stirred for 3 h, ethyl alcohol was used as a dispersion liquid. To remove the excess amount of alcohol, the resulting mixture was dried in a drying oven to a residual moisture content of 3-5%, then granulated by rubbing through a sieve with a mesh size of 200 \( \mu m \). After that, the samples were pressed by the method of semi-dry molding in a steel mold on a hydraulic press at pressures of 25, 50, 75, and 100 MPa.

The samples were sintered in a vacuum furnace in a nitrogen atmosphere at a temperature of 1780 °C with a holding time of 40 min. After sintering, the phase composition was determined, and the physicomechanical characteristics of the samples were also studied.

The porosity was determined by hydrostatic weighing. Three-point bending strength was measured on a ShimadzuAG-300kNX setup. The crack resistance coefficient and Vickers hardness were determined by the method of indentation with a Vickers pyramid on a PMT-3M microhardness tester. The microstructure was examined with a Quanta 200 electron microscope.

3. Research results and discussion

High-quality ceramics with the maximum level of mechanical properties can be obtained by molding high-density materials. The sintering process of oxygen-free ceramics can be controlled by adjusting the dispersity, morphology, and structural defects of covalent refractory compounds. Silicon nitride is characterized by a low concentration and mobility of lattice defects and inhibition of diffusion processes, because diffusion-viscous flow processes responsible for mass transfer and compaction during solid-phase sintering are suppressed in the lattices of covalent compounds.

Sintering can be substantially intensified by introducing activating additives, which, in certain temperature ranges, form a liquid phase at the grain boundaries of the main component. It is also possible to accelerate the compaction of the material by reducing the size of the initial particles using nanosized powders. During sintering of nanosized powders, diffusion paths are shortened and mass transfer increases [21].

The quality of the materials obtained from silicon nitride depends on the presence of impurities (Fe, Al, Ca, Mg, Na, O\(_2\), etc.) in the starting material, which negatively affect the mechanical properties of the finished product. The most chemically pure product with a small amount of impurities and a high degree of stoichiometry can be obtained by furnace synthesis. Plasma-chemical nanosized powder,
along with high dispersion, has a number of disadvantages, such as the presence of impurities of free silicon and oxygen.

During storage and processing, nanosized silicon nitride powder, due to its high activity, absorbs oxygen on the surface, forming thin oxide SiO₂ films, which interact with oxide activators during sintering to form a silicate melt.

Along with the use of nanosized powder for the preparation of high-density silicon nitride materials, various sintering-activating additives are used that form solid solutions with silicon nitride. Among the most energetically active oxides are Li₂O, BeO, MgO, CaO, Al₂O₃, Y₂O₃, Ce₂O, ZrO₂, as well as binary oxide mixtures introduced into the composition of silicon nitride materials, both in the form of initial components and in the form of binary eutectic compounds.

As an activating additive, a mixture of aluminum and yttrium oxides in a ratio of 5: 3 was used in the work, forming at the sintering stage yttrium aluminum garnet [22], the melting point of which (1860 °C) is significantly lower than the melting point of individual oxides. The presence of SiO₂ in the form of a thin molecular surface layer on silicon nitride particles guarantees high wettability (approaching 0°) of nitride with an oxide melt.

The sintering mechanism consists of the following processes: compaction of particles by the solid-phase sintering mechanism; the formation of low-melting silicates and glasses; redistribution of Si₃N₄ particles in the presence of a liquid silicate phase; dissolution of α, β-Si₃N₄ in a silicate melt at the interface and recrystallization in the form of β-Si₃N₄. An important influence is also exerted by the formation of a solid solution of Si₃N₄ in yttrium aluminum garnet with the formation of SiAlON phases, called "sialons".

The study of the isothermal section of the pseudo-ternary systems Si₃N₄-SiO₂-Al₂O₃ and Si₃N₄-Al₂O₃-Y₂O₃ showed that along with the phases present in the pseudo-binary systems Si₃N₄-Y₂O₃, SiO₂-Al₂O₃, Al₂O₃-Y₂O₃, β'-phase (β'-sialon) is also formed. This phase is described by the formula Si₆₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋₋₂₋个百分ents, as well as α→β for Si₃N₄, is observed in the presence of a liquid phase.

Thus, when silicon nitride is sintered with oxide activators, multiphase materials are formed, the structure of which is determined by the following factors: phase composition and dispersion of Si₃N₄; the type and content of the activator, the temperature of activated sintering and the holding time [24].

