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CRITERIA OF EFFECTIVENESS OF REPLACING MATERIALS FOR TRIBOTECHNICAL PURPOSES FOR AIRCRAFT FRICTION UNITS
Report 2. FRICTION MATERIALS

An analysis of general characteristics of materials of tribotechnical purposes, which make up a friction subclass, is carried out. The classification scheme of main types of compositions of friction materials including asbestos-based materials, casting alloys, sintered materials and composites materials with a carbon and ceramic matrix is synthesized. The block-diagram of the formation of basic operational characteristics of friction materials including the main and additional functional frictional properties is developed.

Classification components of the operational characteristics are consistent with relative criteria of efficiency of friction materials which numerical definition is realized within the framework of the proposed conceptual approach to the criteria assessment of the possibilities of increasing of the operational characteristics of the aircraft parts and the method of gradual expansion of their completeness. [dx.doi.org/10.29010/083.3]

Keywords: *friction materials; classification of basic operational characteristic; block-diagram of the formation of properties; criteria of effectiveness for the replacement of materials of friction pairs.*

Introduction

As stated in [1], about 75% of units and assemblies used to fail due to wear and tear of friction pairs. Since various aircraft systems (control system, landing gear, hydraulic system, etc.) are the ones that operate through the movement of their elements, support of their reliable operation is imperative for enhancing the flight safety [2–4].

The paper [1] has analyzed the basic operational characteristics of tribotechnical materials that make up an antifriction subclass. Given below is a similar analysis and criterial efficiency of replacing the tribotechnical materials for aircraft friction joints for a friction subclass.

Friction materials are those meant to be operable in the units which transfer or dissipate kinetic energy (in brakes, couplings, etc.) [5]. Utilization of these materials is based on their high values of friction coefficient and wear resistance. The friction materials should be [4]:

- highly friction heat-resistant (a property of maintaining a stable friction coefficient and wear value within an operating temperature range);
- resistant to seizure and wear;
- quickly conformable;
- resistant to thermal fatigue;
- mechanically strength;
- corrosion-resistant;
- smooth and noiseless in engagement and sliding.

Seeking to further analyze the criteria of efficiency of friction materials replacement, consider (as in the paper [1]) the general characteristic of related types.

Problem Statement and Solution

An analysis of a great number of information sources generalized in the papers [2–4] and others enabled to synthesize the classification scheme of main types of friction material compositions (Fig. 1) that include four subclasses:

1. Asbestos-based materials having their component groups of asbestos/rubber materials and asbestos/resin materials.
2. Casting alloys composed of two groups: friction cast irons and steels (as a friction counterbody).
3. Sintered powdered materials including three groups: copper-based materials, iron-based materials and cermets.
4. Composite materials including carbon-to-carbon materials and ceramic matrix composites.

Consider in more detail the characteristics of the classification components of each subclass of the friction materials.

Subclass 1 of the friction materials includes asbestos-based materials which, according to the type of binding medium, includes two groups [5]:

- asbestos/rubber materials with a synthetic rubber binding medium, various fillers (zinc oxide, iron minium, graphite, etc.) and booster compounds for proper rubber curing;

- asbestos/resin materials with a binding medium of phenolformaldehyde resin and various fillers (barite, iron minium, lead oxide, kaolin, brass chippings, electrocorundum, etc.).

As it was found from the studies of friction heat-resistance of asbestos/rubber materials [11], the friction coefficient varies continuously from 0.45...0.60 to almost 0, as the temperature rises to 400°C, that is caused by the softening of the binding medium. Wear rate of such materials grows with the temperature rise, the wear being particularly high at temperatures ranging from 370 to 400°C.

Also, the changes in friction process parameters have an essential effect on the properties of asbestos/rubber materials. When operated together with steel 65G (65Г) in relatively light modes, the asbestos/rubber materials have a rather high wear resistance. As the specific load and speed increase, these materials get worn much heavier, therefore, their use in highly loaded friction units featured by tense thermal operational modes is limited [11].

A low-heat resistance of the binding media used accounts for a relatively low operating temperature of asbestos/rubber materials. In addition, a low heat conduction of these materials makes the metal counterbody overheat in operation that results in shrinkage in a number of instances [11].

Unlike the asbestos/rubber materials capable of working only under 300°C, the asbestos/resin materials are more stable in terms of friction properties at higher temperatures. As is the case with asbestos/rubber materials, the operating temperature range for most asbestos/resin materials is also defined by the temperature of disintegration of the binding medium [11].

