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High-Temperature Composite Materials and Coatings on the Basis of Glass and Ceramics for Aerospace Technics

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Abstract—High-temperature composite materials and coatings developed in the RIAM, specifically construction composite materials with glass, glass–ceramic, and ceramic matrices, for use at 700–1500°C, ceramic composites on the basis of poly-carbosilanes, erosion resistant coatings with the effect of thermal control for heat shield systems of perspective aerospace technics, are reviewed. These coatings combine a complex of properties: high radiating capacity, phase stability, thermal shrinkage resistance, resistance against acoustic, vibration, atmospheric factors, etc. Technological coatings to protect steels and Ti and Ni alloys during heat treatment and isothermal and hot die forging are developed. New type enamels, pasts, thick-film electric heaters, etc., are described.

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The urgency of the development and application of novel high-temperature materials and coatings resistant to exposure to high (1000–1800°C) and ultrahigh (2000–3000°C) temperatures in oxidative gas media is associated with extreme conditions of atmospheric re-entry of shuttle space vehicles, as well as with the demand for enhanced performance, ecologic, and economic characteristics of aviation and rocket engines. In this connection high-temperature materials and coatings on the basis of silicate, high-silica, quartz, and other glasses, as well as oxide and oxygen-free ceramics have gained firm recognition in aerospace materials science.

The use of glass and ceramics in aircraft and aerospace engineering for solving a whole complex of materials science problems is primarily due to their higher heat resistance compared to polymers and heat-resistant nickel alloys. Such materials include modern carbon–glass–ceramic composites, glass–ceramic, reaction-cured, and oxythermogenic coatings, as well as ceramic materials synthesized by pyrolysis ceramic-forming polymers. The analytical review [1] presents abundant and substantiated evidence showing how the progress in the development of aerospace techniques depends on the availability of light and strong high-temperature materials. Figure 1 presents the calculated temperatures on the surface of the hypersound flying laboratory (HFL) for one of the proposed flight trajectories.

To meet environmental requirements, the pressure trend of the level of nitrogen oxide emissions by aircraft engines should be rigorously controlled and checked for correspondence to ICAO standards. As known, an increase of the working temperatures of aircraft engines entails a more complete fuel combustion and reduction of emission level. According to developed programs, the use of novel high-temperature materials will allow the emissions of nitrogen and carbon oxides to be reduced by 40–87%.

Even the boldest predictions in the field of high-temperature composite materials (CM) and coatings on the basis of glass and ceramics failed to foresee the results of research and the progress in the development of such materials and coatings at the RIAM and their use in the aviation, aerospace, and other fields on new techniques.

The RIAM has pioneered in the development of new fields of research on high-temperature glass and ceramic composite materials and coatings. The RIAM

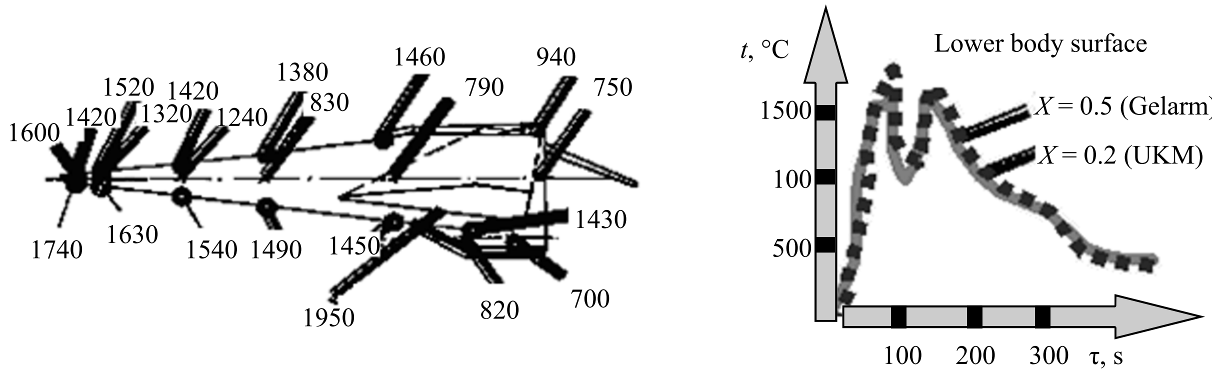

Fig. 1. Calculated temperatures on the surfaces of a hypersound flight vehicle.