It can be seen from the graphs that compositions with a large amount of nanosized silicon nitride powder reach a maximum density at significantly lower molding pressures. Nanosized powders have a large specific surface area; therefore, high-density materials from such powders are obtained at lower molding pressures, which is confirmed by the given graphs [25]. A large amount of nanosized powder reduces the particle packing density (composition 10). The maximum compacting density is achieved for samples containing polydispersed powder fractions with a nanosized powder content of 75 and 60% (compositions 8 and 9).

According to [26], during the sintering of silicon nitride, the α-phase of Si₃N₄ completely transforms into β-phase. This process is active in the temperature range 1100-1400 °C, when the density reaches only 60-65% of the density of the sintered material. With an increase in temperature, sintering passes into the stage of increasing the compaction rate, during the formation of a large amount of the liquid phase, which is accompanied by the maximum shrinkage of the material.
Sample blanks with maximum density had a high density after sintering, reaching values of 97-98% of the theoretical value for the last 2 compositions (Figure. 1). An increase in the density of samples with an increase in the concentration of nanosized powder is explained by the fact that sintering of ultrafine powders achieves the most dense packing of particles due to an increase in the mass transfer of material from the surface to the grain boundaries. The radius of the particles is commensurate with the thickness of the diffusion layer; therefore, sintering is activated and is accompanied by volumetric shrinkage.

With a lower content of nanosized powder, a higher pressing pressure is required to achieve the highest properties. This tendency is observed for specimens 1–3 of compositions, for which the maximum density is reached at a compaction pressure of 100 MPa.

Samples of compositions 4 and 5 show the highest density values at a compaction pressure of 75 MPa, with a further increase in pressure leading to a decrease in density. With an increase in the concentration of nanosized powder in the composition of the material (compositions 6–10), the maximum density on the graph corresponds to a pressing pressure of 50 MPa. The material has the highest density - 75% nanosized Si₃N₄ and 10% micron Si₃N₄. Thus, it can be concluded that the nanosized powder not only increases the density of sintered samples, but also intensifies the process of compaction of particles.

An important parameter in the design of composite materials is porosity, the value of which significantly affects the mechanical properties.

Depending on the composition, the porosity of the samples has different meanings (Table 2).

![Figure 1. Dependence of the density of sintered samples on the compacting pressure for different compositions.](image)

**Table 2.** The value of porosity and grain size of silicon nitride samples.

| № composition | Porosity P (±0,2), % | Pore size, μm | Grain size dmax, μm |
|---------------|---------------------|-------------|-------------------|
|               |                     | Pmax        | Pmin              |                  |
| 1             | 3,5                 | 13,2        | 1,2               | 5,1              |
| 2             | 3,3                 | 12,7        | 1,4               | 4,7              |
| 3             | 3,1                 | 10,4        | 1,2               | 4,8              |
| 4             | 2,5                 | 11,9        | 1,1               | 4,4              |
| 5             | 2,6                 | 10,6        | 0,8               | 3,9              |
| 6             | 2,1                 | 11,3        | 1,1               | 4,0              |
| 7             | 2,0                 | 9,4         | 1,2               | 3,1              |
| 8             | 1,8                 | 8,8         | 1,0               | 2,9              |
As can be seen from Table 2, with an increase in the content of nanosized powder in the composition of the material, its porosity decreases, which is well confirmed by the given data on density (Figure 1). Table 2 also shows the grain sizes of the solid phase obtained by studying the structure with an electron microscope.

The structure consists of elongated clear-cut grains that reinforce the material, which, in turn, are responsible for the high level of mechanical properties of silicon nitride materials (Figure 2). At the final stage of sintering, the content of elongated intertwined grains of a clear cut with a ratio of length to diameter reaching 3-5 increases significantly in the structure of the material. According to experimental data, the active stage of grain growth lasts 7-10 minutes.