The best material out of the asbestos/resin ones is retinax FK-16L (ФК-16Л) with related friction products used for the friction units in aircraft wheels. Retinax FK-16L is a combination of phenolformaldehyde resin, asbestos, barite and brass wire and has the physical and mechanical characteristics as follows: d = 2400...2650 kg/m^3; λ = 0.60 W/(m·K); c = 0,84 kJ/(kg·K); τ_{shear} = 32,5 MPa; $\sigma_{B\,compr}$ = 72 MPa [20, 21].

This material withstands a surface temperature of up to 1000°C and has a relatively stable friction coefficient in disregard of some decrease at about 400°C [5]. As coupled with cast iron ChNMKh (ЧНМХ) at the temperature of 100°C, the friction coefficient of retinax FK-16L is f = 0.328...0.450; at 980°C it is f = 0.210...0.312 [21].

Subclass 2 of friction materials includes casting alloys consisting of two groups: friction cast irons and steels used in friction units as one of the elements of friction pair (as a rule, counterbody).

The friction cast irons are used because of their low cost, ease of fabrication of related parts, good machinability, high strength and satisfactory wear resistance.

Perlitic gray cast irons, essentially, fine-grain gray cast irons with hardness of 2500 HB are used for medium-load friction units. Disadvantage of these cast irons is their possible cracking at variable heat loads due to insufficient heat-resistance and strength. Additionally, these cast irons reveal phase transformations at temperatures above 400°C that is accompanied by an increase in ferrite content and higher wear of the coupled part at specific loads of over 600 kPa [5, 8].

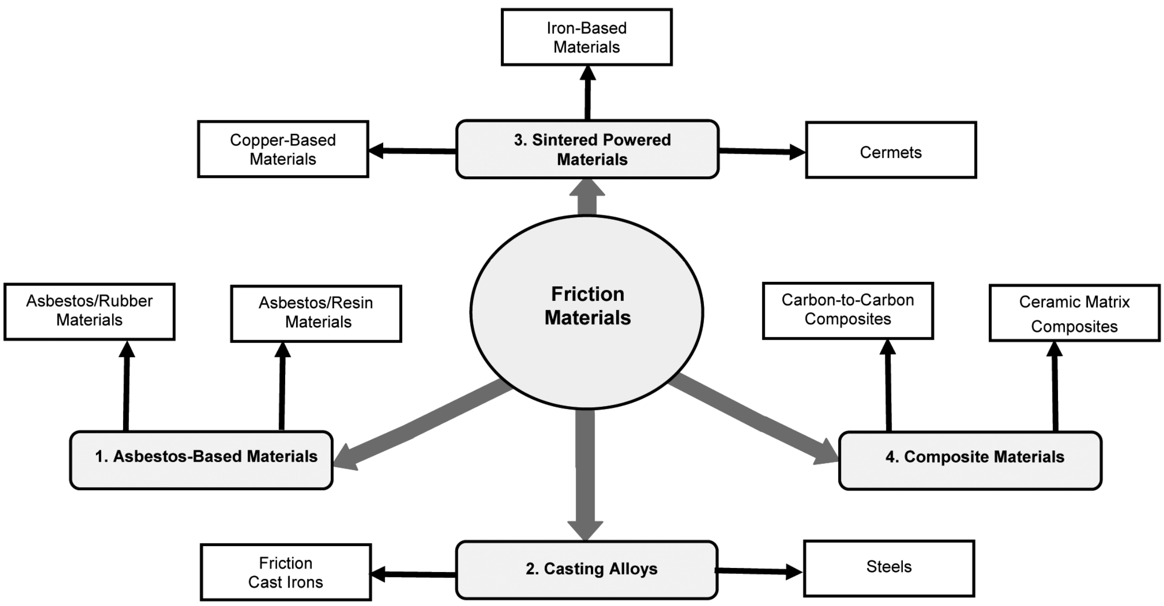

Fig. 1. Classification Scheme of Main Types of Friction Materials Compositions

Alloyed cast irons most closely correspond to the requirements imposed on friction pairs which operate in dry friction conditions. These have higher strength and heat-resistance. For instance, alloyed cast iron ChNMKh has σ_B = 200 MPa; δ = 0.5%; ψ = 13.5%; λ = 50...70 W(m·K); α = (11.7...13.7)·10^{-6} K^{-1} within the entire range of operating temperatures [5].

In the heavy-load friction units, the alloyed cast irons are more operable and durable than the common cast irons or steels, though essential thermal stresses arising from braking lead to cracks on the units' working surface as well [8].