was the first to scientifically substantiate and develop a wide range of compositions and technologies for production of frits, slips, and technological coatings for protecting metals and alloys from oxidation on heating and hot pressing, oxygen-resistant coatings for fire protection of turbopump assemblies of liquid-fuel rocket; heat-resistant enamels with a high (>60%) content of silicon dioxide, for gas corrosion protection of parts of combustion chambers and afterburners of aviation gas turbine engines. The RIAM has developed heat-controlling erosion-resistant moisture-proof coatings for reusable tiled thermal protection of spacecrafts (Buran shuttle) and hypersound aircrafts; oxythermogenic coatings with working temperatures of up to 2000°C; reinforcing coatings for hypersound techniques and sound-and-heat-insulating materials; non-fired repair coatings, as well as ceramic protective coatings for platinum–rhodium thermocouples [2, 3, 5, 6, 8].

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The RIAM has developed water-resistant gas-tight coatings for retaining hydrogen in the closed volumes of air-borne power plants, resistive coatings for film heaters, quasiplastic nanocomposites on the basis of ceramics-forming polymers and carbon fillers; these materials compare in quality with foreign analogs. Type Gelarm composites on the basis of 3 D carcasses (mats) of thread-like silicon carbide crystals, alumina fibers, and silicon dioxide withstand working temperatures of up to 1650°C. The developed composite materials can be applied at temperatures of up to 700°C (Steklarm), and 1500°C under long-term and 1650°C under short-term loads of 2.4–6.9 (Karboks).

In view of the fact that certain facets of the R&D work on high-temperature composite materials and coatings on the basis of glass and ceramics have not been covered in the sufficient detail in the literature and can be lost forever, we set ourselves the task to review and summarize a new informationon this issue.

There are three principal characteristic features of silicate glasses and ceramics: (1) mostly covalent chemical bonding; (2) nanostructural level; (3) lack of melting point; and (4) short-range structure ordering. Just these features make possible application of glass and ceramics at high and superhigh temperatures and are responsible for their high chemical stability, hardness, and erosion and corrosion resistance. The low specific weight, availability and low cost of raw

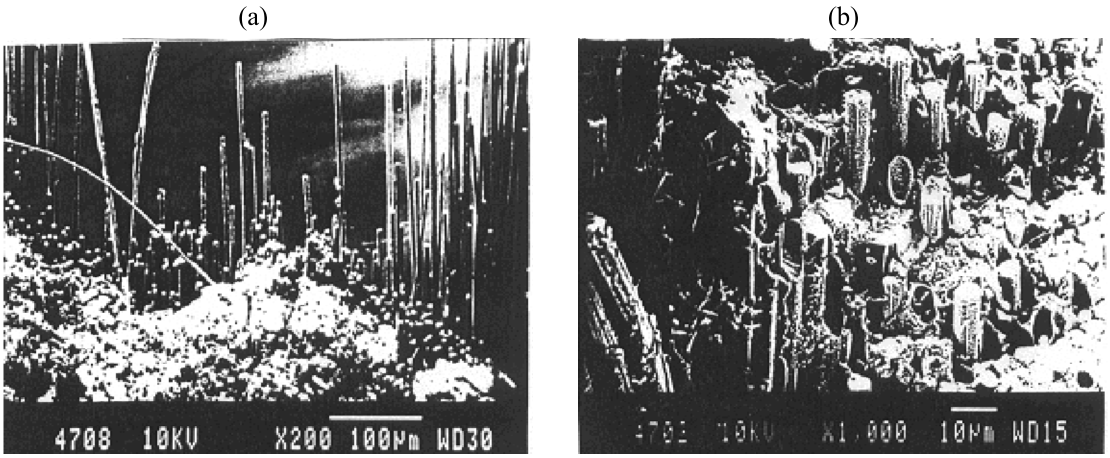

Fig. 2. Structure of the NKKM sample after flexural strength tests. Magnification: (a) ×200 and (b) ×1000.

materials, and fairly simple production technology make these materials competitive.

Quasiplastic Carbon–Ceramic Composites

Nanostructured composites on the basis of organosilicon polymers form on the most important classes of novel synthetic materials which hold promise from the practical point of view.

The use of organoelement ceramic-forming polymers is one of the ways to directed improvement of the performance characteristics of high-temperature glass ceramic and ceramic nanocomposites, specifically increased working temperature, strength, and thermal stability [6, 7].

Organoelement polymers like polycarbosilanes and polysilazanes are promising starting materials for a quasiplastic ceramic composite reinforced with high-strength carbon fibers (UKN-5000, LU-24P) and finely dispersed modifiers (SiC, Si_3N_4).