![Figure 2. Fractogram (a) and microstructure (b) of sintered materials based on Si₃N₄.](image)

The grain size of the solid phase depends on the sintering rate, the duration of isothermal holding, the amount and composition of the liquid phase. So, even at temperatures above 1100 °C, silicon diffusion through the silicate melt layer takes place, accompanied by the formation of complex silicate phases and the transition $\alpha \rightarrow \beta$-Si₃N₄. Above 1400 °C, active formation of yttrium aluminosilicate takes place, and starting from 1600 °C, the formation of yttrium aluminum garnet. As the temperature rises, the rate of diffusion of aluminum into the yttrium lattice increases, thereby accelerating the formation of the liquid phase. At temperatures above 1700 °C, silicon nitride particles begin to dissolve in the liquid phase, with the formation of solid solutions, and crystallize from the melt in the form of elongated "sialon" grains. The formation of the crystal structure depends on the viscosity of the liquid phase. Silicate inclusions present as a film on nitride particles reduce the diffusion of silicon in the early stages of sintering. With the appearance of the liquid phase, the silicon diffusion process intensifies.

The results of mechanical tests of the samples are given in table 3.

The most informative properties that determine the field of application of composite materials are strength and hardness. The strength of materials is influenced by the presence of structural defects (dislocations, impurity atoms, pores and microcracks). The presence of the first two types of defects increases the overall strength of the material, the last two reduce it. A high plasma cooling rate during the synthesis of silicon nitride leads to the production of submicron particles with a significant concentration of crystal lattice defects and, as a consequence, a high activity of the powder. The emergence of a significant number of edge and screw dislocations is due to the kinetic features of the process of obtaining nanosized powders. Substitutional and interstitial solid solutions are formed at the stage of liquid-phase sintering when some of the Si atoms are replaced by Al and N by O, which leads to the formation of phases in the Si-Al-O-N system. The total porosity of materials based on nanosized Si₃N₄, according to [27], does not exceed 2-3% by volume, respectively, the resulting products must have high strength properties.
The strength of oxygen-free ceramics is also influenced by the concentration and nature of micro- and macrodefects, the occurrence of which is associated with the conditions for the synthesis of powders and with the technological features of obtaining materials. The presence of defects determines significantly lower values of the real strength in comparison with the theoretical one.

The modulus of elasticity and the coefficient of crack resistance are indicators of the strength of the material as a whole, therefore, the determination of these characteristics should precede the study of all other mechanical properties. The elastic modulus of a material is a function of strength and also depends on defects in the structure of the material, that is, on the density of the material and on its bulk porosity. In [27], the macrostructure of materials based on ultradispersed Si₃N₄ powders was investigated and it was concluded that with an increase in the concentration of ultradispersed powder in the initial composition, its density increases. The dependences of the elastic modulus of the samples on the pressing pressure are shown in Figure 3.

### Table 3. Physical and mechanical properties of sintered silicon nitride samples.

| № | composition | Shrinkage, % | ρ, g/cm³ | P (+0,3), % | E (+10), GPa | σ (+15), MPa | Kᵦ (+0,2), MPa·m¹/² | Hᵥ (+0,4), GPa |
|---|-------------|--------------|---------|-------------|--------------|--------------|----------------|-----------------|
| 1 | 19,5        | 3,19         | 3,5     | 280         | 380          | 4,12         | 17,5            |
| 2 | 19,5        | 3,19         | 3,3     | 290         | 425          | 4,20         | 17,2            |
| 3 | 19,7        | 3,20         | 3,1     | 300         | 470          | 4,21         | 16,9            |
| 4 | 19,7        | 3,21         | 2,5     | 300         | 470          | 4,26         | 16,5            |
| 5 | 19,8        | 3,21         | 2,6     | 310         | 490          | 4,32         | 16,3            |
| 6 | 20,1        | 3,22         | 2,1     | 315         | 510          | 4,42         | 16,0            |
| 7 | 20,8        | 3,23         | 2,0     | 340         | 520          | 4,43         | 15,9            |
| 8 | 20,9        | 3,24         | 1,8     | 350         | 540          | 4,56         | 15,6            |
| 9 | 21,3        | 3,26         | 1,5     | 355         | 570          | 4,64         | 15,3            |
| 10| 21,8        | 3,29         | 1,1     | 360         | 600          | 4,83         | 15,0            |

**Figure 3.** Dependences of the elastic modulus of the samples on the compacting pressure for different compositions.
For almost all compositions, the curves are extreme, with maximum properties at the point of optimum compacting pressure. There is a tendency to an increase in the elastic modulus index with an increase in the content of nanosized silicon nitride powder in the composition of the samples (Figure 4). Since the modulus of elasticity directly depends on density, more densely sintered materials with the maximum amount of nanosized powder showed better properties, which is confirmed by the given graphs (Figure 3).

