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Adhesives for Aviation Equipment

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Abstract—The properties of high-strength and high-elastic film adhesives, high-strength cold- and hot-setting adhesive pastes, adhesives intended for bonding of metals, different nonmetallic and composite materials are overviewed. The properties of self-adhesive materials of different grades used for temporary repair of airframe surfaces are also described.

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Application of adhesives in aviation engineering started together with the emergence of aviation itself. At the first stage of development of aviation engineering the main aviation material was natural wood. The first synthetic adhesive developed by the All-Russian Scientific Research Institute of Aviation Materials, VIAM, (in the 1940s) was VIAM-BZ phenol-formaldehyde adhesive, which marked the beginning of application of synthetic adhesives in the aviation industry [1].

At present there are more than a hundred of VIAM developments in this field. These adhesives are recommended for application within a temperature range from –269 to 1600°C; they ensure operation of metallic and nonmetallic structures in different climatic zones [2, 3]. This article provides data on adhesives that are widely used in critical aviation units nowadays.

Phenol-Rubber Adhesives

The emergence of jet aviation, with aluminum alloys as the main material for jet aviation equipment, initiated the development of structural phenol-rubber adhesives. During the hardening process there is a chemical reaction between hydroxyl and methylol groups of the phenol-formaldehyde oligomer with nitrile, hydroxyl, carbonyl, and other functional groups of the rubber, resulting in formation of a cross-linked structure. The hardening process follows the polycondensation mechanism with emission of volatile products.

Modification of phenol-formaldehyde oligomers with rubbers makes it possible to obtain adhesive systems combining positive properties of both the phenol-formaldehyde oligomer (high strength and heat resistance) and the rubber (high elasticity). Examples of this type of adhesives are VK-3, VK-32-200, and VK-25, providing the shear strength of the adhesive joints of up to 20 MPa and elasticity of the hardened film of the adhesive layer reaching 150–200%. Phenol-rubber adhesives made it possible to solve a crucial national-economic task on creation of domestic load-bearing bonded aviation structures, including honeycomb structures, characterized by a long serviceable life and high reliability.

The first phenol-rubber adhesives emitted volatile products during the hardening process, in connection with which it is necessary to apply high pressure during hardening and to perforate the honeycomb filler during bonding of honeycomb structures in order to remove these products. VK-50 phenol-rubber adhesive does not have these weak points. The composition of this adhesive is based on a phenol-formaldehyde oligomer with unsaturated bonds. Unlike all the other phenol-rubber adhesives, VK-50 hardens following the polymerization mechanism and emits no byproducts due to the use of peroxide in its composition; moreover, it does not require high pressure during bonding.

Table 1. Properties of selected phenol-rubber adhesives

Indicator	Brand			
	VK-3	VK-32-200	VK-25	VK-50
Working temperature range, °C	from –60 to +80	from –60 to +200	from –60 to +80	from –60 to +150
Shear strength, τ_v, MPa	15	13,5	23	25 ± 5
Tear strength, σ_v, MPa	–	–	22	25 ± 5
Peeling strength, S_{peel}, kN m^{-1}	–	–	5–6	10
Percent elongation, γ, %	–	–	140–200	135–150
Long-term strength, $\sigma_{l.s}$, MPa (based on period, h)	–	–	18.5 (500)	17 (500)
Fatigue strength, τ_{max}, MPa (based on cycles $N = 10^7$ cycles)	–	–	9	10

Table 2. Properties of selected epoxy film adhesives

Brand	Working temperature range, °C	Adhesive strength properties					
		τ_v, MPa	σ_v, MPa	S_{peel}, kN m^{-1}	γ, %	$\sigma_{l.s}$, MPa (period, h)	τ_{max}, MPa at $N = 10^7$ cycles
VK-36	from –130 to +160	37 ± 2,5	50	2–3	80–100	34 (500) 33 (1000)	8
VK-41M	from –60 to +80	35 ± 2,5	–	3–4	–	30 (500)	–
VK-46B	from –60 to +80	36 ± 2,5	–	3–5	–	32 (500)	–
VK-51	from –60 to +80	40 ± 2,5	–	3	70–120	32.4 (500)	9
VK-51A	from –60 to +80	37.5 ± 2,5	–	3	40	22.4 (500)	9

The properties of phenol-rubber adhesives applied in aviation engineering nowadays are given in Table 1.

