UDC 666.762.93:621.433

ROTOR SEALS FOR GAS-TURBINE ENGINES FABRICATED FROM Si_3N_4 – BN HIGH-TEMPERATURE COMPOSITE MATERIALS

I. Yu. Kelina,[1] N. I. Ershova,[1] A. V. Arakcheev,[1] and E. N. Chasovskoi[1]

Translated from Novye Ogneupory, No. 2, pp. 38 – 43, February, 2004.

The development of rotor seals for gas-turbine engines is reported using Si_3N_4 – BN-based composite materials molded by hot-pressing technology. The mechanical and thermophysical properties of the newly-developed materials are determined and compared with results of a thermal stress analysis by numerical simulation method. Potential use of rotor seals of different design, in particular, multilayer components, for practical applications is discussed.

To prevent rotor seizure in gas-turbine engines (GTE), thermal gaps are provided between rotating and stationary parts; when appropriate, the gap can be narrowed to increase the engine efficiency. However, decreasing the gap width incurs the risk of damaging the rotor blading because of accidental contact between the turbine rotor and the rim. To prevent this, various seal assemblies have been proposed.

In practice, seal assemblies are in service that admit contact between the rotor and the static shroud using cellular elements and easily wearable materials that are mounted in the form of sectors, coatings, or two-layer metal-ceramic inserts [1]. The first layer in these inserts provides strength, and the second, soft layer provides the property of wearability; however, their operating temperature should not exceed the melting point of the metal and the temperature of the onset of oxidation (about 1000°C). Rather stringent demands are placed on the rotor seals (RS) such as thermal stability (up to 1300°C), erosion resistance to the gas stream, resistance to temperature fluctuations, easy wear on contact with the rotor blade, and stability of material strength characteristics.

The Kyocera Corporation (Japan) has developed ceramic silicon nitride materials SN281 and SN282 exhibiting high temperature strength and resistance to oxidation that can be used in GTE parts and assemblies, including rotor seals [2]. The ceramic shroud for CGT302-type engine made from SN282 material can be equipped with a wearable insert made of soft, porous silicon carbide (Table 1, Fig. 1). This appliance makes it possible to narrow the thermal gap width to 0.1 mm and thus to improve the efficiency of operation.

With this in mind, promising for that purpose are materials in the Si_3N_4 – BN system that combine advantageous properties, viz. high strength, thermal stability, and good machinability [3, 4].

In [5], a ceramic material was described specifically intended for use in GTE rotor seals. The Si_3N_4 – BN-based ceramic was prepared by reaction sintering; it exhibits a high resistance to oxidation. Because of rather high porosity, mechanical properties of this material are modest: the bending strength does not exceed 195 MPa. Still, the material can find good use as a wearable insert in structures operating under moderate stress conditions.

Our goal in this study was to develop a material capable of operating at high mechanical and thermal loadings. In designing a multilayer ceramic in the Si_3N_4 – BN system, the complex built-up construction for rotor seal can be replaced by a one-piece ceramic component of variable composition.

TABLE 1. Typical Characteristics of the Wearable Material

Property	Wearable material	SN282
Density, g/cm^3	1.9	3.4
Bending strength, MPa, at the temperarure, °C:		
25	96	738
1000	101	635
Temperature linear expansion coefficient (TLEC), 10^{-6} K^{-1}, at the temperarure, °C (about):		
400	2.0	2.5
800	2.5	2.9
1000	2.7	2.9
1200	2.9	3.0

[1] Tekhnologiya Research and Production Enterprise, Obninsk, Kaluga Region, Russia.

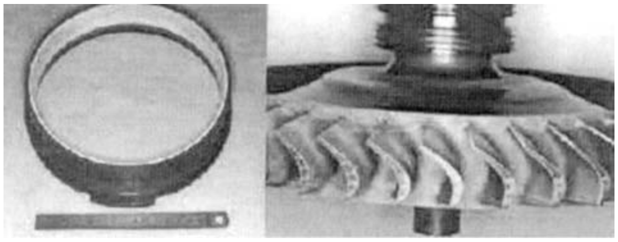

Fig. 1. Ceramic shroud with an inner wearable layer and a rotor (subjected to testing [2]).