An important characteristic of composite materials is the coefficient of fracture toughness (fracture toughness) (Figure 5), which also depends on the density and on the presence of structural defects (porosity) in the bulk of the material. It was shown in [19] that with an increase in the density of Si₃N₄-based ceramics, its fracture toughness increases. The nature of the intergranular phase has a great influence on the mechanical properties of silicon nitride materials. So the addition of yttrium oxide increases the viscosity of the material, and aluminum oxide softens it somewhat. The $K_{IC}$ value of brittle ceramics can be increased by introducing dispersed inclusions of the second phase. It was shown in [22] that when a small amount of TiN is introduced into ceramics based on silicon nitride, its fracture toughness coefficient increases by 1.5 times. According to [27], with an increase in the concentration of nanosized powder, the volume percentage of pores decreases, which leads to a decrease in the probability of propagation of local cracks (Figure 5).

The ultimate strength in transverse bending was determined on specimens 6 × 6 × 55 mm; the data obtained are shown in Figure 6.
According to [28, 29], the introduction of silicon carbide or silicon nitride whiskers into the composition of silicon nitride ceramics significantly increases its strength properties. The $\alpha \rightarrow \beta$-Si$_3$N$_4$ transition promotes the crystallization of elongated "sialon" grains, due to which the strength of such a material increases. An increase in the concentration of nanosized powder promotes the fastest and most complete phase $\alpha \rightarrow \beta$ transition [30].

It is of interest to study the effect of porosity on the transverse bending strength (Figure 7). The limiting porosity at which the material retains the level of mechanical properties is $\sim 5\%$. With an increase in porosity to 10\%, the strength drops significantly. The maximum loss of properties is observed with an increase in porosity from 5 to 10\%. With a further increase in porosity to 20\%, the decrease in strength proceeds more smoothly.

![Figure 7. Dependence of the transverse bending strength of specimens on porosity.](image)

![Figure 8. Dependence of the compressive strength of the samples on the content of nanosized silicon nitride powder.](image)

The dependence of the ultimate strength in compression on the content of nanosized silicon nitride powder is shown in Figure 8. For materials obtained by powder technology, porosity is a structural component present even in the most dense, hot-pressed materials. The flexural and compressive strength of non-porous ceramics can reach values of 900–1000 MPa and 1500–1700 MPa [20], respectively, which is 2.0–2.5 times higher than the values obtained on liquid-phase sintered ceramics from micron-sized powders of furnace synthesis. In this work, by the method of liquid-phase sintering of materials based on nanosized powders, it was possible to obtain ceramic materials with the properties $\sigma_{ben} = 600 \pm 15$ MPa, $\sigma_{co} = 860 \pm 25$ MPa.

For the materials under study, the hardness is slightly lower than for ceramics based on micron-sized Si$_3$N$_4$ powders (Figure 9). The hardness of a heterophase material is determined by the additivity method between the hardnesses of the phases included in it. During sintering, Si$_3$N$_4$ particles begin to dissolve on the surface in the oxide binder, forming a "sialon" phase, which reduces the overall hardness of the material.

![Figure 9. Dependence of Vickers hardness on the amount of nanosized silicon nitride powder.](image)
Using the method of activated sintering of silicon nitride, it was possible to obtain materials with sufficiently high physical and mechanical characteristics, which make it possible to recommend them for use in various industries in the production of plain bearings, balls for rolling bearings, mechanical seals for centrifugal pumps, cutting tools and abrasive nozzles, blades turbines and refractory products.

4. Conclusions
A high-density material ($\rho = 3.28$ g / cm$^3$) was obtained based on nanosized silicon nitride powder by the method of activated sintering. The process of material structure formation during sintering has been studied. The sintering mechanism consists of the stage of compaction of grains in the solid phase (up to 65-70% of the theoretical density of the material) and the stage of liquid-phase sintering (maximum compaction). The densification process at low sintering temperatures is initiated by a viscous melt of yttrium aluminosilicate, which, with increasing temperature, transforms into yttrium alumina garnet, which activates the crystallization of "sialon" grains. An increase in the amount of low-melting oxide components accelerates the growth of elongated grains of the solid phase, which reinforce the material, thereby increasing the mechanical properties of ceramics based on silicon nitride.

5. References
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