To synthesize this material, principal components were chosen and their preparation methods were developed, and also temperature and time ranges were determined for forming a quasiplastic ceramic composite.

The ceramic matrix was formed by thermal transformations of the polymer. The characteristic feature of the technology of producing silicon carbide quasiplastic composite materials from polymer precursors is that involves solid-phase synthesis of the ceramic matrix.

Scanning electron microscopy of fractures of nanostructured ceramic composite materials (NCCMs) showed that microcracks originating in the nano-particle-filled matrix are arrested at the fiber–matrix interface. Fiber pull from the matrix could be observed (Fig. 2).

The above effects enhance the deformation stress and strength of NCCMs and allow to prevent their destruction.

In view of the established regularities, samples of quasiplastic ceramic composites with the flexural strength $\sigma_{\rm flex}^{20°}$ = 180–300 MPa, density 1.8–2.0 g cm^{-3}, and the maximum temperature resistance of up to 1500°C.

The advantages of this type of material are primarily associated with the possibility of controlling its properties by means of varying the nature and ratio of components, uniform distribution and orientation of nanoparticles in the bulk of the quasiplastic nanostructured composite, and additional protection system.

Gelarm Glass–Ceramic Heat Shield Composite

Progress in the development of new thermal equipment, specifically thermal chambers for test machines, depends on the availability of new materials capable of operating at temperatures above 1400°C. As such a material for aggressive media there has been developed a Gelarm multifunctional high-temperature glass–ceramic composite material (GCCM) containing domestic easily accessible disperse aluminosilicate reinforcing fillers instead of expensive SiC.

The characteristic feature and undeniable advantage of this material is that it, unlike traditional ceramics, is produced by a "cold" sol–gel technology which involves no high-temperature firing. The key physicochemical process underlying the production of Gelarm coatings and composites is controlled synthesis of ceramic gel coatings and gel matrices directly on the surface of reinforcing fibers and gel growth in voids of the reinforcing carcass followed by thermochemical compaction.

The developed unfired power-consuming technology allows production of varied thickness heat shield large-size panels (Fig. 3) with preset physicochemical characteristics stable over a wide temperature range: working temperature up to 1650°C; density ≥1.5 g cm^{-3}; compressive strength 15–37 MPa; thermal conductivity 0.5–0.8 W m^{-1} K^{-1}; linear temperature expansion coefficient (LTEC) (2.8–3.0)×10^{-6}; radiative capacity ≤0.8; thickness 1–15 mm.

The development of thermostable cold-cure repair compositions and a resource-saving technology for repair and restoration of large-size panels, which allows the heat shield constructions to be restored without their disassembling and dismounting from the equipment.

The developed Gelarm heat shield materials with the EVGS unfired coating were successfully tested for erosion resistance in an aircraft engine jet on the test stand at the Gromov Flight Research Institute. The impact pressure q was ≈ 6000 kg m^{-2} for 160°C. The temperatures of the outer surface of the materials were 330–480°C. The materials can be used for heat shielding and insulation of heating devices (ovens, calorifers, etc.) in different industries.

Ceramic Composites

The structure and properties of dispersion-compacted quasi-isotropic silicon carbide composites are most affected by high-temperature synthesis which involves physical (evaporation–condensation, liquid-phase recrystallization, diffusion-viscous flow, etc.) and chemical processes forming a continuous carbide matrix.

Reactive sintering which occurs by the mechanism of solid-phase sintering in the presence of a liquid phase allows one to control such characteristics as density, porosity, breaking stress, and others, by varying the structure of the composite. The strength of materials like Carbox is virtually independent of the test temperature in the temperature ranges studied. These materials exhibit quite high oxidative resistance.

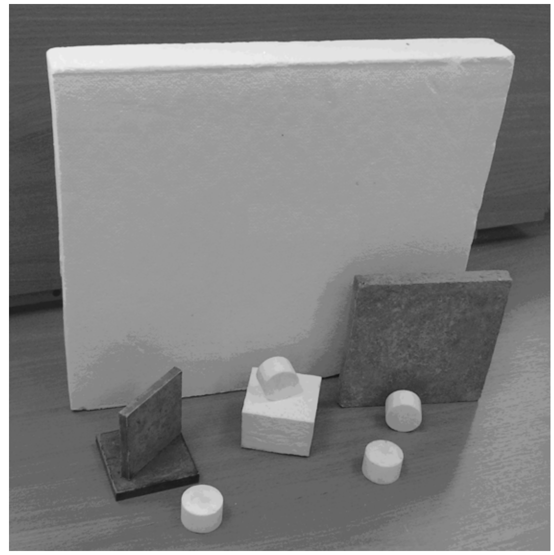

Fig. 3. Large-size panel and samples of Gelarm glass ceramic composites.