The perlite-class alloyed cast irons having a perlite-graphite structure have better friction properties as the ferrite available in the structure contributes to a reduced friction coefficient and seizure of coupled parts [5, 8].

When operating together with sintered iron-based friction materials, the alloyed cast irons ChNM (ЧНМ) and ChNMKh have a rather high and stable friction coefficient at different temperatures [5].

Also, carbon steels (steel 20, steel 35, steel 40, steel 45, steel 65G and other) can be used as a material for friction counterbodies. Advantages of steels are easy manufacturing friction elements from them by machining, good thermal physical properties and mechanical strength. Weaknesses include higher wear and lower friction coefficient, as the friction elements get overheated, and shrinkage and contraction of parts in operation. In this connection, the steels are used for manufacturing the counterbodies which operate at relatively low heat loads in pair with asbestos friction or sintered materials [8].

Heat-treated steels (40–50 HRC) are generally used for lubricated friction units. In dry friction, however, although heat treatment does decrease steel wear twofold or threefold, the sintered material gets worn by 1.5 times more [8].

For the friction units operating without lubricant in pair with sintered materials, low-carbon steels are used due to low wear of the friction pair's both elements (the wear of sintered materials is thrice as low as that of high-carbon steels when rubbing against the counterbody) [8].

A diversity of original components and technological possibilities of the powder metallurgy allow fabrication of a wide range of friction sintered materials (metal ceramics) with high operational properties that represent *Subclass 3* of the friction materials. Application of the friction metal ceramics contributes to increased durability, reliability and efficiency of friction units and creation of new structures with high energy-saving, wear resistance, heat-resistance as well as high and stable values of the friction coefficient. Such materials do not only improve performance of aircraft but also provides for the aircraft's high cost effectiveness by the effect of longer service life of friction units and lower operating costs [6–7].

As shown in the classification scheme in Fig. 1, this subclass of friction sintered materials includes three groups: copper-based materials, iron-based materials and cermets.

Metal ceramics FMKM-1 (ФМКМ-1) based on copper composition of are Cu – 8Sn – $3SiO_2$ – 6Pb – – $3MoO_3$ – 3C used for friction electromagnetic and overriding clutches in aircraft units at dry friction and temperatures of up to 200°C [3]. Physical and mechanical properties of the metal ceramics FMKM-1 are given in Tables 1 and 2.

For ν = 0.1...6.3 m/s, when coupled with chrome-plated steel, the material FMKM-1 has f = 0.28...0.30 and the wear of the metal ceramics is 8 μm/hr [3].

The friction material FMKM-1 is produced by pressing burden under the pressure of 250...350 MPa and sintering under the pressure of 0.8...1.2 MPa at the temperature of 760...780°C in hydrogen [10].

Compared to the copper-based metal ceramics, the sintered iron-based friction materials representing the second group of the friction materials subclass considered have higher strength and withstand higher specific loads and higher friction temperatures (1000...1200°C) [11].

Brake rotors and friction washers with metal ceramics FMK-79 (ФМК-79) based on iron composition of Fe – 10Cu – 3BN – $6BaSO_4$ – 6SiC – 6C are used for aircraft wing devices, on-board loading cranes in air transport, ground handling main booms and other friction units in aircraft [10].

Physical and mechanical properties of the metal ceramics FMK-79 are shown in Tables 1 and 2.

For ν = 20 m/s, when couples with ChNMK cast iron, the friction coefficient of metal ceramics FMK-79 is f = 0.3...0.4; stability of the friction coefficient is no less than 0.7; the wear is no more than 12 μm/braking [3, 4].

The friction material FMK-79 is produced by pressing burden under the pressure of 500...700 MPa and sintering under the pressure of 1.5...2.0 MPa at the temperature of 970...1000°C in hydrogen [10].

Developed for aircraft's brake rotors are the frictional metal ceramic materials FMK-8 (ФМК-8), FMK-11 (ФМК-11) and MKV-50A (МКВ-50А) which work in couple with cast iron ChNMKh or steel 3Cr13 (3Х13). The materials are fabricated on the basis of iron while the metal ceramics FMK-8 contains a minimum quantity of iron and maximum quantities of alloying elements Ni, W, Cr. The rest of metal ceramics have a much greater percentage of iron while the above alloying elements are none (Table 3) [13]. Physical and mechanical properties of these materials are shown in Table 4.