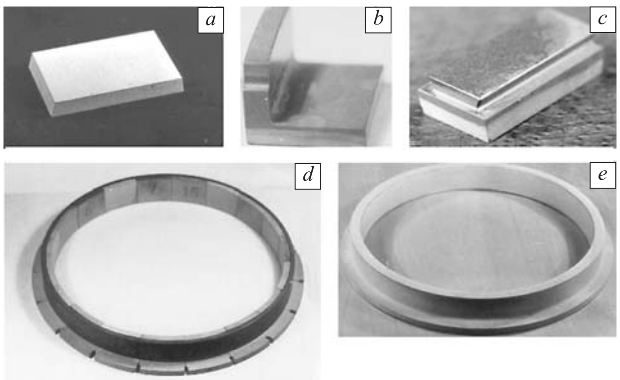

Fig. 2. Rotor seals made of Si_3N_4 – BN composite material: *a*) homogeneous inserts; *b*, *c*) multilayer inserts; *d*) assembly of segments and rotor ring; *e*) one-piece shroud with internal wearable layer.

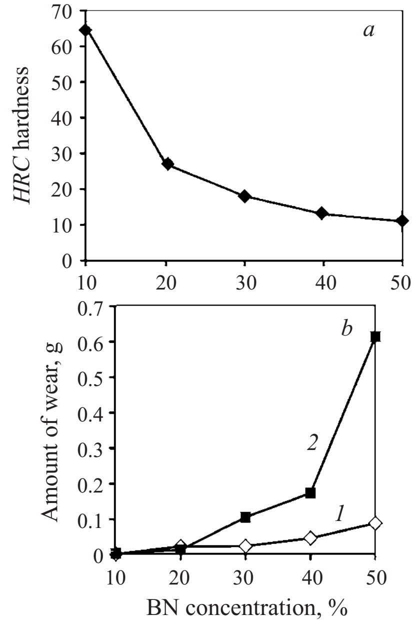

Fig. 3. *HRC* hardness (*a*) and amount of wear (*b*) of the Si_3N_4 – BN composite material plotted as a function of BN concentration: *1*) intact specimen; *2*) treated at $t = 1300°C$ for $\tau = 10$ h.

Experimental. Si_3N_4 – BN-based composite material was used to develop rotor seals using hot-pressing technology. The precursor materials were ultra-fine powdered compositions of [Si_3N_4 – Y_2O_3 (MgO)] and hexagonal BN. The boron nitride mass fraction varied from 10 to 60 wt.% [3].

Multilayer components composed of materials of different composition were prepared in steps involving briquette shaping and hot pressing of briquettes, assembled in the required combination in graphite press molds [4]. The arrangement of layers was either horizontal or vertical. In the former variant, inserts and segments were fabricated, which later were built up into an assembly; in the latter variant, one-piece rims with an inner wearable layer were fabricated.

Two- or three-layer specimens were tested in which the hard layer contained 0 – 20% BN, and the soft layer 40 – 60% BN. When appropriate (to reduce a property gradient), an intermediate layer with 10 – 40% BN was sandwiched between the two. The bending strength at room temperature and 1300°C was determined using three- or four-point bending techniques. Microhardness of the material was measured using a microhardness tester under the indenter load $P = 0.98$ N. Thermophysical characteristics for specimens of different composition were measured in the temperature range from room to 900 – 1300°C. Resistance to high-temperature oxidation was determined at 1300°C for 50 h and at 750 – 900°C for 250 h. The multilayer specimens were tested for operability using a heat-and-cool cycling technique (10 cycles) in a gas stream of power $3000 \text{ W}/(\text{m}^2 \cdot \text{K})$ at 1530°C. Thermal stability was determined by measuring the temperature drop that the material is capable of sustaining without damage (PM 596.1006 method "Determination of the thermal stability of glass, glass-ceramic and ceramic materials") and by calculating the thermal stability criteria R_1 and R_4 .