They show almost no weight loss for a long time (up to 500 h) at temperatures of up to 1500°C; by contrast, weight gain is observed. Such behavior of the material is associated with the formation of a thin amorphous SiO_2 film on the SiC grain surface. Outer protective coatings prevent oxidation of the composite and allow controlled oxidation rate and depth. Samples of the SiC–SiC composite were tested on the stand of the Progress Zaporozh’e Mechanical Engineering Design Bureau (ZMEDB) (Ukraine) under thermocyclic loads (1500°C ↔ 800°C) in fuel combustion products and withstood without decomposition more than 5000 cycles (1 cycle per min).

Reinforced Glass Composites

Borosilicate, high-silica, and quartz glasses, as well as ceramic-forming glasses were reinforced with continuous carbon fibers. The material was given the name “steklarm.” Scientific basis for the synthesis and production technology of glass-forming, ceramic, glass-ceramic, and glass-crystalline matrices with carbon yarns, fabrics, needle-like crystals, and silicon carbide and silicon dioxide fibers have been developed at our country for the first time.

Glass-ceramic matrices allow composite materials to be formed at fairly low temperatures, thus making less probable oxidative strength loss of carbon fibers. Ceramization induces directed crystallization of the glass matrix, which substantially increases the load

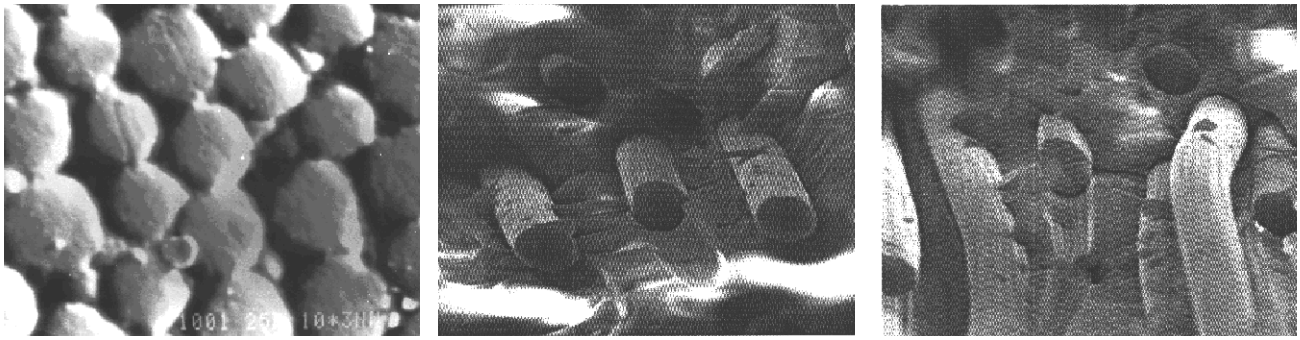

Fig. 4. Micorostructure of the Steklarm composite.

distortion and working temperatures. Foreign materials on the basis of glass-crystalline matrices reinforced with carbon or SiC fibers have a strength of 1000–1500 MPa and a working temperature of 1250–1500°C. Figure 4 shows the microstructure of a borosilicate glass composite reinforced with continuous carbon fibers.

Reinforcing Coatings for 3D Fiber Matrices

The performance properties of heat shield, heat-insulating, and sound-absorbing materials of glass and other chopped (short) or continuous fibers can be much improved by applying coating which modifies the surface and simultaneously binds fibers together in their contact points. Such coatings were given the name "reinforcing," and they favorably affect the mechanical properties of composites on exposure to high temperatures. The use of such coatings can be considered a way to enhance the thermal stability and construction parameters of fibrous heat shield and other materials [2].

The technology of production of reinforcing coatings from polymer precursors characteristically involves the solid-phase synthesis of a specified ceramic layer on the surface of fibers in the material bulk.

Reinforcing coatings were synthesized on the basis of silicon dioxide, carbide, and nitride. Coatings of a complex composition were produced by pyrolysis of polysilazanes, polycarbosilanes, and polyborosiloxanes doped with thermodynamically stable nanodisperse oxygen-containing and oxygen-free compounds (Figs. 5 and 6) [9].

