STRATEGIC TRENDS OF DEVELOPMENT OF STRUCTURAL MATERIALS AND TECHNOLOGIES OF THEIR PROCESSING FOR MODERN AND FUTURE AIRCRAFT ENGINES

E.N. KABLOV, O.G. OSPENNIKOVA and **B.S. LOMBERG**
FSUE «All-Russia Scientific Research Institute of Aircraft Materials»
17 Radio Str., 105005, Moscow, Russia. E-mail: admin@viam.ru

Strategic directions of development of materials and their processing technologies for the main parts of new generation GTE are determined for the period up to 2030. Modern tendencies of development of cast and wrought heat-resistant alloys are described, including nickel- and titanium-base intermetallic alloys. Characteristics of new vacuum equipment mounted at FSUE «VIAM» for melting of heat-resistant alloys and deformation of high-temperature materials under the conditions of isothermicity in air are given, as well as the results of developments in the field of ion-plasma deposition of protective high-temperature, strengthening and thermal barrier coatings on blades and other GTE parts and development of a new generation of plasma-chemical equipment. Technology of producing a wide range of superpure ultradisperse powders by the method of atomization for vacuum diffusion brazing and additive technologies has been developed. 24 Ref., 10 Figures.

Keywords: *materials and processing technologies, gas turbine engine parts, cast and wrought heat-resistant alloys, intermetallics, vacuum equipment, blades, technologies of ion-plasma spraying of coatings, manufacturing superpure powders*

Analysis of progress of science and technology in the field of development and application of alloys and steels with special properties, formed world tendencies, as well as raw material and resource capabilities demonstrate the urgency of the problem of development of a package of technological solutions for creation of a new generation of cast and wrought alloys and steels with special properties, including complex protection systems and thermal barrier coatings.

Main principles of development of modern materials for complex technical systems should be based on the results of fundamental and fundamentally-oriented research, derived by leading research organizations in cooperation with the Institutes of RAS and on the following postulate: inseparability of materials, technologies and structures, including application of «green» technologies in development of materials and complex protection systems, as well as realization of a full life cycle (with application of IT technologies) — from material development to its operation in a structure, diagnostics, repair, service life extension and recycling.

Considering priority directions and critical technologies in development of science, technology and engineering in the Russian Federation, approved by the Decree No. 899 of President of the Russian Federation of July 7, 2011, priorities in state policy in the industrial sphere, development strategies of state corporations, and integrated structures for analysis of tendencies in materials development in the world, FSUE «VIAM» determined the following strategic directions of development of materials and their processing technologies for the period of up to 2030 [1, 2]:

- «intelligent» structures;
- fundamentally-oriented research, material qualification, nondestructive testing;
- computer methods of simulation of material structure and properties at their development and operation in a structure;
- intelligent, adaptive materials and coatings;
- materials with shape-memory effect;
- laminated metal-polymer, bimetal and hybrid materials;
- intermetallic materials;
- light, high-strength corrosion-resistant weldable alloys and steels, including those with high fracture toughness;
- single-crystal, heat-resistant superalloys, natural composites;
- energy-effective, resource saving and additive technologies of manufacturing parts, semi-finished products and structures;
- magnetic materials;
- metal-matrix and polymatrix composite materials;

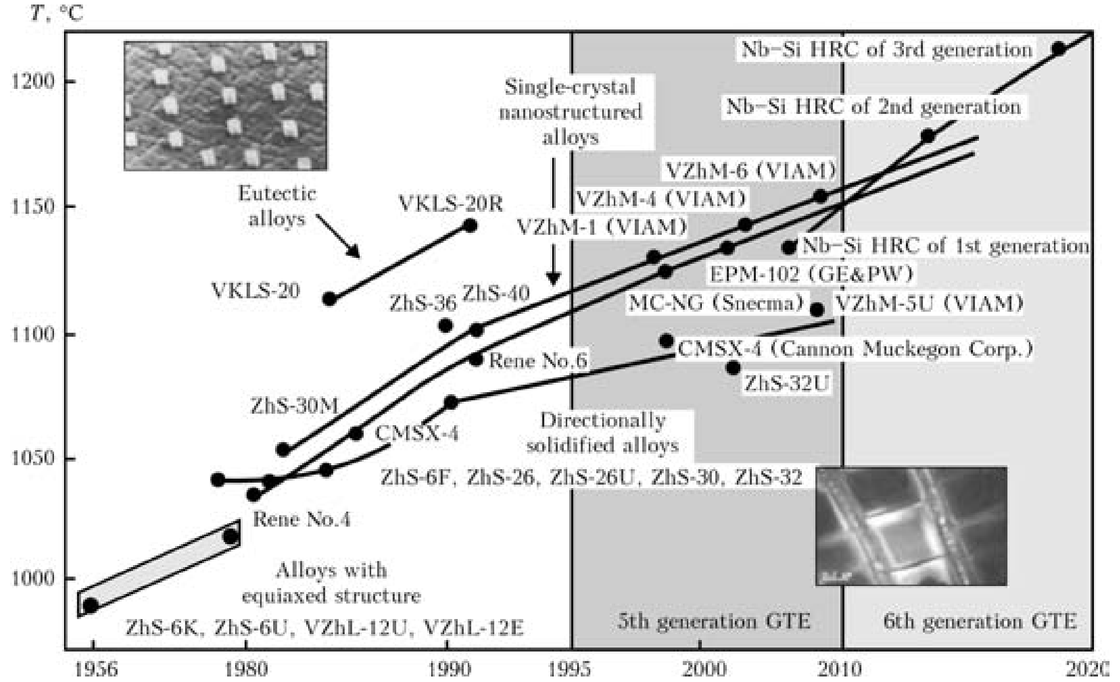


Figure 1. Dynamics of development of cast heat-resistant alloys

- polymer composite materials;
- high-temperature ceramic, heat-resistant and ceramic-like materials;
- nanostructured, amorphous materials and coatings;
- superlight foam materials;
- complex anticorrosion protection, strengthening, wear-resistant protective and heat-resistant coatings;
- climatic tests to ensure safety and protection from corrosion, ageing and biodamage of materials, structures and complex technical systems in natural environment.