The mechanical and thermophysical characteristics thus determined were used as the basis for strength and thermal analyses with a view to specifying conditions that would minimize thermal stresses in the material. The composition of individual layers was optimized by numerical simulation of the thermal-stress state (TSS) in the engine startup and shutdown regimes. The time integration step in a transient heat-conduction problem was 0.001 sec over the thickness spanning a total of 100 assemblies. The properties of the matrix material and materials with a BN varying concentration were plotted as a function of temperature. The maximum tensile stress σ_{max} was used as an optimum criterion to characterize the strength of components. The thermal stresses in components generated during heating and the bending strength of a homogeneous material were used as the basis for comparative analysis. Proceeding in this manner, the safety margin of a material and its constituent layers could be evaluated.

Rotor seals of different design — from plain-shaped inserts of homogeneous material to multilayer segments and monolithic one-piece shrouds with an inner wearable layer (Fig. 2).

TABLE 2. Properties of Hot-Pressed Materials Based on Si_3N_4 – BN System*

Manufacturer	Density, g/cm^3	Bending strength, MPa, at the temperature, °C	
		20	1300
Tekhnologiya R&D Enterprise	2.57 – 3.17	200 – 490	190 – 455
ETC Technologie Co.	2.4 – 3.0	100 – 400	–

* Data for ceramics with 10 – 40% BN.

The rotor ring made of a homogeneous silicon-based material and multilayer structures were tested for heat resistance in a nozzle jet stream at a maximum gas temperature of 1220°C. The thermoerosive ablation of the run-in layer was determined at 1300°C over a time of 1.5 h. The multilayer inserts for rotor seals were tested under the action of a heat flow with a heat-transfer coefficient of 3000 W/(m^2 · K) at 1150°C on a test rig; the rotation speed was 70 – 100 rpm.

Results and discussion. The mechanical characteristics (hardness and wear) of the Si_3N_4 – BN composite material plotted as a function of BN concentration are shown in Fig. 3. The decrease in strength with BN concentration occurs because of a change in the structure of specimen — replacement of the Si_3N_4 matrix by a less dense BN matrix with its weak bonds typical of the tabular BN [4]. In composite materials with BN content less than 40%, the microhardness of the main phase varies from 14 to 9 GPa and that of the boron-containing phase — from 1.4 to 0.5 GPa [6]. With BN concentration increasing from 40 to 60%, the total microhardness decreases from 5.2 to 0.2 GPa. The microhardness data show that the density of boron-containing phases is little affected by hot pressing.

The newly-developed material is superior to other materials prepared by slip casting and hot pressing in density, strength (at room and elevated temperatures), and resistance to oxidation (Table 2) [7 – 9].

Mechanical properties of the multilayer material as a function of BN concentration behave in a manner similar to those of homogeneous specimens. Specimens with horizontally arranged layers suffered failure mostly along the layers high in BN or at the layer boundary.

The materials showed high resistance to oxidation: the change in mass was 0.005 – 0.8% for composites with 10 – 60% BN. In the multilayer material exposed to a gas jet stream with a heat-transfer coefficient of 3000 W/(m^2 · K) at 1530°C, the change in mass did not exceed 0.2%. The processes involved were erosive ablation and oxidation of BN to yield B_2O_3. The erosive ablation of composite material containing 20 – 40% BN at 1300°C for 1.5 h was 0.005 – 0.02 g.

Testing the composite materials for thermal stability did not reveal much difference in their behavior: all composites suffered no failure from the temperature drop ΔT of 1200°C, which was 160 – 300°C higher over the thermal stability of matrix material. The thermal stability criteria $R_1 = \sigma(1 - \mu)E/\alpha$ and $R_4 = R_1 \lambda$ [10] calculated for the composite material at room and elevated (900 – 1300°C) (Table 3) reveal a maximum for compositions 20 – 40 and 60% at room temperature and 20 – 40 % BN at elevated temperature (Table 4) [12].