Adhesives Based on Epoxy Oligomers

There is a wide range of high-strength film and paste structural adhesives based on epoxy oligomers characterized by a wide range of strength and strain properties. With regard to their properties, these domestic adhesives are as good as the best foreign analogous products. The properties of high-strength film adhesives are given in Table 2.

Such adhesives are used in production of honeycomb and laminated load-bearing structures from metals and polymer composites. The adhesive joints are characterized by a high long-term strength, resistance to vibration, crack propagation, climatic factors, and aggressive media. VK-46B is classified as a flame-resistant adhesive with a low smoke emission level; it is used for gluing of honeycomb structures with low flammability. High-strength film adhesives are applied as an adhesive matrix of long-lived adhesive prepregs for polymer composites with improved properties.

Adhesive pastes based on epoxy oligomers are widely used in the aviation industry.

Great importance is given to works on development of adhesives for composite joints: VK-9 and VK-27 cold-setting adhesives and VK-37 and VK-39 hot-setting adhesives. They are intended for bonding of metals and different nonmetallic materials in adhesive and composite (adhesive-riveted, adhesive-welded, adhesive-threaded) joints in various industrial sectors.

Adhesive joints made on the basis of these adhesives are characterized by a high water and tropical resistance and provide a reduction in the weight of riveted structures.

VK-37 and VK-39 adhesives harden at an elevated temperature (120°C, 3 h) and make it possible to produce adhesive-riveted and adhesive-welded structures with a long serviceable life and high reliability.

Table 3. Strength properties of cold-setting adhesives

Properties of adhesive joints	Test temperature, °C	Brand				
		VK-9	VK-27	VK-67	VK-93	
					5 h hardening	24 h hardening
Shear strength, τ_v, MPa	20	15	25	30	9.0	22
	80	–	10	19	9.0	12
	125	4	–	10	–	–
Delamination strength, S_{del}, kN m^{-1}	20	1–2	2–3	3–5	–	2

Cold-setting adhesives are extremely important in aviation equipment repair works. At present almost in all products of the domestic aerospace engineering there are bonded units of honeycomb and laminated structure. They are made from Al-alloys and polymer composites exposed to various operational damages. VIAM experts have developed VK-67, a high-strength two-component cold-setting adhesive, which is superior to all previously developed adhesives of this class. VK-67 exceeds VK-27 adhesive in strength by 20 and 75% at test temperatures of 20 and 80°C, respectively, and in elasticity by a factor of 3–4. It is also characterized by a higher heat resistance (working temperature reaches 125°C instead of 80°C) and processability, as it can be applied under conditions of elevated humidity and on wet surfaces at temperatures above 12°C.

Another VIAM development is VK-93, a quick-setting epoxy adhesive ensuring a sufficient level of the initial strength of adhesive joints several hours after the hardening at a temperature of (23 ± 5)°C. This feature makes it possible to significantly reduce labor intensity of the bonding process due to the possibility to perform further technological steps before the bonding process is fully completed. Such adhesives are indispensible in repair works when it is not possible to apply heating for acceleration of hardening of the adhesive joints. VK-93 has the following advantages over VK-27: the initial strength of adhesive joints is reached after 5 h of hardening at a temperature of (20 ± 5)°C ($\tau_{v20°C} \geq 7.0$ MPa), the shear strength of the joints after thermal aging (80°C, 1000 h) at a test temperature of 80°C increases by 33%, and the time of the final hardening at 20 ± 5°C is reduced twice (24 h instead of 48). The properties of cold-setting adhesives are given in Table 3.