Modern tendency in development of cast heat-resistant nickel alloys consists in application of deficit elements of VII and VIII group of D.I. Mendeleev periodic table, such as rhenium and ruthenium (Figure 1).

A special high-duty refractory ceramic shell mould operable up to the temperature of 1750 °C was developed for casting single-crystal GTE blades [3].

Modern heat-resistant nickel alloys (HRA) for GTE blade casting have reached working temperature limit of 1100–1150 °C, that is equal to 80–85 % of their melting temperature. Evolutionary development of heat-resistant nickel alloys led to creation of alloys of I, II, III, IV, and V generations, in which the melting temperature was increased through alloying by refractory elements such as tungsten, rhenium and ruthenium, reaching 1350–1370 °C. At present heat-resistant rhenium-ruthenium containing nickel alloy VZhM4 of the IV generation with long-term strength level of 120 MPa at 1150 °C on the base of 100 h is being introduced into production for manufacturing single-crystal blades [4, 5].

One of the promising directions of development of super heat-resistant alloys for blades exposed to temperatures above 1100 °C in operation, is development of natural composites, produced by the method of high-gradient directional solidification of complex-alloyed nickel-base eutectic alloys. Such developments resulted in creation of eutectic alloys with natural-composite structure of γ/γ'-MeC. To achieve 1250 °C working temperature of blades with natural-composite structure from HRA based on nickel eutectics, heat-resistant rhenium-ruthenium containing nickel alloys have to be used as matrix. It is intended to perform development of such eutectic alloys with increased content of rhenium and ruthenium by 2025 [2, 6].

To increase the temperatures of gas before entering the turbine, and, consequently, increase the engine efficiency, a new class of cast structural high-temperature sparsely-alloyed materials based on Ni_3Al intermetallics from VKNA series has been developed. These materials are designed for manufacturing gas-turbine engine parts operating in the temperature range of 900–1200 °C.

Intemetallic alloys feature low density (by 10–12 % lower than in heat-resistant nickel alloys), and high values of heat resistance at working temperatures. Application of light alloys based on nickel intermetallics as blades will allow lowering the load on turbine discs and increasing GTE resource 2.5–3.0 times.

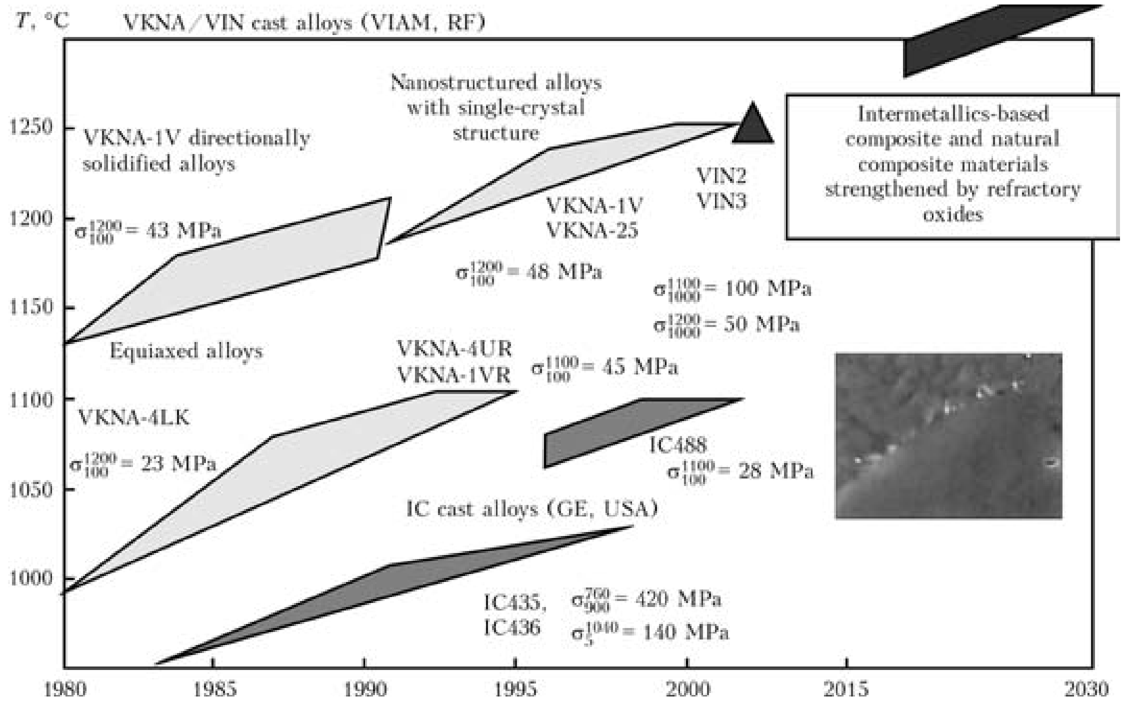


Figure 2. Development of nickel intermetallics based cast alloys

In keeping with their set of physico-mechanical properties, intermetallic alloys of VKNA grade are recommended for cast nozzle blades, parts of flue tubes, flaps and spacers of reactive nozzle with single-crystal structure for long-term operation at temperatures of 900–1200 °C. Alloys based on nickel intermetallics are applied in aeronautical engineering for the first time in the world (Figure 2) [7–9].