The geometry and composition of the multilayer rotor seal were optimized using a numerical simulation method. The computations were carried out for both startup and shutdown engine regimes. The heat flow to which the rotor seal (RS) surface was exposed was parametrized by a gas temperature of 1150°C and heat transfer coefficient α = 3000 W/(m^2 · K). A one-dimensional model was used to calculate thermal and strength characteristics for a number of variants (over 100) to optimize the composition and thickness of layers, their number and stacking arrangement. The computational results were presented in the form of graphs and nomograms for maximum (tensile) and minimum (compressive) stresses varying over time within individual RS layers and for temperature versus stress distributions. A TSS analysis of the RS multilayer insert shows that, for any layer combination, the presence of a layer with 10% BN results in

TABLE 3. Mechanical and Thermophysical Properties of the Si_3N_4 – BN Composite Ceramics

Material	Apparent density, g/cm^3	Bending strength at 20 – 1300°C, MPa	Young's modulus, GPa	Poisson's ratio	TLEC (20 – 1300°C), 10^{-6} K^{-1}	Heat conductivity, W/(m · K)	ΔT (heat-and-cool cycle, water), °C
OTM-906	3.30	700 – 600	246.0	0.25	3.20	16.0	840
OTM-918 with BN concentration, %:							
10	3.17	490 – 455	197.0	0.21 [11]	3.92	17.2	> 1200
20	2.85	350 – 260	99.5	0.18	3.25	17.6	> 1200
30	2.66	270 – 250	89.7	0.13	3.00	18.0	> 1200
40	2.57	200 – 190	72.5	0.13	2.87	15.4	> 1200
50	2.33	140 – 152	52.8	–	3.38	14.7	1000
60	2.10	75 – 57	33.0	–	3.50	14.1	1000

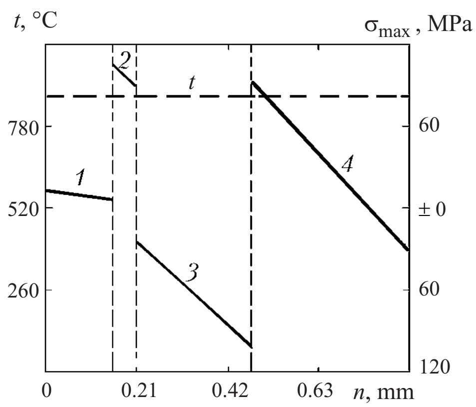

Fig. 4. Temperature and stress profiles in a four-layer insert of composition 0, 10, 30, and 50% BN at 1600 sec under transient heating conditions; n is the insert thickness.

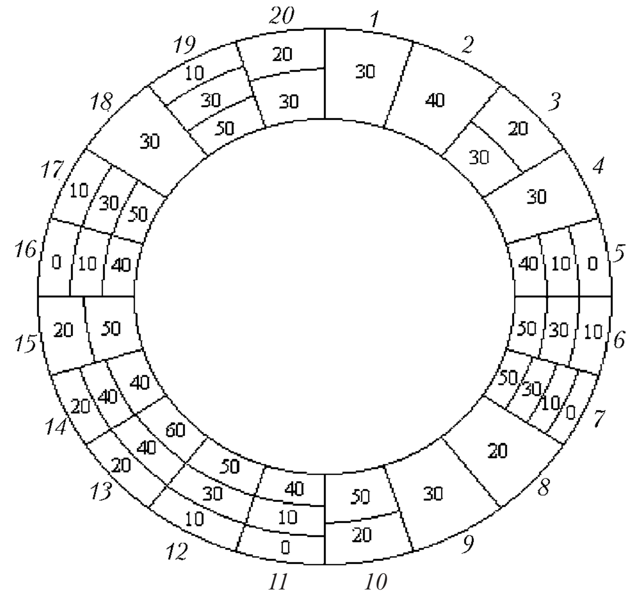

Fig. 5. Schematic diagram of a rotor seal assembled from 20 inserts (*1 – 20*); boxed numerals indicate BN concentration, %.

a sharp increase in σ_{max} in the neighboring layers (Fig. 4). This feature in the σ_{max} distribution is due to the fact that the thermal linear expansion factor (TLEC) of the 10% BN layer is 1.1 – 1.4 times that of the matrix material and layer of different composition.

