Silicon nitride-based ceramic composite materials for corrosion-resistant rolling bearings

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Abstract. The technological process of obtaining material and manufacturing ceramic rolling elements of the bearing is considered. The composition of a silicon nitride-based ceramic composite material was investigated. The chemical inertness of ceramic materials determines the low adhesive wear in the mating parts of the supporting elements and makes it possible to use the rolling elements of the bearings in conditions of poor lubrication. Bearings with ceramic rolling elements show excellent running performance in emergency conditions and do not lead to sudden failures. The excellent corrosion resistance of ceramic materials allows them to be used in aggressive environments. The combination of such properties is accompanied by a decrease in temperature in the working area and allows the use of higher rotational speeds. The feasibility of using ceramics for the production of balls for bearings and the main advantages of using a ceramic material compared to metal products are shown. The process mode of hot pressing of blanks of ceramic rolling elements has been developed.

1. Introduction
Rolling bearings are classified into the following main types: ball, roller cylindrical, roller conic, double-row self-aligning, needle, thrust ball, thrust roller. Bearings are widely used in such mechanisms as electric motors, lifting and transporting and agricultural machines, aircraft, locomotives, wagons, machine tools, gear reducers and many machines and mechanisms.
Rolling bodies of bearings perceive compression loads, cyclic loads, and must comply with the conditions of operability, reliability and durability of the structure. The peculiarity of the bearings is that the materials from which they are made must have high strength, hardness, wear resistance, toughness. In critical structures most often bearings for special purposes are used, which should have improved properties. In some cases, steel, commonly used for the manufacture of bearings, do not meet the criteria of high heat resistance, heat resistance, corrosion resistance. Ceramic composite material meets these requirements [3, 4].
For harsh operating conditions of bearings, the most promising solution is the use of ceramic materials with high physicomechanical properties that are resistant to wear and change in geometric shape during operation. Ceramic materials are dominated by the following advantages over bearing steel: low density; high hardness; high modulus of elasticity; chemical inertness; the coefficient of dry friction in a pair of ceramics-steel is less than in a steel-steel pair; low thermal expansion coefficient, high heat capacity and heat resistance, as well as the fact that ceramics is a dielectric [5].

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Due to the low density in combination with high physicomechanical and tribotechnical indices, the following operational properties provide the advantages of ceramic rolling bodies over steel rolling elements of bearings: reduction of centrifugal forces; reduce preload in the bearing; reduction of the radial clearance in the bearing; reduced vibration and noise; reduction of bearing operating temperatures. The chemical inertness of ceramic materials determines the low adhesive wear in the mating parts of the supporting elements. This property of ceramic materials makes it possible to use rolling elements of bearings in conditions of poor lubrication or even without the use of lubricants. Therefore, bearings with ceramic rolling elements show excellent running performance in emergency conditions and do not lead to sudden failures. The excellent corrosion resistance of ceramic materials allows them to be used in aggressive environments.

The low coefficient of friction in combination with favorable lubrication conditions allows the support elements to work under conditions of significant reduction of friction, which is accompanied by a decrease in temperature in the working area and allows the use of higher rotational speeds [6, 7].

Silicon nitride Si3N4 is the only compound of silicon and nitrogen and exists in two versions - α- and β-Si3N4. Silicon nitride is characterized mainly by the covalent type of chemical bond (approximately 70%). Here, in contrast to compounds with the ionic type of chemical bond, the processes of diffusion-viscous flow during the sintering of covalent compounds are shown to a minor extent. In connection with this circumstance, it is rather difficult to obtain high-density single-phase silicon nitride material using powder technology in practice.

2. Materials and methods of the experiment

The grinding of the charge components was carried out in the Pulverisette-5 planetary mill (Fritschi Germany). The powders that were ground together were crushed and ground by carbide grinding balls with a diameter of 10 mm in the grinding cups of a planetary mill. At the same time, the impact energy is many times greater than the impact energy in conventional ball mills. Due to this, good efficiency and short grinding time are achieved. The rotation speed of the drum 400 rpm allows an order to reduce the grinding time by an order of magnitude compared to drum and vibratory mills.

Ceramic composite material consisted of a mixture of powders of silicon nitride, yttrium oxide and aluminum oxide in an environment of isopropyl alcohol with a dispersion of not more than 3 microns. Powder weight ratio: grinding bodies: fluid was 1:3:1. The chemical composition of the ceramic material for the manufacture of blanks of the tested rolling elements of the bearing is presented in Table 1.

| Composition number | Silicon nitride, % | Aluminum oxide, % | Yttrium oxide, % |
|--------------------|--------------------|-------------------|------------------|
| 1                  | 85.0               | 5.0               | 10.0             |
| 2                  | 83.3               | 4.2               | 12.5             |
| 3                  | 80.0               | 5.0               | 15.0             |

After grinding, the suspension was poured onto a baking sheet, placed in a heating chamber and dried at a temperature of (80 ± 5)°C for 5 h. The charge powder was separated from the grinding balls by sifting through a sieve No. 2, and then sieved additionally through a sieve No. 0063. The compacts were made on a hydraulic press PYE 25Х355 by compacting the batch powder in a 23 mm steel cylindrical single-press mold with a pressure of (30 ± 3) MPa in order to reduce shrinkage during sintering.