Development of new promising GTE is related to increase of working temperatures that requires creation of high-temperature alloys based on refractory matrices. In order to solve this problem, it is necessary to develop high-temperature processes of directional solidification using calculation-based methods of controlling variable temperature gradient, specialized high-temperature equipment and technologies of producing GTE parts from alloys based on refractory matrices.

FSUE «VIAM» set up a production area of up to 200 t/y capacity for production of modern super heat-resistant cast nickel alloys, including nanostructured alloys. The area includes modern vacuum induction furnaces: VIAM-2002 with up to 20 kg crucible, designed and manufactured by FSUE «VIAM» and VIM-50 and VIM-150 furnaces of «ALD Vacuum Technologies» (Germany) of 350 and 1000 kg capacity. Furnaces are fitted with computer control systems, allowing taking samples for chemical analysis of the produced metal during its melting and subsequent optimizing of its composition, as well as melt filtering during its pouring into steel pipes through hot ceramic foam filter. The above-listed features of melting equipment allow maintaining stable optimum composition of melted alloys, low level of impurities and gases, high purity by non-metallic inclusions, preservation of optimum quantity of microalloying additives that ensures producing nanostructured castings from them.

Monitoring of mechanical properties of the produced alloys, content of the main alloying elements, impurities and gases is performed in modern computerized equipment and at FSUE «VIAM» Testing Center (Figure 3).

Proceeding from the results of research work performed at VIAM in cooperation with Baikov IMET of RAS, a resource-saving technology of refining remelting of all kinds of wastes generated in metallurgical and casting production, has been developed and is applied in batch production. This technology allows producing alloys from 100 % wastes, which fully meet the requirements of currently valid specifications as to their purity, and are not inferior to alloys made from raw charge materials.

This technology allows development of a closed cycle for returning expensive and deficit alloying metals (rhenium, ruthenium, tantalum, cobalt, vanadium, etc.) to production. VIAM purchased and is now mounting a new vacuum induction furnace VIM-150 of «ALD» company (Germany) of the last generation with 1 t crucible capacity, the design of which according to VIAM's specification, incorporates modern con-

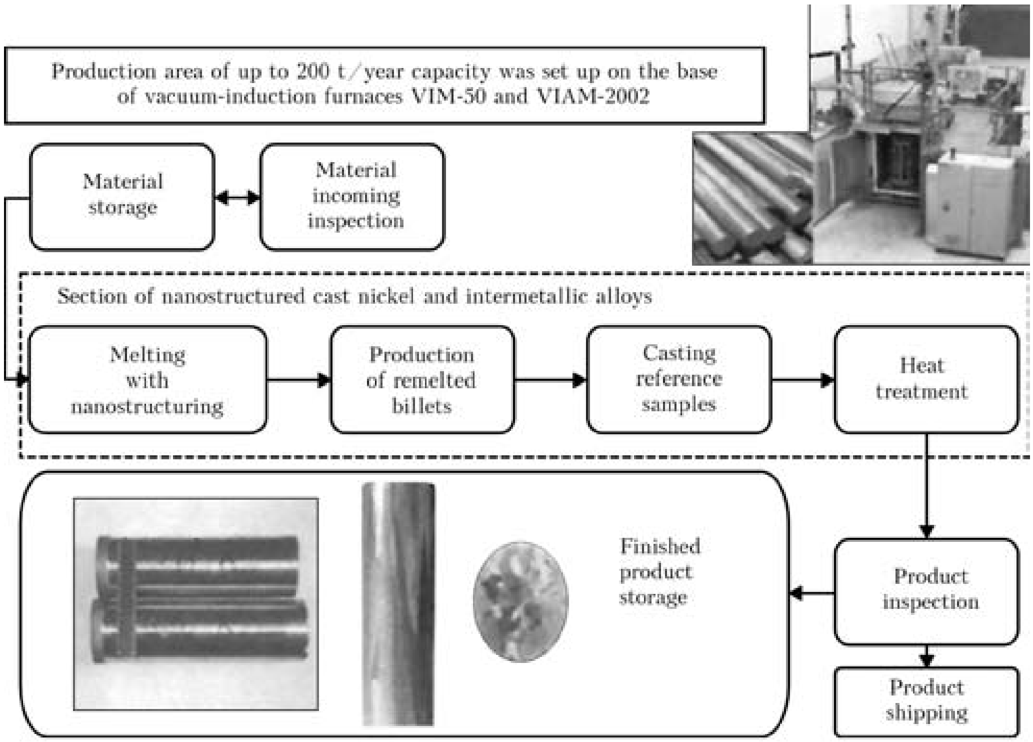


Figure 3. Production of heat-resistant cast alloys

trols and control systems, which allow additional improvement of deposited metal quality [10–13].

VIAM is technology developer and world's leading enterprise in the field of ion-plasma deposition of protective high-temperature, strengthening and thermal-barrier coatings on blades and other GTE and GTU parts. VIAM developed commercial automated equipment (MAP-type installations), in particular MAP-2 installation for gas ion-assisted deposition with ion energy of up to 40 kV (ion current density of up to 200 μA/cm^2), allowing modification of structural-phase state of condensates (coatings) through bombardment of the surface of growing condensate (coating) by accelerated gas ions (Ar, N_2) and, thus improving functional properties of the produced coatings. VIAM supplied to OJSC «Motor Sich» automated MAP-2 installation and a contract for supply of MAP-3 installation is being prepared now [14–19].