For the wear resistance and conformability required, the hardness of the metal ceramics following

Table 1

Physical Properties of Friction Sintered Materials FMKM-1 (Copper-Based) and FMK-79 (Iron-Based) [4]

Metal Ceramics	d, kg/m³	λ, W/(m·K)	c, kJ/(kg·K)	α, K⁻¹
FMKM-1	7000...7500	9.24	0.348	$16.8\cdot10^{-6}$ (T = 20...100°C)
FMK-79	5500...5600	18.90 (T = 25°C) 17.64 (T = 800°C)	0.546 (T = 100°C) 0.798 (T = 600°C)	$14.3\cdot10^{-6}$ (T = 20...600°C)

Table 2

Mechanical Properties of Friction Sintered Materials FMKM-1 (Copper-Based) and FMK-79 (Iron-Based) [4]

Metal Ceramics	T, °C	σ_B	$\sigma_{B\ bend}$	$\sigma_{B\ compr}$	τ_{shear}	Hardness	KCU (α_n), kJ/m²
	MPa						
FMKM-1	20	50...60	70...80	140...150	70...80	600 HB	9.8...14.7
FMK-79	20	40...50	110...120	250...260	90...110	800...1050 HRF	9.8...10.8
	600	30...40	70...80	150...160	30...40	600...700 HRF	6.9...7.8

Table 3

Chemical Composition of Iron-Based Metal Ceramics (mass %) [12]

Metal Ceramics	Fe	Cu	C	S	Si	Ni	Cr	W	B	Asbestos
FMK-8	Base	5...7	5.5...6.6	1.3...2.3	–	23...27	8.5...10.5	5...7	–	–
FMK-11		14...16	6.5...8.0	0.5...1.0	1...2	–	–	–	–	2.0...3.5
MKV-50A		9...11	8.5...11.0	0.6...1.2	3.0...4.3	–	–	–	3.0...4.3	2.5...4.0

Table 4

Physical and Mechanical Characteristics of Iron-Based Non-Lubrication Friction Metal Ceramics [11]

Parameters	Metal Ceramics		
	FMK-8	FMK-11	MKV-50A
d, kg/m³	7000	6000	5000
σ_B, MPa	90...100	55...65	30...40
$\sigma_{B\ compr}$, MPa	450...500	300...350	155...210
τ_{shear}, MPa	80	80...100	67...85
$\sigma_{B\ bend}$, MPa	–	160...200	100...140
KCU ($\alpha_н$), kJ/m²	–	–	7.85...11.77
$\alpha\cdot10^6$, K⁻¹, in interval T = 20...500°C T = 20...900°C	–	13.3...14.8 –	10.9...11.3 10.9...13.8
c, kJ/(kg·K), in interval T = 100...800°C	–	0.503...0.711	0.503...0.837

sintering must be within the range of 630...830 HRF for FMK-8, 700...950 HRF for FMK-11 and 600...1000 HRF for MKV-50A [12]. In this case the hardness of the counterbody made from cast iron ChNMKh should be 1600...2200 HB and 2700...3000 HB for the counterbody made from steel 3Cr13. An increase in the hardness of both metal ceramics and cast iron deteriorates inter-conformability [13]. The frictional properties of the iron-based metal ceramics and the wear rate of the friction pair elements are given in Table 5.

The merits of the sintered material FMK-11 are its workability at high temperatures and within a wide range of loads and speeds. With the alloying components in mind, the metal ceramics FMK-8 is noted for its high wear resistance at friction temperatures of up to 500...600°C. The friction material MKV-50A features high performance in high-load brake conditions [14].

The friction metal ceramic material FMK-845 (ФМК-845) on the basis of iron composition of Fe – 5C – 2.2Si – 1.2Ni – 0.6Cr – 0.8W – 1Mn having the hardness of 650...1000 HRF (as sintered) was developed for brake rotors for operation in couple with the sintered materials FMK-11, MKV-50A and FMK-79 [12]. The frictional properties and the wear rate of the friction pairs with both elements being metal ceramics are shown in Table 6.

The third group of the sintered friction material subclass is represented by cermets used for aircraft's landing gear brakes. In addition to the taking of high dynamic loads, these materials, when used, reduce the weight and space of the structure [6].

A binding phase for the cermet is chiefly copper alloys having good heat conductivity or, in special cases, iron and its alloys. Borides, carbides, nitrides, oxides or their mixtures are used as ceramic phases. Generally, the contents of the ceramic phase are in excess of 40%. By combining plastic metals with strength but brittle high-melting compounds in a cermet, the materials are produced that have better properties than with the original materials [5].

The cermet-based friction materials operate at about 1000°C. Depending on the operating conditions, the friction coefficient varies within 0.3...0.7. Such materials feature high wear resistance and heat-resistance [5, 6].