Temperature and time conditions of coating production, as well as mechanical properties and sound-absorption coefficients of samples with reinforcing were studied. It was found that the TZMK material with a reinforcing coating is thermally stable up to 750°C for 1000 h and at 1500°C for 2 h, and the mechanical strength (σ_{compr}, σ_{flex}) increases 2–3 times.

It was shown that perforation decreases the input acoustic resistance of samples and increases substantially the sound absorption coefficient a which reaches in its broad-band maximum the value of 0.75–1 at the spund absorption band of 800–5000 Hz.

Thermostable Thin-Film Protective Coatings for Metal Fiber Porous Abrasive Materials

A thin-film coating (TFC) from polymer precursors and its production technology were developed. A

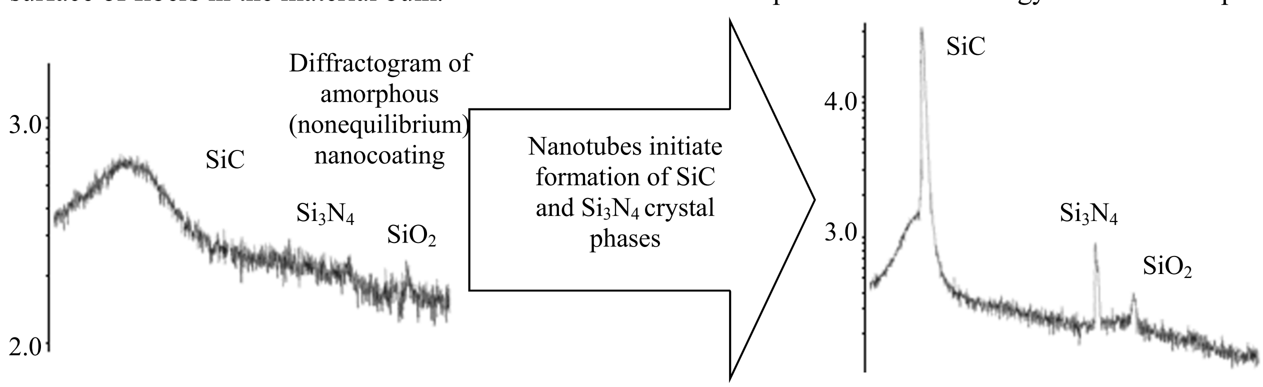

Fig. 5. Scheme of formation of crystal phases in a nanocoating on introduction of carbon nanotubes.

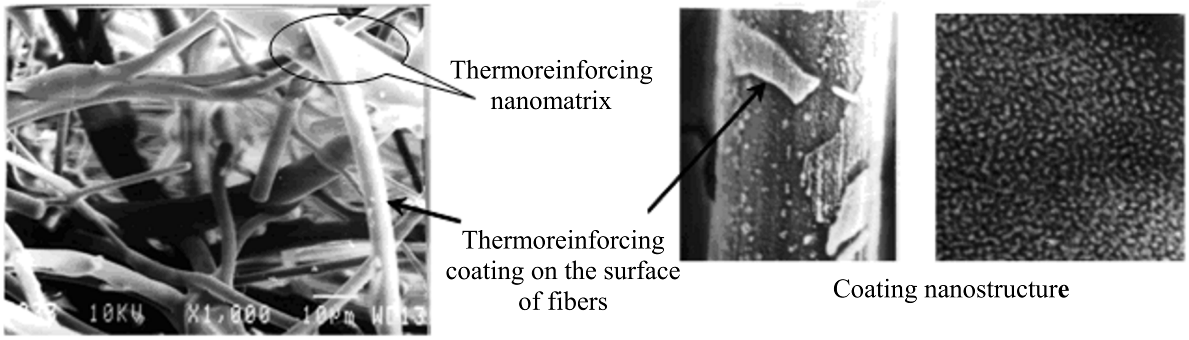

Fig. 6. Microphotographs of the structure of a 3D matrix of a reinforcing nanocoating.

characteristic feature of this technology is a multistage solid-phase synthesis providing a high yield of ceramic residue with a minimum oxygen content which is a necessary condition for enhancing the heat resistance of porous abraded metal materials. The resulting porous abraded material with a thermally stable thin-film protective coating possesses unique properties: high thermal stability, erosion resistance, and low density. The coating increases the working temperatures by 200–300°C and endurance 1.5–2 times. A technology for applying the TFC on fibrous composites was developed and conditions of forming the coating were determined.