Technology supports deposition of all types of protective coatings (based on metals and alloys of various alloying systems, based on nitrides, carbides, oxycarbonitrides, nanolayered coatings from periodically alternating two to four layers of different materials of more than 15 μm total thickness, etc.), in particular, high-temperature gradient coatings of condensation-diffusion types (not having any analogs), and also allows conducting the processes of ion treatment of the surface in metal plasma (most recent process of ion beam surface modification, for instance, low-temperature (up to 600 °C) titanizing or titanizing-zirconating of a structural steel substrate) and processes of HRA strengthening (Figure 4).

For PD-14 engine FSUE «VIAM» developed high-temperature TBC bond coat of cementation + gas aluminizing + VSDP-3 (Ni–Cr–Al–Hf–Re–Y) + VSDP-16 + T/O type and together with OAO «PMZ» optimized the technology of deposition of a complex thermal-barrier coating with deposition of TBC ceramic layer by EB/PVD method on HPT blades in electron beam EB/PVD installation of «ALD» Company (Germany).

VIAM began development of new generation plasma-chemical equipment for deposition of protective and strengthening coatings from plasma gas flows, containing elements of the synthesized coating. Equipment will allow producing in a single-step process multilayer high-temperature TBC with barrier layers based on self-organizing nanocomposites for turbine blades from HRA based on refractory elements (niobium, molybdenum, chromium, tantalum), including eutectic composite materials based on niobium (or molybdenum, chromium) with intermetallic strengthening to working temperature of 1300–1500 °C, as well as functional strengthening single- and multilayer 2-D and 3-D nanostructured coatings with self-organizing ordered structure based on hard compounds of metals and alloys for GTE parts at up to 800 °C temperatures [14–19].

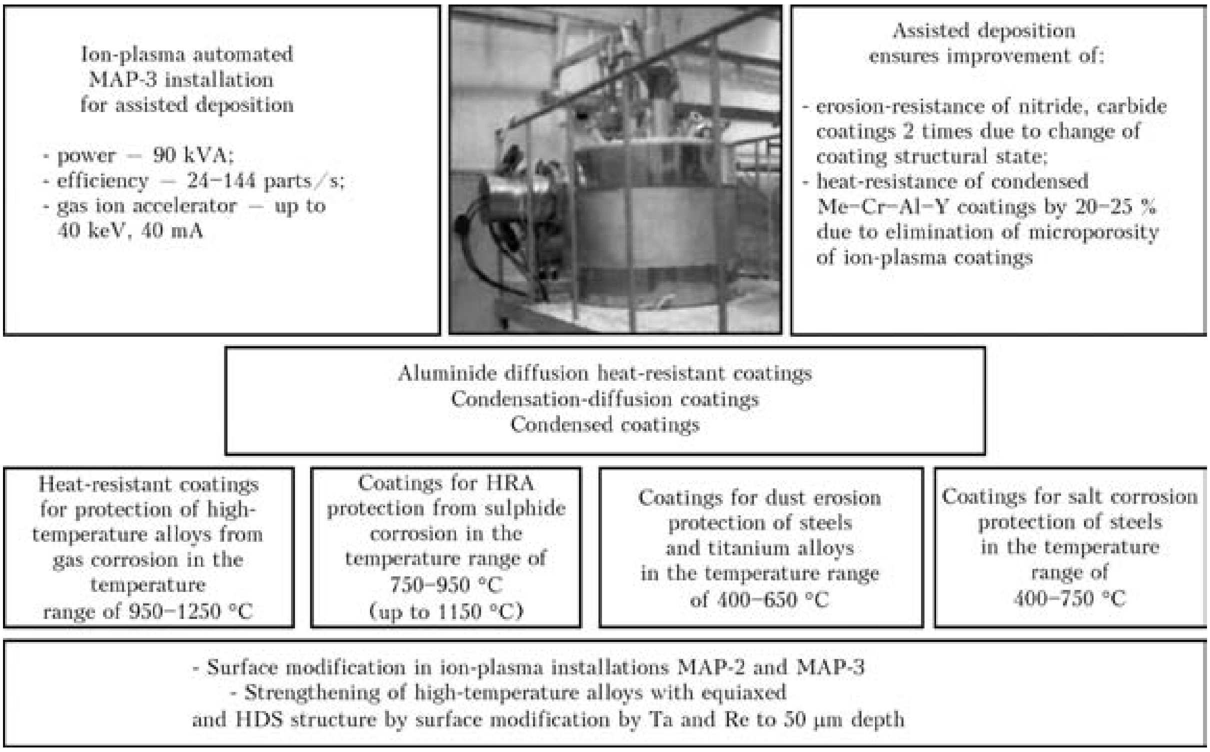


Figure 4. Ion-plasma protective and strengthening coatings

Special attention is given to development of the technology of producing finely-dispersed metal powders for various applications. These are powders of braze alloys and fillers for high-temperature vacuum diffusion brazing, including composite brazing, as well as powders of various alloys (on nickel, iron, titanium, aluminium and other bases) for additive technologies and powders of REM-based magnetic materials.