High contents of nonmetals in cermet compositions lead to a reduction in cermet strength. A special process of double pressing and sintering and hot pressing and pressurized sintering is used for enhancement of strength characteristics of cermets [6].

For manufacture of friction linings for multiple-disk brakes, the cermet SMK-80 (СМК-80) having a composition of Fe – 23Cu – 6.5Mn – 2.5MoS_2 – – 6.5BN – 10B_4C – 3.5SiC has been developed. The material has the following physical and mechanical characteristics: d = 5900 kg/m^3; σ_B = 40...50 MPa; $\sigma_{B\,compr}$ = 150...250 MPa; τ_{shear} = 80...100 MPa; α = (11.0...12.3)$\cdot10^{-6}$ K^{-1} in the interval of T = 20...500°C [6].

Table 5

Frictional Properties of Iron-Based Metal Ceramics [13]

Friction Pair	f	α_{st}	l, µm/braking	
			Metal Ceramics	Counterbody
FMK-8 + ChNMKh	0.16...0.20	0.65	16	4
FMK-11 + ChNMKh	0.25...0.29	0.77	22	4
FMK-11 + 3Cr13	0.18...0.22	0.80	24	6
MKV-50M + ChNMKh	0.34...0.38	0.77...0.80	20	4

Table 6

Frictional Properties of Friction Pairs Made from Metal Ceramics [12]

Material	f	α_{st}, not less than	l, µm/braking, not more than	
			Metal Ceramics	FMK-845
FMK-11	0.241...0.309	0.72	22.0	6.0
MKV-50A	0.330...0.404	0.70	16.0	12.0
FMK-79	0.300...0.400	0.65	16.0	12.0

Table 7

Friction Properties of SMK-80 + ChNMKh Friction Pair in Operational Modes of Aircraft Multiple-Disk Brake [11]

N_{spec}, MPa/m·s	p, MPa	f	α_{st}	l, μm/braking	
				SMK-80	ChNMKh
1	0.16	0.52	0.88	2.3	1.8
2	0.54	0.31	0.82	4.7	4.7
3	0.95	0.26	0.75	2.0	4.7
4	1.33	0.22	0.69	6.0	8.2

Friction characteristics of the friction pair SMK-80 + ChNMKh in the operating modes of aircraft's multiple-disk brake (v_{start} = 26.5 m/s) are given in Table 7.

Subclass 4 of the friction materials includes composite materials (CMs) with carbon matrix (carbon-to-carbon CMs – CCCMs) and ceramic matrix (ceramic CMs – CCMs) stiffened with carbon and other types of fibers. These composites relate to the latest-generation friction materials. Primary benefits of the braking systems based on CCCMs and CCMs are:

- relatively low density that allows a reduction in the weight of braking systems by 40 to 60%;
- high wear resistance in different atmospheric environment that does not essentially enhance the number of braking prior to repair;
- ability to absorb a great deal of kinetic energy during braking by converting it to heat energy;
- high resistance to thermal shock;
- high allowable operating temperatures (over 1000°C) [15].

The technological scheme of producing friction-intended items from fiber-reinforced composites with a carbon and ceramic matrix includes procedures for making fiber carcass (preform) with fibers positioned in a chaotic or oriented manner, saturating (packing) the fiber carcass with a matrix material and machining the blank so produced [15].

The second vital operation of the process – the packing of the carcass – is performed by using various solid-phase, liquid-phase and gas-phase methods and their combinations [15].

The solid-phase procedures are least spread and only used to produce ceramic composites. Generally, these are modifications of the powder method for producing technical ceramics. Powder of the matrix component is mixed with the reinforcing filler shaped as short fibers or whiskers, then a small quantity of polymer binder is added, and then the mixture produced is pressed and heat-treated. In the case of CCMs reinforced with carbon nanotubes, a method is used where the mixture of ceramic powder and carbon nanotubes is hot-pressed and sintered. In so doing, the mixture could be produced using both the dry technology and the solution technology (for better dispersion of carbon nanotubes) [15].

The gas-phase methods for producing CCCMs and CCMs are based on the packing of porous fiber carcasses as the gaseous chemical precursors are filtrated through them and disintegrated homogenously and heterogeneously while the matrix material is settled on the surface of heated reinforcing fibers (CVI Method – Chemical Vapor Infiltration). Gaseous hydrocarbons (methane, propane, ethylene, benzene, acetylene, etc.) are used as precursors to produce the carbon matrix. In CCMs production by CVI method, studies are also underway to utilize diverse ceramic materials as a matrix. CCMs with SiC matrix are currently pretty widely used for industrial applications [15].