The suggested coated thickening material can be used in high-temperature and sound-absorbing filters for compressor or gas turbine wheel spaces and gas- and oil-pumping stations.

Oxythermogenic Coatings

The RIAM has been developing a number of new high-efficiency lines of research in the field of physical chemistry and technology of glass-forming and ceramic systems, which resulted in the development of protective engineering, reaction-fused, erosion-resistant, temperature-controlling, reaction-cured, and resistive coatings.

Protective engineering coatings. The complex research on coatings was based on the following basic postulates.

(1) A protective engineering coating (PEC) is a chemically complex multiphase composition formed by thermal treatment of metal workpieces.

(2) Alloy surface is not only an object to be protected, but also a factor affecting formation and protective properties of coatings, which changes following the laws of multiphase heterogeneous surfaces.

(3) The protective action of coatings is defined by a complex of extreme processes depending on the composition of the protective layer, specific effects of exhaust gases of the coating and its protected surface, reactions on contacting phase interfaces, conditions of thermomechanic treatment of the “coating–alloy” system, and factors inherent in the metal processing technology.

(4) Engineering coatings can fulfill not only protective functions, but also act as high-temperature lubricants and thermoinsulating layers, as consistent with the regularities of variation in their viscosity and thermophysical characteristics.

The theory of PECs suggests that the coating is a component of a dynamic system developing according to chemical thermodynamics laws. The characteristic feature of PECs consists in that the components of the coating–alloy system are in contact with a gas medium and form a dynamic unity. The genesis, development, and destruction of protective layers of these coatings are largely controlled by the thermodynamic factor.

In this connection, we can recognize different stages of their thermogenesis: (1) transfer of components (oxygen, water vapors) from the gas medium to porous coating and to alloy; (2) formation of a continuous (poreless) melted coating layer; (3) heterogeneous reactions; (4) accumulation of reaction products at the coating and alloy boundaries, dissolution of reaction products in the coating; and (5) self-removal of the coating from surface upon cooling to room temperature. The first and second stages are treated in terms of the first and second Fick’s laws. The third, fourth, and fifths stages are generally treated in terms of electrochemical metal corrosion with oxygen depolarization. Protective engineering coatings resemble, to a certain degree, biological objects. They originate and form a continuous protective layer under the action of heat energy, undergo self-treatment, provide oxygen protection, capture the oxide layer and self-remove together with it from the alloy they protect, thereby ceasing their existence.

Reaction-fused coatings for working temperatures of up to 2000°C. The unusual phenomenon described in [2] as coating thermogenesis is based on the use of oxygen and other atmospheric gases. Synthesis and self-organization of inorganic materials during their operation at high temperatures is like to processes that occur in plant leaves which absorb CO_2 or in certain live organisms which uptake oxygen.

Our approach in based on the use of atmospheric oxygen and aerodynamic heating energy and other heat sources for the synthesis of high-melting oxides. oxycarbides, silicides, etc. in coatings and surface layers of components and workpieces.

The ability of the coating substance to react in a controlled manner with the gas medium to form new compounds, in particular, viscous and liquid, suggests a possibility of curing fractures and pores, stress relaxation, and reduction of acoustic and vibration loads. Reactions of coating components with atmospheric oxygen bind the latter, attenuate its diffusion to the matrix, and, therefore, decrease the probability of oxidation and strength degradation of supporting structures [3].

Reaction-Cured Heat-Controlling Erosion-Resistant Coatings for Heat Shield of Shuttle Space Vehicles

Black, white, unfired, and repair coatings were developed for the repeated-use heat shield at the Buran space shuttle. Black reaction-cured and white erosion-resistant temperature-controlling coatings possessing unique thermophysical properties were formed from a low erosion-resistant superfine quartz fiber on a plate material. The porosity of the plate material is > 90%, and this material is impossible to use for heat shielding without an erosion-resistant coating.

Three types of chemical reactions were used for oxythermosynthesis of erosion-resistant reaction-cured temperature-controlling heat shield coatings and materials: redox, glass formation, and fusion.

The redox reactions of coating components may involve atmospheric oxygen, silicon, boron, silcides, and borides like SiB_4.