At present there is no batch production of such powders in the country. At FSUE «VIAM» the newest atomizer HERMIGA 10/100VI has been mounted and put into operation. It is designed for production of finely-dispersed metal powders based on nickel, iron and aluminium, and was the base to set up a production area for manufacturing of powder braze alloys and pilot batches of alloy powders for additive technologies. Powders are supplied to leading enterprises of the industry: JSC «Aviadvigatel», JSC «PMZ», JSC «Saturn», JSC «PDC «Teploobmennik», etc. [20].

Further progress in this direction is associated with development of technologies of producing active alloy powders of specified grain-size distribution, using crucibleless melting of consumable electrode.

Transition to powder manufacture by this technology will allow batch production of powders of local grades, based on titanium, nickel, niobium, etc., with their cost commensurable with those of foreign manufacturers, at wide range and volume of production of up to 30 t/m (Figure 5).

Braze alloys of VPr grades (Vpr1, Vpr2, Vpr4, Vpr7, Vpr16, Vpr28, Vpr24, VPr27, VPr36, Vpr42, VPr44, Vpr50, etc.), as well as technologies of brazing various materials with these braze alloys have been developed by VIAM and are widely applied in aircraft industry.

At present technologies of brazing, including diffusion brazing, developed at VIAM, became widely applied in manufacture of GTE parts and components.

Titanium-base intermetallic alloys are in greatest demand in the field of propulsion engineering. To achieve positive results in commercial production, the following technological tasks should be solved with success:

• development of alloys based on γ-phase of TiAl intermetallic with precision alloying system and density of 3.5–3.9 g/cm^3 and working temperature of up to 800 °C.

• development of technologies of melting intermetallic γ-alloy with ingot structure control;

• development of technologies of machining parts and blades (Figure 6).

Evolution of heat-resistant alloys for GTE discs, both local alloys and their foreign analogs is associated, primarily, with increase of working temperature and improvement of the set of mechanical properties, namely long-term and short-term strength, as well as fatigue characteristics (primarily LCF).

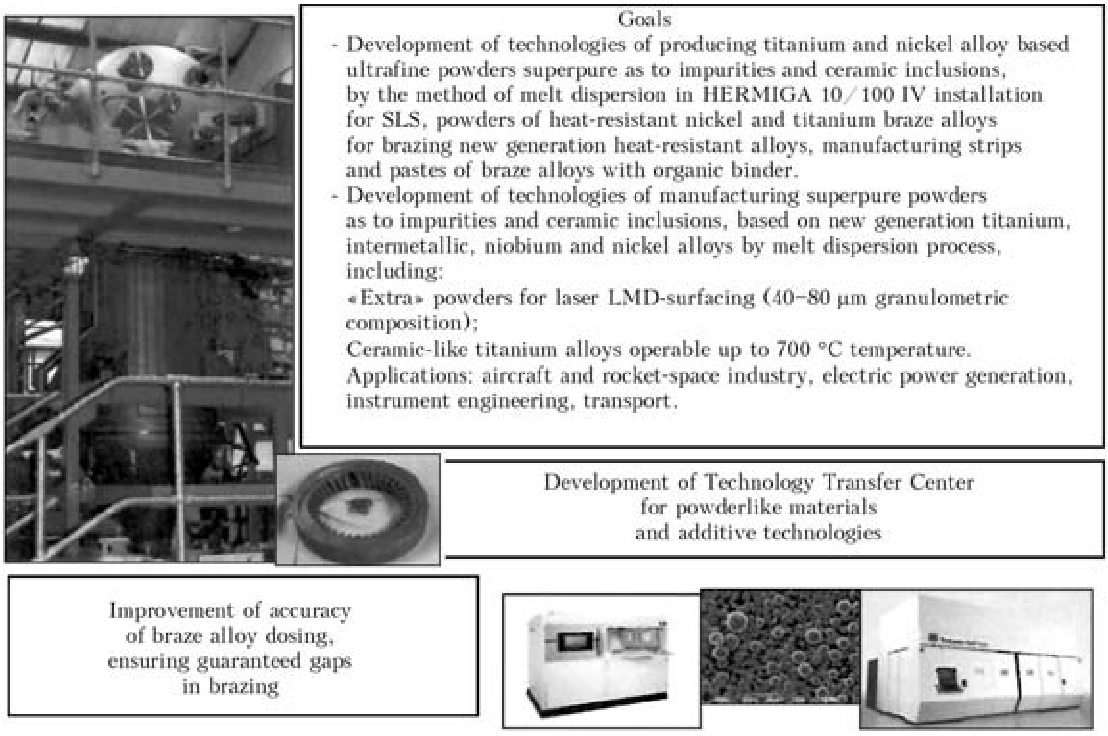


Figure 5. Development of atomization technologies to produce fine high-quality metal powders

FSUE «VIAM» specialists developed a new wrought heat-resistant alloy VZh175, which is characterized by a unique combination of mechanical properties, superior to the known local and foreign alloys as to short-term and long-term strength by up to 15 %, and as to low-cycle fatigue by up to 30 %, with maximum operating temperature of up to 800 °C. Such values have been achieved owing to balanced alloying, uniform fine-grained structure (15–30 μm grain) and original heat treatment mode, providing precipitation of strengthening phases of varying dispersity, including particles of less than 80 nm size.

Commercial production of large-sized stampings for discs (up to 550 mm diameter) from VZh175 alloy for fifth generation GTE has been mastered at OJSC «Electrostal» and OJSC «SMK» [21].