Liquid-phase packing of the fiber carcass is made in two options. The first option is based on the high-temperature pyrolysis of precursors based on thermoplastic and thermoset polymers which the fiber carcass is permeated with. Thermoset phenol and furfuryl resins and pitches from coal tar or petroleum are used as initial material for producing the carbon matrix. SiC matrix is produced by using polycarbosilanes or alternative Si-containing polymers which are disintegrated during further heat treatment to release SiC-enriched fixed residue. The second option of the liquid-phase packing is used to produce CMs with SiC matrix by way of reactive sintering of the blank material as it is silicided (permeated with molten silicon) [15].

In order to improve operational properties of CCMs braking elements, gradient friction materials have been developed in which high wear resistance of surface layers is combined with high impact resilience of inner layers [15].

CCCMs are used for high-load friction units noted for large heat emission. CCCMs have a high friction coefficient, especially at elevated temperatures, and exhibit low sensibility to the specific contact pressure, speed and air moisture. It is typical for CCCMs to have no seizure of brake disks. In addition, these produce little noise in operation. CCCM's primary disadvantage is its low friction coefficient (f = 0.05...0.28) at negative or low temperatures (below 100°C) for which purpose either various stepwise braking schemes are used or the materials of braking units are heated after several pre-brakings. To increase the initial friction coefficient, abrasive powders (SiC, Al_2O_3, B_4C, etc.) are added to the polymer binder from which the carbon matrix is produced following pyrolysis, or the carbon fibers themselves are modified by applying ceramic coatings onto their surface. In this case the initial friction coefficient may be doubled, however, this brings about some reduction in maximum values of the friction coefficient. Another disadvantage of these materials is higher oxidation susceptibility of the fiber's and matrix' carbon starting from the temperatures of 400...600°C that results in faster degradation of the friction surface and lowered average wear resistance at different temperature and force conditions of the braking systems operation. Therefore, wear of brake disks and linings made from CCCMs is assessed, as a rule, by the weight loss or size per braking (1.5...3.0 μm for airplanes). In addition, for great stopping powers, these materials tend to raise vibration whilst related control makes the braking system design more complicated [15].

CCMs are used to improve the braking efficiency when the temperature on the friction pair surface can reach 1000...1200°C. The ceramic materials used for friction pairs are divided into those reinforced with a variety of fibers and whiskers and those not reinforced (hot-pressed, reactively sintered) [15].

Chief drawback of the ceramic-based materials is their low resistance to mechanical and heat shock loads that restrains the scope of application for the non-reinforced ceramics. Most widespread in the friction units are friction CCMs with carbon reinforcing filler (chopped fibers, tissues, bans, mats) SiC-based ceramic matrix which is produced using the method for impregnating a carbon-to-carbon blank with molten silicon. These friction materials have good tribotachnical characteristics: a high friction coefficient and its minor dependence upon the speed at the start of braking (reduction from the initial 0.6...0.7 to 0.45...0.55 at v =15 m/s), a lower temperature of the surface within the friction area (reduced by 5...15% at 500°C), a lower contact pressure (reduced by 10...20% as pressure goes up to до 4 MPa), and weather conditions. The materials with ceramic matrix wear to a lesser degree in operation as opposed to the materials considered [15].

Materials with carbon matrix are widely used for fabrication of braking devices for aircraft. Production of braking disk from CCCMs for airplanes is steadily growing with an annual average of 12%. Currently, the braking devices are fabricated with monodisks or section-type disks, the former being more preferred. The braking devices with CCCMs monodisks are used in Russian airplanes – IL-96T/M, TU-204, TU-214, TU-160; in US-made airplanes – B767, B777, F-15, F-16, F22, B-32; EU – A330/340 and others [15].

The CMs braking disks with ceramic matrix are not widely used in aircraft braking systems so far. Nonetheless, the world-largest firms are making efforts to create a commercial product shaped both as the friction material proper and aircraft brake disks based on the material [15].

An analysis of the sources of information [1–15], etc., allowed a synthesis of the block-diagram for forming major operational characteristics of the whole subclass of friction materials (Fig. 2). The block-diagram displays primary functional tribotechnical (frictional) properties making up three group characteristics and five additional functional properties that provide jointly the regulated modes of operation of friction pairs including sixteen comprehensive properties that define appropriate single and/or grouped properties of the friction pairs material.