The resulting compacts were visually controlled for the absence of cracks, chips, and shells. Making blanks of ceramic rolling bodies was carried out by the method of hot pressing. The resulting compacts were placed in a 12-nest graphite mold.

The working surfaces of the graphite mold were pre-treated with a suspension based on hexagonal boron nitride. Hot pressing was carried out on the press KCE HP W 200/250-2200-180. The study of the fine structure was carried out on a scanning electron microscope.
TESCAN version VEGA 3. The apparent density and porosity of the blanks was determined according to GOST 473.4 on the VIVAFLOW-50 device (Sartorius, Germany) by saturating ceramic samples with water followed by hydrostatic weighing. Hardness at a temperature of 20°C by Vickers was determined according to GOST 2990 by the static indentation of the diamond pyramid indenter into the sample surface. Using plasticine, the sample was fixed on the stage of the PMT-3 hardness tester (LOMO firm, Russia).

The strength under static bending at a temperature of 20°C was determined on a VTK-2 testing machine as per GOST 24409 on samples (width 10.0 mm, thickness 8.0 mm) made from a mixture. Distance between supports 100 mm. Each test was conducted at a constant loading rate until its failure. On a scale, the position of the arrow at which the specimen was destroyed was fixed.

3. Experimental results and discussion

Hot pressing of the ceramic composite material was carried out according to the regime shown in Figure 1. The hot-pressing mode of the blanks consisted of three main stages.

Figure 1. Technological scheme of hot pressing of blanks.

Technology of hot pressing included the following operations:
1. Raising the temperature to 700°C and holding for 20 minutes at this temperature. Heating and aging took place in a vacuum. At this stage, adsorbed gases, moisture and volatile impurities are removed.
2. At the end of curing at 700°C, nitrogen was fed into the press chamber and the pressing was loaded with a pressing pressure of 7 MPa. Then, the temperature was raised to (1750 ± 50) °C with curing at a maximum temperature of 30 minutes. With the rise of temperature, at the same time gradually increase the pressure of pressing to 30 MPa. At this stage, the pressing shrinks, which is controlled by the movement of the plunger of the press and the readings of the press device, and the final sintering of the powder occurs. During the process of hot pressing the following parameters were controlled: vacuum discharge value and nitrogen pressure; temperature; shrinkage.
3. Cooling with a furnace. At a temperature of 1200 °C, the pressure is removed from the mold. After cooling, the cylindrical blanks are removed from the mold, the surface of the blanks is subjected to sandblasting, after which the blanks are transferred to the control operation.

The technological stage of hot pressing is performed in order to give the product a predetermined density and the necessary physical and mechanical properties. The results of measurement of porosity, apparent
density, hardness and strength under static bending are shown in Table 1, and the microstructures of the studied samples are shown in Fig. 2.

**Table 2. Test results of samples of blanks based on silicon nitride and sintering additives**

| Composition number | Properties of sample blanks of silicon nitride |  |
|--------------------|-----------------------------------------------|---|
|                    | Apparent density, g/cm³ | Porosity, % | Hardness at a temperature of 20°C by Vickers, GPa | Static bending strength, MPa |
| 1                   | 3.26                           | 0.06        | 15.70                                         | 629.00                      |
| 2                   | 3.23                           | 0.08        | 16.10                                         | 637.00                      |
| 3                   | 3.25                           | 0.05        | 15.30                                         | 644.00                      |

**Figure 2.** Microstructure of ceramics based on silicon nitride and sintering additives: (a), (b), (c) - compositions 1, 2, 3 according to Table 2.

The microstructure of ceramics is characterized by a fine-grained matrix phase, represented by prismatic silicon β-nitride crystals with sizes of 0.5 to 1.0 μm and elongated prismatic crystals with widths of about 0.5 to 1.0 μm, length - about 5 to 8 microns.

The test results of samples of ceramics based on silicon nitride showed that the strength under static bending at a temperature of 20°C is (629 - 644) MPa, which significantly exceeds the strength values of steel balls [5]. The best results were shown by the material composition 2.

Silicon nitride has an extremely high chemical resistance. Silicon nitride is practically resistant to all acids, many molten metals, and water vapor. It is resistant to oxidation not only in air, but also in oxygen at moderately high temperatures [2]. The hardness and modulus of elasticity of silicon nitride is more than 1.5 times higher than similar characteristics of steel. This factor makes the bearing harder and increases its life when working in conditions of high pollution.

Rolling bodies of silicon nitride have a lower degree of thermal expansion than steel bodies of a similar size, which means that structures are less sensitive to temperature changes inside the bearing and are able to withstand large preload forces [8-10].

Thus, taking into account the physicomechanical and electrical insulating properties, it is advisable to use silicon nitride as a material for the manufacture of ceramic balls, components of rolling bearings.

**4. Conclusions**

1. The use of ceramics based on silicon nitride increases the strength of rolling elements of bearings. The selected chemical composition of ceramic material for the manufacture of blanks of ceramic rolling elements of the bearing, containing 83.3 wt. % silicon nitride, 4.2 wt. % aluminum oxide, 12.5 wt. % yttrium oxide.

2. The developed process of hot pressing to obtain the material of ceramic rolling elements of bearings, will ensure their strength under static bending.
up to 644 MPa and hardness up to 16.1 gPa according to Vickers.

3. Ceramic composite material based on silicon nitride is a promising material for corrosion-resistant rolling bearings.

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