Further increase of service properties of nickel-base heat-resistant alloys through increase

γ-TiAl titanium intermetallic based cast alloys

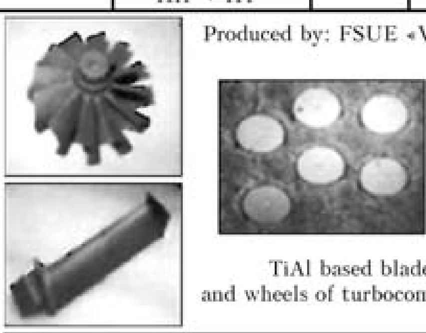
Alloy	Semi-finished product	σ_t, MPa	$\sigma_{0.2}$, MPa	E, GPa
Experimental VIT-Kh	Casting 25 mm HT	≥554	≥538	169
VTI-3L	Casting 25 mm HIP + HT	≥545	≥535	168

Produced by: FSUE «VIAM»

Titanium intermetallic based wrought alloys

Alloy	Semi-finished product	σ_y, MPa	$\sigma_{0.2}$, MPa	δ, %
VTI-4	Sheet 2.5 mm	≥1150	≥1100	6
VIT1	Rod 25 mm dia.	≥1300	≥1150	8

Produced by: JSC «VSMPO-AVISMA» Corporation



TiAl based blades and wheels of turbocompressors

CM advantages (compared to traditional alloys):
- 40 % lower density;
- 1.5 times higher ultimate strength;
- 2 times higher high temperature strength

CM application will provide:
- 40 % lower component weight;
- 250 °C higher working temperatures;
- increased fire safety up to 900 °C.

Applications:
- aircraft industry;
- transport engineering

Figure 6. Promising titanium-intermetallics based materials

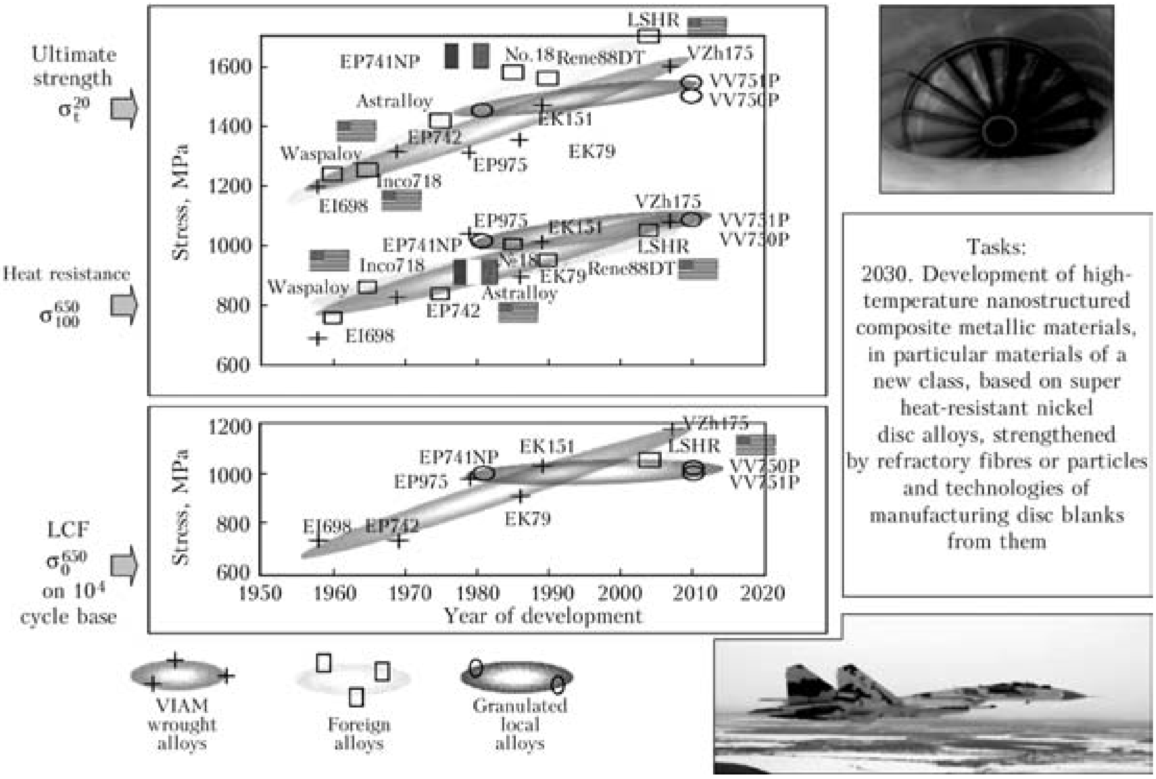


Figure 7. Development of heat-resistant nickel alloys for GTE discs

of srengthening refractory and γ′-forming element content is highly problematic, as today already the alloying level of these alloys has reached a critical value. Therefore, the main directions of development of GTE disc materials involve creation of new nanostructured composite materials, in particular those based on super heat-resistant wrought nickel alloys, strengthened by refractory fibres or particles (Figure 7).

High-strength weldable alloy VZh172, owing to balanced alloying and optimal content of strengthening phase, is superior, in terms of strength and heat resistance values, to currently available local and foreign alloys for similar purposes by 15–70 % with preservation of weldability and technological ductility values high for this material class.

VZh 172 alloy is designed for application as material for casing of combustion chamber and turbine and other heavy-duty parts and components of GTE hot circuit stator, operating at up to 900 °C temperature. In addition, VZh172 alloy can be applied as material for discs of HPC welded rotor and HPC rolled blades with operating temperature of up to 750 °C.