Among adhesives applied in instrumentation it is necessary to mention VKP-11, a current-conductive adhesive intended for bonding of aluminum alloys, corrosion-resistant steel, brass, and copper, and for establishing of the electrical contact in structures operated within a temperature range from –60°C to +120°C. This adhesive stands the tests for 1000 hours at 120°C. Its volume resistivity at 20°C does not exceed 5×10^{-4} Ω-m. This adhesive contains no precious metals.

The properties of VKP-11 are given in Table 4.

Table 4. Properties of VKP-11 conductive adhesive

Indicator	Value
Hardening conditions:	
temperature, °C	120
time period, h	3
specific pressure, MPa	0.05…0.1
Working temperature range, °C	from –60 to +120
Shear strength, τ_v, MPa, at temperature, °C	
20	14.0
80	13.0

Temperature Resistant Adhesives

Temperature resistant adhesives developed by VIAM are widely used in engine-building, in special-purpose equipment, and in production of consumer goods. These adhesives are applied for bonding of heat-insulating and other heat-resistant nonmetallic materials; for gluing of high-density ceramic items (with no special surface preparation required); for fixing of strain gauges and various sensors on the surface of the items under testing; for repairing and sealing of joints; for gluing of magnetic cores and for chipping; and for production of optical pyrometers.

The adhesives ensure the adhesive joints serviceability within a temperature range of 300–350°C (durably) and up to 1600°C (briefly). At present the following temperature resistant adhesives are in use.

VK-26M, a one-component (at delivery) low-viscosity adhesive intended for bonding of core stacks in high-precision instruments; the adhesive is serviceable at temperatures reaching 300°C.

VK-78 adhesive is intended for bonding of nonmetallic heat-insulating ceramic materials based on silicon nitride and carbide that are operated in an oxidizing environment within a short period (30 min) at temperatures reaching 1400 and 1600°C, respectively. The adhesive is recommended for bonding of high-temperature sensors and mounting of auxiliary equipment on the surface of the engine elements, produced from ceramicson the basis of silicon nitride, which make it possible to perform bench-run tests of the new product at temperatures reaching 1200°C. The adhesive requires no special preparation of the ceramic surface before bonding.

VK-58, a heat-resistant cold-setting adhesive, has a multi-component composition and is used within a temperature range from –60 to +250°C (durably) and at 500°C (briefly). Application of VK-58 is a part of the technology of elimination of typical defects in the air-conditioning system in the engine zone.

At present VIAM has gathered great experience in development and application of temperature resistant cold- and hot-setting adhesives for thermal and strain-gauge testing.

VK-58 adhesive is applied for bonding of strain gauges used for strain measurements within a temperature range from –60 to 300°C in articles of aerospace equipment as well as in items of household measuring equipment at temperatures ranging from –60 to +60°C. The adhesive is in full compliance with the requirements for adhesives applied in strain-gauge testing: it is processable (working life of 7 h); the adhesive makes it possible to create thin adhesive lines and ensures reliable fixation of strain gauges to the surface within a temperature range from –196 to +300°C. During the tests carried out by experts of the "Research Institute of Physical Measurements" Federal State Unitary Enterprise (works performed by L.V. Kulakova and L.A. Shamrakov) it has been found out that VK-58 adhesive does not require any additional thermal treatment of the attached strain gauges for stabilization of their readings. Even at the first heating it ensures a high-quality transfer of strain from the surface under investigation to the strain gauge grid. When heated repeatedly, the strain gauge readings are almost the same. The value of the strain gauge factor for gauges attached to the surface with the use of VK-58 adhesive is 1.82 at a test temperature of 300°C and the creep value at the indicated temperature amounts to 5.56.