As is evident from the block-diagram (Fig. 2), all the operational characteristics are interrelated either directly or indirectly through the group relationships. For example, the functional tribotechnical (frictional) properties are linked through the high friction coefficient, high wear resistance and no jamming and seizure between mating parts. It is to be noted that the results of numerous fundamental and applied studies on identification of such relationships both theoretically (analyticcally) and experimentally (or experimental-theoretically) have been integrated into the scientific fundamentals of triboengineering.

Thus, the tribotechnical materials of the frictional subclass of all the basic compositions shown in the classification scheme of Fig. 1 have been investigated in a rather in-depth manner in terms of formation of their basic characteristics systematized in the block-diagram of Fig. 2, and the studies are going on.

However, the problem of a system synthesis of criteria of friction materials replacement effectiveness has not yet actually been formulated. Therefore, basing on the above brief analysis of the status of formation of operational properties of basic types of related compositions (Fig. 1), it is thought useful to extend the conceptual approach described in the paper [1] to the assessment of efficiency of replacement of one or the other friction material. Like for antifriction materials [1], the tribotechnical properties of friction materials are largely interdependent and hinge upon the operating modes of friction pairs.

Following the conceptual approach to the criterial evaluation of effectiveness of rational replacement of

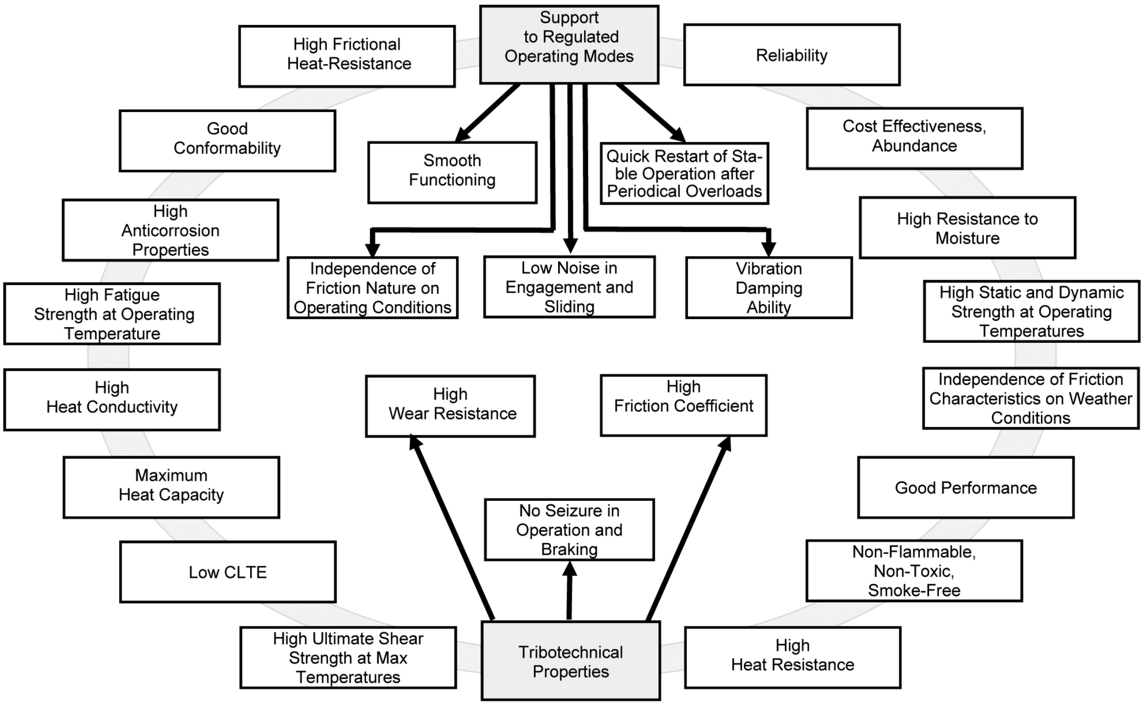

Fig. 2. Block-Diagram of Formation of Basic Operational Characteristics of Friction Materials

various compositions, as actualized in [1], with the criteria graded into single, grouped, complex and integral, these are converted to a relative dimensionless form by virtue of relevant numerical values of constituent properties of the basic material*.

As is the case with [1], the relative integral criterion of a replacing friction material $\overline{K}_{\text{int}}$ is found by the relationship

$$\overline{K}_{\text{int}} = \sum_{i=1}^{n} \alpha_i \overline{R}_{\text{compl}\,i}(\overline{K}_i) > 1, \qquad (1)$$

where $\overline{R}_{\text{compl}\,i}(\overline{K}_i)$ is the i-th complex criterion of the replacing friction material $R_{\text{fr}\,i}$ related to a similar criterion of the basic material $R_{\text{fr bas}\,i}$

$$\overline{R}_{\text{compl}\,i}(\overline{K}_i) = \frac{R_{\text{fr}\,i}}{R_{\text{fr bas}\,i}}, \qquad (2)$$

α_i is a rating factor of relevant complex criteria (Fig. 2) that is determined by a decision-maker's expertise [16–18].