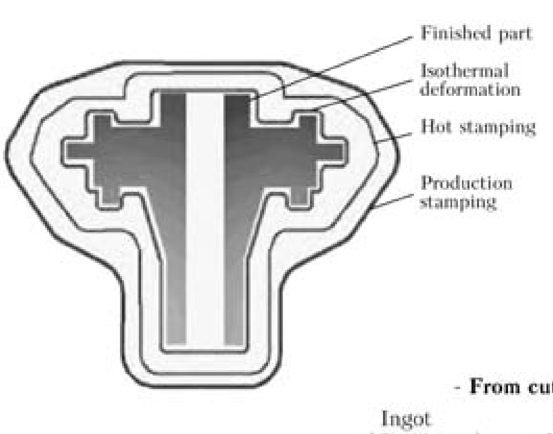
Technological parameters have been determined for argon-arc welding of new super heat-resistant plate nickel alloy VZh171, strengthened by chemicothermal treatment (internal nitriding) and designed for manufacturing welded parts and components of combustion chambers, their highest-temperature resistant elements and other parts of future GTE. Nitrides feature higher thermodynamic stability than intermetallics and carbides, allowing working temperature to be increased up to 1200–1250 °C. Welding of VZh171 alloy with nitriding after welding with application of base material in the form of filler, allows producing welded joints with high hot cracking resistance ($A_{cr} \geq 4.5$ mm/min), with strength close to that of base material ($\sigma_{w.j} = 0.95$–$1.0\sigma_{b.m}$) [22].

FSUE «VIAM» developed and realized an innovative technology of isothermal stamping in air to produce low-cost high-quality disc blanks from super heat-resistant nickel alloys for small-sized GTE.

New energy-effective and resource-saving technology features a high coefficient of material utilization (its values are 2–3 times higher compared to stamping in open dies, used in large industrial enterprises), better processing of metal structure, thus ensuring high stability of mechanical properties.

Both batch-produced extruded rods of 80–150 mm diameter and cut-to-length ingots produced by the process of high-gradient directional solidification (HGDS) can be used as initial billet for isothermal stamping.

Compared to foreign developments, high-temperature isothermal stamping is performed in air, and not in low-efficient vacuum units of complex



Effectiveness:
- 1.5–2.0 increase of CMU through reduction of allowances and optimization of form change in stamping transitions;
- 20–30 % reduction of labour consumption in machining;
- lowering of power consumption due to reduction of technological processing operations and use of lower power equipment;
- reduction or elimination of operations of intermediate removal of surface defects in production of stampings from difficult-to-deform super heat-resistant and high alloys.

FSUE «VIAM» organized batch production of disc stampings for small-sized GTE

Production volume: up to 1500 pcs/year

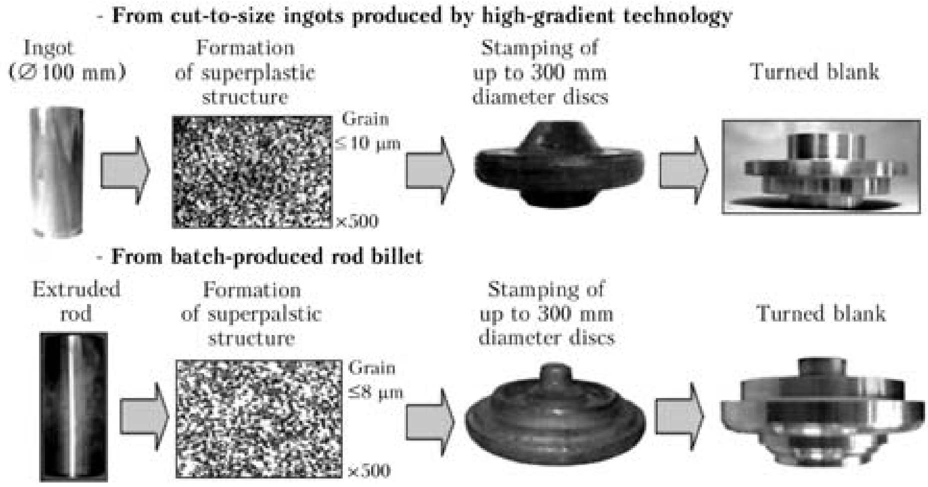
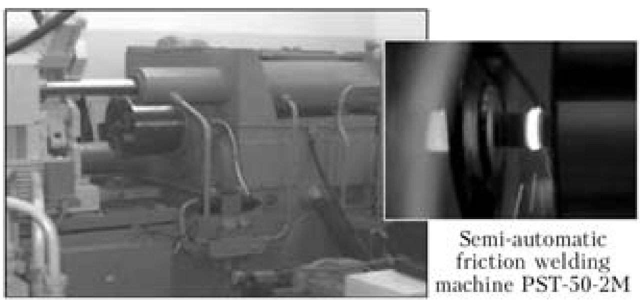


Figure 8. Isothermal stamping of heat-resistant disc alloys in air for small-sized GTE

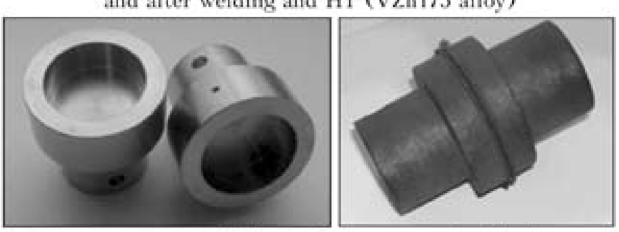


Semi-automatic friction welding machine PST-50-2M

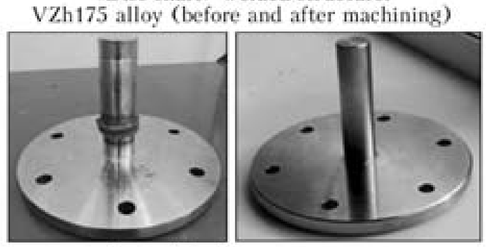
Rotational friction welding provides:

- possibility of welding parts from materials difficult-to-weld by fusion welding;
- producing welded joints with strength close to base material strength;
- increasing the effectiveness of welded component manufacturing;
- considerable lowering of manufacturing labour consumption;
- possibility of welding process automation.