High-Temperature Adhesive Cements

VIAM experts have found a solution to the problem of increasing the working temperature range for adhesives that are intended for high-temperature thermal and strain-gauge testing. They have developed VKP-88TS, a high-temperature hot-setting adhesive cement, the composition of which is based on a combination of nonorganic compounds. VKP-88TS is recommended for bonding of working thermocouples of the PR 30/6 type (platinum-rhodium-platinum-rhodium) to the surface of samples made of the C/SiC system composites during bench-run tests in an oxidizing environment under thermal cycle conditions (up to 24 cycles) at temperatures ranging from 20 to 1440°C (with 5-minute exposure to 1440°C). VKP-88TS adhesive cement is also used for attaching of working thermocouples of the TR type (tungsten-rhenium) to the surface of samples made of the C/SiC system composites during bench-run tests in vacuum at temperatures reaching 1600°C with 10-minute exposure to 1600°C.

VKP-26TS high-temperature hot-setting adhesive cement, based on a modified organosilicon binder, is intended for attaching of the wire grid and the lead-out wires of ZhTSN-10-120 high-temperature strain gauges to parts of gas-turbine engines in order to measure dynamic strain within a temperature range of 20–800°C.

Aqueous-Based Adhesives

VK-69 hot-setting adhesive is a water dispersion based on a phenol-formaldehyde oligomer and a modifying polymer with no toxic organic solvents in its composition. By strength properties this adhesive is at the same level as VS-10T and VS-350 heat-resistant structural adhesives, containing ethyl acetate (toxic organic solvent). VK-69 is applied for bonding of strain gauges, for production of strain modules in pressure and force sensors in studies of stress conditions of various structures and equipment operated within a temperature range from –100 to +200°C and briefly at 300°C. VIAM experts have

Table 5. Properties and applications of temperature resistant adhesives

Brand	τ_v, MPa		Working temperature range, °C	Special properties	Application
	at 20°C	at elevated temperature			
VK-58	14.0	0.5 (500°C)	from –60 to +500	Contains no solvent	Gluing of strain gauges
VK-26M	20.0	5.0 (300°C)	from –60 to +350	One-package	Bonding of magnetic cores, chipping
VK-69	14.0	7.0 (300°C)	from –60 to +300	Contains water instead of organic solvents	Gluing of strain gauges
VK-78	12.0	5.0 (400°C)	1100	Requires no special preparation of surfaces	Bonding of ceramics, thermal sensors
VK-89	16.0	5.0 (400°C)	from –60 to +400	Temperature- and corrosion-resistant	Bonding of heat-resistant nonmetallic materials, heat insulation
VK-91	10.0	3.5 (400°C)	from –60 to +400		
VKP-26TS	Not controlled		from 20 to +800		Gluing of strain gauges
VKP-88TS	1.5	–	from 20 to +1600	Emits no degradation products	Bonding of thermal sensors
TPK-2	2.5	2.5 (400°C)	from 20 to +1000	Ecologically sound. Ensures gas impermeability of adhesive joints	In heating structures

developed VK-69M, a modification of VK-69 adhesive with improved processing characteristics: the strength properties of this adhesive at temperatures varying from 20 to 300°C exceed VK-69 characteristics by 15–20%.

TPK-2 adhesive is an aqueous solution of a modified nonorganic binder. It is serviceable at temperatures reaching 1200°C and is used as a filler material in manufacturing of electrical connectors for heaters. The adhesive can be also applied for bonding of lining, gluing of elements, and sealing of clearances between the structural elements in heaters.

New Temperature Resistant Adhesives by VIAM

At present a number of temperature resistant adhesives applied in products of the domestic aviation industry have become scarce due to the termination of industrial production of the required feedstock, including D-20 oligoestercarborane. In this connection VK-20 hot-setting and VK-20M cold-setting heat-resistant adhesives, which were developed earlier on the basis of D-20 product and are intended for fixation of heat- and sound-insulating materials and production of gas generator parts with sound suppression, are manufactured on the basis of the limited available stock of this component.

VIAM experts have solved this problem through development of temperature resistant adhesives that do not contain oligoestercarborane.