An analysis of the multilayer structure stacked as 0 + 10 + 40 and 10 + 30 + 50 wt.% BN predicts that for transient processes with times of 6, 9, and 67 sec, the stress reaches a maximum in layers with 40% (σ_{max} = 43 MPa), 10% (69 MPa), and 0% BN (105 MPa). Allowing for the strength of each layer, one comes to the conclusion that the multilayer system in question has a definite safety margin. The change in mass on exposure to a heat flow with a power of 3000 W/($m^2 \cdot K$) at 1530°C did not exceed 0.2% (erosive ablation and oxidation BN $\rightarrow B_2O_3$). An inspection revealed no flaws (cracks, spallings) in the specimens tested.

The computational results were supported by bench testing. Most inserts tested had a multilayer structure, and a smaller part were homogeneous. The insert arrangement was as indicated in Fig. 5. Some of the specimens tested suffered structural damage that might arise from a variety of factors: (i) high stresses at the boundary with a 10% BN layer [inserts Nos. 6, 7, 12, 16 (Fig. 6*a*), and 19]; (ii) high hardness of the run-in layer in inserts Nos. 8 and 9 (Fig. 6*b*) because of which the material suffered spalling rather than abrasion; (iii) occurrence of a low-strength material in the fastener zone (lock zone) (insert No. 6, Fig. 6*c*). Factor (i) was recognized as being responsible for most failures. The adverse effect due to high-temperature gas stream was seen in the occurrence of longitudinal cracks in soft and, consequently, less durable layers adjacent 10% BN layers. A repeated TSS analysis carried out with allowance for the actual testing conditions showed, indeed, a significant increase in σ_{max} in layers adjacent to the 10% BN layer (Table 4).

Tests gave good results for inserts composed of 20, 50 and 20, 40, 60% BN layers (Fig. 6*d*): here the 20% BN layer provided the required strength, and 50 and 60% BN layers —

TABLE 4. Thermal Stability Criteria R_1 and R_4 for Si_3N_4 – BN-based Composite Ceramics

BN concentration, %	R_1, at the temperature, °C		R_4, at the temperature, °C		R_1 [11]
	20	900 – 1300	20	900 – 1300	
0	1010	390	16,150	4325	–
10	1090	465	18,775	10,100	550
20	1800	660	31,730	14,830	850
30	1745	780	31,425	14,550	1120
40	1845	760	28,430	15,350	1280
50	1440	605	21,190	12,705	–
60	1980	420	27,880	8180	–

TABLE 5. Maximum Stresses Generated in Rotor Seal Layers under Transient Heating Conditions

Insert No.	Flaws	BN concentration, %	Layer thickness, mm	Maximum stress, MPa
6	Cracks	50, 30, 10	5.4; 0.1; 2.1	9.47; 81.24; 7.93
7	Spallings	50, 30, 10, 0	1.5; 0.5; 2.8; 3.6	16.16; 101.26; 7.55; 97.45
8	Spallings	20	8.5	13.37
9	Spallings	30	8.5	12.43
13	None	60, 40, 20	0.2; 2.6; 4.2	7.44; 20.84; 15.50
16	Cracks	40, 10, 0	3.2; 0.8; 5.0	29.23; 0; 28.10
20	None	50, 20	5.7; 3.1	5.30; 9.45

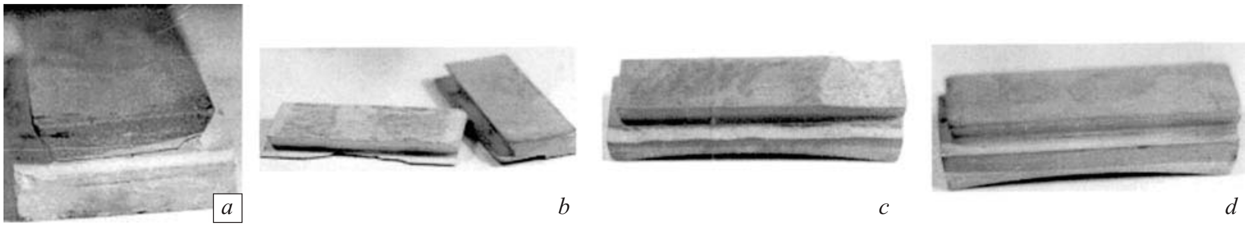

Fig. 6. Multilayer inserts showing post-testing flaws: *a*) cracks in the soft layer adjacent to the 10% BN layer; *b*) spallings in the lower high-hardness layer; *c*) affected lock zone in a low-strength material; *d*) damage-free specimen.