«Tube-to-tube» welded joint before and after welding and HT (VZh175 alloy)



«Disc-shaft» welded structure. VZh175 alloy (before and after machining)



Mechanical properties of welded joints of heat-resistant wrought nickel alloys

Welded materials	Technology variant	σ_t^{-20}, MPa	σ_t^{650}, MPa	σ_{100}^{750}, MPa	σ_t^{750}, MPa	KCU^{-20}, kJ/m²	$K = \sigma_{w.j}/\sigma_{b.m}$
VZh175 + VZh175	Quenching + ageing + welding	1232	1295	638	–	295	≥0.8
	Quenching + welding + ageing	1550	1500	940	–	220	0.90–1.0
	Welding + quenching + ageing	1560	1510	850	–	280	0.85–1.0
EI698 + EI698	Welding + quenching + ageing	1120	–	–	770	400	≥0.9
EP975 + EP975	Welding + quenching + ageing	1120	–	–	990	360	≥0.9
VZh172 + EK79	Welding + quenching + ageing	1300	–	–	850	380	≥0.8–0.95

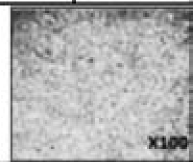
Figure 9. Development of technologies of rotational friction welding

For power parts of engines (shafts, fasteners)
(steel working temperature of up to 450 °C)

Alloy	σ_t	$\sigma_{0.2}$	σ_t	$\sigma_{0.2}$	σ_{100}^{400}	$\sigma_{0.2/100}^{400}$
	MPa (20 °C)		MPa (at 400 °C)			
VKS-170	1570	1520	1300	1200	1000	800
VKS-180	1720	1600	1400	1350	1000	825
EP517 (batch-produced)	1100	950	850	800	880	490
Maraging 250 (USA)	1725	1690	1523	1447	ND	ND

Engine part weight lowering by up to 30 % is ensured

Fine-grained structure of steel after strengthening heat-treatment of semi-finished products →



Application: LPT shaft of PD-14 engine of JSC «Aviadvigatel» (steel VKS-170TU 14-1-4479–88; forging code number «6-33» TU 1-80121-5421–2009)

Quality control

Produced by: OJSC «MZ «Elektrostal», OJSC «SMK»

Figure 10. Mechanical properties of high-strength maraging steels

design with expensive molybdenum dies (Figure 8).

FSUE «VIAM» will set up a Center for transfer of technologies of isothermal deformation in air of new generation heterophase difficult-to-deform HRA [23, 24]. Technologies of rotational friction welding of heat-resistant wrought nickel alloys in similar and dissimilar combinations have been developed for manufacture of items of «disc-shaft», «blisc», «bling» type, providing welded joints with the strength of 0.8–0.9 of the less strong alloy ($K = \sigma_{w.j}/\sigma_{b.m}$). Main parameters of the process of alloy friction welding have been selected. Dependence of friction welding modes and welded joint mechanical properties on heat treatment of welded items was studied. Friction welding of a disc model from VZh175 alloy of up to 300 mm diameter and shaft model of 35 mm diameter was performed (Figure 9).

FSUE «VIAM» developed high-strength structural maraging extra low-carbon steels of 18Ni–8Co–5Mo–Ti alloying system: VKS-170 ($\sigma_t \geq 1570$ MPa) and VKS-180 ($\sigma_t \geq 1720$ MPa), recommended for operation up to 400–450 °C.

Table (Figure 10) gives mechanical properties of VKS-180 and VKS-170 steels compared to EP517 steel used in batch production and foreign analog — Maraging 250. Data given in the Table show that structural maraging steels VKS-180 and VKS-170 are superior to EP517 steel as to strength properties up to +400 °C, and are not inferior to foreign analogs as to the respective characteristics. These steels are also superior to currently applied ones in terms of fatigue life, fatigue resistance, long-term strength and creep.

High-strength structural maraging steels VKS-180 and VKS-170 will be used for GTE shafts to lower the shaft mass by approximately 30 % compared to applied martensitic steels (Figure 10).

Over the period of 2010–2012 VIAM developed the composition of heat-resistant VKS241 steel for GTE bearings and helicopter gears; technology of melting, hot plastic forming and strengthening heat treatment, providing not less than *HRC* 60 hardness at 20 °C, heat resistance of 500 °C, adaptability to fabrication and structural homogeneity.

By the level of properties (impact toughness, hardness) VKS241-VI steel is on the level of its analog — M50 (USA) and is approximately 2 times superior to currently applied EI347 steel as to impact toughness.

New heat-resistant bearing steel VKS241 is 1.5 times less expensive than EI347 as to alloying element cost.

In conclusion it should be noted that application of new materials developed at FSUE «VIAM» will allow solving important scientific-technical tasks, namely developing GTE with power-to-weight ratio of 20:1, increasing gas working temperature to 2000 K, extending GTE service life by 1.5–1.7 times, thus ensuring fast advance of aircraft engine construction industry.

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Received 18.04.2013