One of VIAM developments in this field is VK-89 hot-setting adhesive, which is superior to analogous VK-20 in terms of higher strength characteristics of adhesive joints at temperatures reaching 400°C (by 15% at 300– 350°C and by 53% at 400°C) both in the initial state and after exposure to various factors, including aggressive media, tropical climate enclosure, and water. At the same time, at 20°C VK-89 strength properties remain at the same level as VK-20 characteristics. VK-89 is intended for bonding of metals (carbon and corrosion-resistant steels) and nonmetallic materials (fiber glasses of SK-9FA, SK-101, and other types) among themselves and in various combinations. VK-89 adhesive is recommended for application within a temperature range from –60°C to +400°C, including 5 h of service at a temperature of 400°C.

Table 6. Properties of adhesives for rubber-mechanical joints. Test temperature of 20°C, 24 h after bonding

Brand	Peeling strength of adhesive joints between 3826 rubber and 3826 rubber, kN m^{-1}	Delamination strength of adhesive joints between SIL-35 organosilicon rubber and SO-120A plexiglas, kN m^{-1}	Shear strength of adhesive joints between 3826 rubber and 30KhGSA steel, MPa	Delamination strength of adhesive joints between 3826 rubber and 30KhGSA steel, kN m^{-1}
VKR-61	0.59 (after 20 min) 2.6	–		
VKR-86	–	not less than 3.0		
VKR-60			–	4.0
VKR-85			3.9	–
VKR-90			6.8	–
VKR-95[a]			2.2	4.0

[a] Cold-setting adhesive.

VIAM experts have also developed VK-91 cold-setting adhesive ensuring the performance capability of the adhesive joints at temperatures reaching 400°C in the initial state and after exposure to various factors (aggressive media, tropical climate enclosure, and water). As compared to analogous VK-20 adhesive, VK-91 is characterized by a higher strength of adhesive joints.

VK-91 is recommended for bonding of metals (carbon and corrosion-resistant steels and titanium alloys) and nonmetallic materials (fiber glasses of SK-9FA, SK-101, and other types). The adhesive can be used within a temperature range from –60°C to +400°C, including 5 h of service at a temperature of 400°C.

The main characteristics of some temperature resistant adhesives are given in Table 5.

Adhesives for Rubber-Mechanical Joints

VIAM experts have developed a range of adhesives for bonding of unvulcanized rubbers with metals in the vulcanization process and for bonding of vulcanized rubbers between themselves, with metals, and rubber-fabric materials in structures of all items of modern aviation equipment (rubberized blades, brackets, counterbalances, bladder tank fittings etc).

VKR-85 adhesive is recommended for bonding of unvulcanized rubbers based on butadiene-nitrile, chloroprene, natural, and butadiene caoutchouc with further vulcanization (as a substitution for Leikonat adhesive). The working temperature range is from –60 to +130°C.

As a substitution for VKR-15, VIAM experts have developed VKR-60 adhesive intended for bonding of unvulcanized rubbers based on SKN, SKI, and SKS caoutchouc grades, nairit with metals in the pan vulcanization process. The working temperature range is from –60 to +100°C.

For import-substitution purposes VIAM experts have developed an adhesive system consisting of VKR-90, which is intended for bonding of metals with rubbers based on SKN in the vulcanization process, and a sublayer enhancing VKR-90 adhesion to rubbers based on non-polar caoutchouc (SKI, SKI+SKD etc.). The adhesive system ensures that the strength characteristics of the adhesive rubber-metallic joints are at the same level as the properties of the Chemosil family manufactured by Henkel and exceed the properties of VKR-85, a domestic analogous adhesive. This system is serviceable within a temperature range from –50 to +130°C both in the air and in aggressive media. The adhesive composition contains no scarce, imported, or expensive materials and is fully based on the domestic raw materials.