Of particular interest are processes involving formation of new structural forms from oxygen-free compounds and oxides, which contain one, two, and even three identical glass-forming elements, first of all silicon and boron. During R&D on erosion-resistant coatings for heat shield plates for the Buran space shuttle the author with co-workers developed a technology for production and produced pilot batches of silicon tetraboride (SiB_4) and hexaboride (SiB_6). The introduction of these compounds into the composition of "black" coatings imparted to the latter not only quite a high (>0.9) degree of blackness and low surface catalytic characteristics of the space shuttle, but also, due to the oxythermal reactions of silicon boride with the high-silica matrix glass, quite a high thermal stability, as well as a fire-polished plate surface of a high aerodynamic quality [4].

Such high characteristics of the coating are explained, in our opinion, by the unique structure of the material, formed by chemical reactions between atmospheric oxygen, silicon boride, and high-silica matrix glass. Therewith, of key importance here is the formation of a unique chemical bond between the oxide and oxygen-free components of the coating. As a result, the coating is likely to work as a viscoelastic body, thus providing high thermal stability and thermal elasticity.

Unfired Erosion-Resistant Protective Coating for Flexible Heat Shield

The demand for development of unfired erosion-resistant protective coatings for flexible heat shield materials is associated with the fact that such materials without erosion-resistant coating are insufficiently resistant to air jet and mechanical damage. This task is quite difficult to solve, since coating should not make the heat shield material less flexible.

We developed formulations of fixing and erosion-resistant unfired coatings on the basis of colloid and polydisperse systems and components for organic synthesis of ceramic-forming polymers for flexible heat insulation of high-silica glass fiber (GTZI-N) and fabric (MKKhT-8). The developed unfired erosion-resistant protective coating for flexible heat shield (EVGS-1) is designed to prevent erosion damage of flexible fibrous heat shield mats and fabrics under exposure to high-temperature air jet. Such coatings are recommended for use in aerospace and electrotechnical industry.

Technical characteristics of the coating: service temperature up to 1000°C, density ≤ 2 g cm^{-3}, thermal stability > 100 cycles. Such coatings enhance resistance of heat shield to cyclic thermal loads 2–5 times and resistance to thread extension 1.5–2 times, and also reduces thread crumbling 1.5–3 times.

Coatings for Operation in Strong Oxidant Media and at High Temperatures and Pressures

During start-up and operation of turbo pump aggregates of liquid fuel jet engines (LJE) metal parts are exposed to powerful oxidants (atomic oxygen, etc.), high pressures (hundreds atm) and temperature, attendant with juvenile surface formation, which causes their intense oxidation or inflammation. The most part of metal (engine) undergoes heavy damage within a very short time. Moreover, the experience in exploitation of oxygen systems showed that even very small amounts of foreign particles in the generator gas jet, as well as stresses can induce, under certain conditions, juvenile surface formation and engine inflammation.

In the United States, LJE parts are protected from inflammation by means of gold or silver coatings.

Our research showed that silicate glass coatings are characterized by a high uniformity, gas tightness, and strong adhesion to metal and resistance to atomic oxygen at high temperatures and pressures. They are fairly accessible and inexpensive.

Du to the amorphous structure of the coating matrix, bulk microcrystallization, optimization of the chemical composition, and optimization of the ratio of high-melting and glass-forming components, we developed coating meeting all technical requirements. These coatings are applied to protect junction pipes, rotors, and stators of EP-202, ZhS3DK, and other alloys, considerably enhance resistance of materials to aggressive media, and allow the working medium temperature to be elevated by 100–150°C. The coatings increases the number of engine start-ups from 1 to 10–12.

Hydrogen-Resistant Gas-Tight Coatings. To keep hydrogen in a closed volume, dense glass enamel coatings like EV-27 were developed. The formation temperature of such coatings does not exceed tha intense micrograin growth temperature in steel and does not adversely affect the principal mechanical characteristics of the latter.

The coatings possess a high vacuum stability and withstand sharp temperature changes. The hydrogen permeability of the coating at a film thickness of 120 μm is 1.6×10^{-4} cm^3 cm^{-2} h^{-1}, which makes it possible to prolong the full service life of on-board nuclear power stations to more than 4000 h.

Heat-Resistant enamels. Unlike known foreign aviation enamels which are based on SiO_2 (35–45 wt %) and BaO (30–40 %), we developed high-silica (55–65% SiO_2) low-BaO polyboron enamels which bypass foreign analogs by 150–200°C in fire resistance and possess unique engineering characteristics: high coverage and wettability, uniformity, plasticity, strong adhesion, and good thermal stability.