the required cut-in depth of 0.5 mm. These data were found to be in agreement with computational results.

CONCLUSIONS

A high-temperature composite material in the Si_3N_4 – BN system with superior physicomechanical characteristics at temperatures up to 1400°C has been developed. The properties of the material can be controlled by varying the proportion of its main components.

A technology for fabrication of rotor seals of different configuration has been developed ranging from homogeneous inserts with dimensions of 20 × 30 × 5 mm to multilayer segments and one-piece shrouds of diameter 250 mm with an inner wearable layer.

A numerical simulation method was used to optimize the properties of the material and the geometry of multilayer and homogeneous rotor seals. The method has a sufficiently wide range of applications that would allow savings in both cost and time in the fabrication technology of homogeneous and multilayer components.

REFERENCES

1. *A Review of Foreign Patents on Applications of Ceramics in the Components of Gas-Turbine Engines, No. 207* [in Russian], TsIAM, Moscow, 62 – 78 (1985).
2. K. Tanaka, M. Yoshida, T. Kubo, et al., "Development and evaluation of ceramic components for small gas turbine engine," in: *ASME TURBOEXPO'2000, May 8 – 11, 2000, Münich, Germany.*
3. N. I. Ershova, I. Yu. Kelina, and V. M. Zemlyanskaya, "Hot-pressed composite materials in the silicon nitride-boron nitride system," *Ogneupory*, No. 11, 17 – 21 (1995).
4. N. I. Ershova and I. Yu. Kelina, "Multilayer ceramic components from silicon nitride-boron nitride composite material," *Ogneup. Tekh. Keram*., No. 5, 6 – 10 (1997).
5. V. V. Vikulin and I. N. Kurskaya, "Structural materials based on the reaction-bound silicon nitride," *Ogneupory*, No. 9 (1990).
6. *R&D Report "Mechanical, Thermophysical, and Operational Characteristics of Structural Ceramics in Engine Building," File No. 01.87.0078328, Part II. Thermophysical and Operational Characteristics* [in Russian], Institute for Engineering Physics Problems in Power Engineering, Lithuanian Academy of Sciences (IFTPE), Kaunas (1989).
7. H. L. Ekkehard and M. V. Swain, "Fracture toughness and thermal shock behavior of silicon nitride-boron nitride ceramics," *J. Am. Ceram. Soc*., **75**(1), 67 – 70 (1992).
8. I. Keiishiro, F. Toshiaki, and U. Ryoji, "Development of machinable Si_3N_4 – BN composite ceramics," *Kawasaki Seitetsu Siho T* (*Kawasaki Steel Giho*), **21**(4), 281 – 286 (1989).
9. *Technical Characteristics of Ceramic Materials Available from FCT Technologie GmbH. Prospectus* (2001).
10. V. Dauknis, K. Kazakyavichyus, G. Prantskyavichyus, and V. Yurenas, *Thermal Stability of Refractory Ceramics* [in Russian], Mintis, Vilnius (1971).
11. I. Keiishiro, F. Toshiaki, O. Kazuki, et al., "Microstructure and mechanical properties of Si_3N_4 – BN composite ceramics prepared by slip casting," *Tetsu To Hagane, J. Iron Steel Inst. Jpn.*, **5**(9), 1612 – 1619 (1989).
12. I. Yu. Kelina, N. I. Ershova, and E. N. Chasovskoi, "The behavior of composite materials based on silicon and boron nitride subjected to thermal shock," *Ogneup. Tekh. Keram*., No. 12, 12 – 17 (1998).