Another VIAM development is VKR-61, a cold-setting adhesive substituting VKR-17. It is intended for bonding of vulcanized rubbers based on butadiene-nitrile caoutchouc between themselves as well as with rubber-fabric materials. The strength of adhesive joints (σ_{peel}) amounts to 0.59 kN m^{-1} after 20 minutes and reaches 2.6 kN m^{-1} after 24 h. The adhesive joints are resistant to various factors and media and are serviceable within a temperature range from –50 to +150°C (durably) and up to 200°C (briefly).

VIAM experts have developed VKR-95, a cold-setting adhesive ensuring the minimum strength of adhesive joints of 4.0 kN m^{-1} after 24 h of hardening at

Table 7. Properties of self-adhesive materials

Property	Brand			
	ZPPK	FLC	SAF	VSMT
Working temperature, °C	from –60 to +60	from –60 to +80	from –60 to +150	from –60 to +80
Delamination strength, N cm^{-1}, min	5.0	5.0	6.0	6.0
Shear strength, kPa, min	300	300	500	400
Static shear resistance (creep) for 1 h at P_{stat} = 0.2 kg at elevated temperatures, mm	0	0	0	0

a temperature of (23±5)°C. VKR-95 adhesive is recommended for bonding of vulcanized rubbers based on natural and butadiene-nitrile caout-chouc and rubberized fabric between themselves and with metals (30KhGSA steel and D-16AT aluminum alloy). The adhesive is serviceable within a tem-perature range from –60 to 100°C under conditions of elevated humidity as it is characterized by high humidity and tropical resistance.

VKR-86 cold-setting adhesive has been developed for bonding of rubbers based on organosilicon caoutchouc with plexiglas (as a substitution for K-131-37) and titanium alloys. This adhesive provides the strength of adhesive joints of (σ_{delam}) ≥ 3.0 kN m^{-1}. The adhesive joints are operated within a temperature range from –60 to +100°C.

The properties of adhesives for rubber-mechanical joints are given in Table 6.

Self-Adhesive Materials

VIAM experts have developed ZPPK self-adhesive film multi-layer sheet coating with a sticky adhesive base (not more than 120 μm thick), which is principally new for the domestic industry. ZPPK combines protective and decorative properties; it is serviceable within a temperature range from –60 to +80°C. This coating ensures protection of damaged areas of paint coatings during repair works of the airframe exterior surfaces, also in field conditions. The material has passed the tests during operation of IL 96-300 aircrafts in various climatic zones (more than 2000 h). The environmentally sound technology of ZPPK application makes it possible to reduce labor intensity of repair works and ensures the absence of toxic substances.

At present in connection with a high demand for domestic self-adhesive materials intended for imme-diate repair of aircrafts there is a necessity to perform additional detailed studies of previously-developed aluminum foil with permanent sticky layer (FLS) which is serviceable within a temperature range from –60 to +80°C. Fol'goplen, a domestic material of the same purpose, has been taken out of production.

FLS self-adhesive foil provides adhesive joints resistance to various factors and media. Application of this foil for temporary repair of the airframe exterior surfaces (scratches, chippings, and coating flaking) ensures a high static shear resistance, reduced labor and energy intensity, and an environmentally sound technology of repair works.

Additional research works have been carried out and have made it possible to expand the fields of applications of SAF self-adhesive material, which is serviceable at temperatures reaching +150°C, and to recommend it for new technologies of immediate repair of the airframe exterior surfaces made from carbon-fiber and fiber-glass reinforced plastic. Application of SAF for repair purposes will make it possible to extend the periods between planned maintenance and repair works.

VSMT, a self-adhesive material with a fabric base, has been developed for immediate repair of complex curvature surfaces. It is characterized by improved pro-cessability ("imbedding capability"): τ_{shear} = 400 kPa, σ_{delam} = 6.0 N cm^{-1}. The properties of self-adhesive materials are given in Table 7.

Therefore, adhesives and adhesive materials developed by VIAM are applied in structures of almost all aviation engineering products and ensure a long serviceable life and high reliability of the bonded units.

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