The high-temperature oxidation susceptibility of alloys with enamels with enamel coatings was stu-died by activation autoradiography, tracer O^{18}. Glass enamels varied in chemical composition and softening (T_g): $Na_2O–B_2O_3–SiO_2$ (500°C), $K_2O–B_2O_3–SiO_2$ (650°C), $BaO–B_2O_3–SiO_2$ (720°C), $MgO–Al_2O_3–SiO_2$ (800°C) [2].

If damage is associated with diffusion of atmospheric gases from the gas medium, then the mechanism of the protective action of coatings is limited to physical isolation of the metal from oxidative atmosphere. In this case, to develop a coating one should choose a formulation with a present diffusion coefficient of the aggressive agent. Protection is efficient if the time required for the diffusion flow of aggressive gases to reach the metal surface is longer than the time required to heat the metal. Consequently, if a coated metal is heated in a neutral atmosphere or in a vacuum, its surface should remain intact. Otherwise, the quality of the metal surface depends on the interaction with coating. The above conditions are difficult to meet, but they can provide necessary reference points in the development of coating formulations.

If the diffusion coefficient of oxygen is higher than 10^{-8} cm s^{-1}, then the effect of diffusion processes on metal protection from oxidation with atmospheric oxygen sharply increases. In this case, a 0.1–0.2-mm coating is not a reliable protective layer, since the diffusion flow is capable of reaching the metal surface within 10–15 min.

For protection of a wide range of fire-resistant alloy parts (combustion chambers, afterburner chambers, flame tubes, stabilizers, etc.) we developed a series of fire-resistant coatings (EVK-103, EVK-103M, EVK-112, EVK-75, EVK-127, etc.).

The coatings feature strong adhesion to the surface of fire-resistant alloys, bulk microcrystallization, gas tightness, strong chemical bond, high fire-resistance, and thermal stability in high-speed aggressive gas jets at 900–1100°C (for a long time) and 1200°C (for a short time).

The developed cold-cure repair enamels with high performance characteristics prolong the service life of parts and considerably decrease the labor and power consumption for repairing commercial coatings.

For prompt repair of parts with their enamel coatings damaged during setting, assembly, transportation, and exploitation the RIAM developed a series of repair enamels. The application of cold-cure repair enamels in motor industry will allow the power and labor consumption for repairing commercial coatings to be decreased by a factor of 3–5, oxidability of steel and alloys by a factor of 4–6, and to prolong the service life of enameled parts by a factor ~1.5–2.

Glass–Ceramic Resistive Dielectric Coatings and Pastes

The theoretical and experimental research resulted in the development of conceptual атв methodical approaches to synthesis of pastes and coatings comprising a thermodynamically stable carcass (matrix) and a complex filler, such as dielectric and protective coatings and pastes DS5 and DS 5-1 and resistive pastes PR-1 and PR-3). The developed pastes and coatings surpass foreign analogs (Dupont, Ferro) in that they are produced from available materials, contain no silver and palladium, and exhibit enhanced stability, reliability, and cost efficiency.

Principal characteristics of the dielectric pastes and coatings: service life in rigid conditions, specifically from –180 to 500°C at sharp temperature changes; radiation resistance; isolation resistance at 20°C about 10^{11}–10^{14} Ω; isolation resistance at temperatures of up to 10^8 Ω. The pastes are environmentally friendly.

Principal characteristics of resistive pastes: specific resistance 0.05–20 Ω m^{-1}, specific power dissipation up to 40 W cm^{-2}, working temperature up to 500°C.

The developed pastes and coatings were commercialized as electrical insulating layers for industrial and household heaters and large-size commutation plates.

Protective Coatings for Beryllium and Beryllium Alloys

A complex system of coatings was developed for heat shield of beryllium and its alloys and prolonging their service life. The advantage of the developed coatings is that their formation temperature (520–560°C) is low compared to service temperature (up to 900°C).

The enhanced protective properties of the complex protective system are provided by chemical transformations at the passivating film–protective coating interface to form beryllium and chromium compounds which dissolve in the protective layer of the glass coating and increase its melting point and inertness.

Application fields of modern high-temperature glass and ceramic materials and coatings [10, 11]:

Working temperature,°C	
700–2500	hypersound flight vehicles
600–1650	thermomechanical processing of metals and alloys
600–2000	Buran-type space shuttles
550–1250	gas turbine engines
< 500	liquid fuel jet engines
< 500	film heaters, resistive pastes

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