The relative complex criteria $\overline{R}_{\text{compl}\,i}(\overline{K}_i)$ as part of (1) include relevant grouped criteria

$$\overline{K}_{\text{compl}\,i} = \sum_{i=1}^{m} \beta_i \overline{R}_{\text{gr}\,i}, \qquad (3)$$

$\sum_{i=1}^{m} \beta_i = 1$, β_i are the rating factors for relevant criteria $\overline{K}_{\text{gr}\,i}$ assigned by the decision-maker on the basis of the expertise assessments.

In turn, $\overline{K}_{\text{gr}\,i}$ includes single $\overline{K}_{\text{sin}\,i}$

$$\overline{K}_{\text{gr}\,i} = \sum_{i=1}^{r} \gamma_i \overline{R}_{\text{sin}\,i}, \qquad (4)$$

$\sum_{i=1}^{r} \gamma_i = 1$, γ_i are the rating factors for relevant criterion $\overline{K}_{\text{sin}\,i}$.

If, when lowered, the complex criterion constituents as part of the material to be replaced tend to enhance, by their nature, the efficiency (growth) of the complex criterion, the relative complex criterion of such a replacement should be reflected by inverse dependence in relation to (1).

For instance, the complex criterion of cost K_c predetermines the effectiveness of the basic material replacement by another one, if the sum of the basic material R_i group criteria making part of it is lower than its value of the material to be replaced, i.e. the inverse dependence is the case (1)

$$\overline{R}_i(K_c) = \frac{R_{\text{fr bas}\,i}}{R_{\text{fr}\,i}} \geq 1. \qquad (5)$$

* As stated in the paper [1], the choice of a basic material is not crucial, however, it is thought worthwhile to take friction cast iron as such a material.

It should be noted here that the current absence of a sufficient number of performance data both for the basic material and replacing friction material justifies the limited completeness of the properties available depending upon the replacement purpose [1, 19].

Conclusion

1. An analysis of general characteristics of tribotechnical materials representing the friction subclass has been carried out.

2. The classification scheme of main types of friction material compositions including asbestos-based materials, casting alloys, sintered materials and composites as well as the groups of these subclasses differing in performance values in given friction pairs operating conditions has been synthesized.

3. A block-diagram has been elaborated for establishing primary operational characteristics of friction materials including basic and additional functional properties which ensure regulated working modes for appropriate friction pairs as well as 16 interrelated complex properties which make up any particular group and single characteristics.

4. Relevant classification components of the operational characteristics are consistent with relative criteria of effectiveness of friction material replacement that have been defined numerically within the proposed conceptual approach to the criterial evaluation of a possible increase in performance of aircraft parts and of a method for gradual expansion of their range predefined by the objectives couched for replacement of basic friction materials.

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УДК 629.715.33/617.62

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КРИТЕРИИ ЭФФЕКТИВНОСТИ ЗАМЕНЫ МАТЕРИАЛОВ ТРИБОТЕХНИЧЕСКОГО НАЗНАЧЕНИЯ ДЛЯ УЗЛОВ ТРЕНИЯ САМОЛЕТОВ
Сообщение 2. ФРИКЦИОННЫЕ МАТЕРИАЛЫ

Проведен анализ общих характеристик материалов триботехничского назначения, составляющих фрикционный подкласс. Синтезирована классификационная схема основных видов составов фрикционных материалов, включающая материалы на основе асбеста, литейные сплавы, спеченные материалы и композиты с углеродной и керамической матрицей. Разработана блок-схема формирования основных эксплуатационных характеристик фрикционных материалов, включающая основные и дополнительные функциональные фрикционные свойства.

Классификационные составляющие эксплуатационных характеристик согласованы с относительными критериями эффективности фрикционных материалов, численное определение которых реализовано в рамках предложенного концептуального подхода к критериальной оценке возможностей повышения эксплуатационных характеристик деталей авиаконструкций и метода последовательного расширения их полноты. [dx.doi.org/10.29010/083.3]

Ключевые слова: фрикционные материалы; классификация основных эксплуатационных характеристик; блок-схема формирования свойств; критерии эффективности замены материалов пар трения.

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