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Material Analysis of Selected Parts of the MPM-20 Jet Engine

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Abstract:

The article deals with the issue of the material analyses performed on the selected parts of the MPM-20 jet engine, made within the framework of reverse engineering. The analyses were necessitated due to the absence of appropriate technical documentation to the engine. The engine is a result of conversion made on the original TS–20B/21 turbo starter. This device was formerly used for starting up of more powerful military jet engines. The material analyses were focused on the most thermally stressed parts of the engine – combustion chamber consisting of a flame tube and a combustion chamber casing, turbine blades and a turbine outer ring. The findings are expected to be applicable for further technological modifications of the engine assumed to extend its operational time and total engine efficiency.

Keywords:

Small jet engine, combustion chamber, turbine blade, material engineering

1. Introduction

Reverse engineering is a process of learning and duplicating of already existing component, assembly, or product in operation. It can be used to reveal the original process of design, or as a starting point for the re-design process. It is justified to start with reverse engineering if the need for spare parts arises, whilst the relevant technical documentation is lost, damaged, and/ or incomplete, owned by another entity, or has never been developed [1].

Our effort is to reuse some still functional parts, which are no longer suitable for the utilization in the air transport, for other purpose. It is also the case of the TS-20B/21 turbo starter. This small engine can be converted into an energy-producing

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device or used as an experimental laboratory jet engine [2]. However, the TS-20/21 has not been designed for the long-term operation (only for a short time needed to start-up an engine). The long-term operation of the MPM-20 small turbojet engine increases thermal stresses of the hot engine parts – mainly of the flame tube, turbine stator vanes, rotor blades and turbine rotor disc. In order to increase its operation time, durability and also performance, it is necessary to make certain structural modifications. That is the reason why reverse engineering has been applied [3].

2. MPM-20 engine

The small MPM-20 jet engine (MPM = Slovak abbrev. for small jet engine) was created by modifying the design of the TS-20B/21 turbo starter, shown in Fig. 1, for the needs of experimental measurements in the Laboratory of Intelligent Control Systems of Jet Engines at the Faculty of Aeronautics at the Technical University of Košice [3].

Fig. 1 TS-20B/21 turbo starter

Due to the fact that the product comes from the former Soviet Union and has been used in military aircrafts, there was no available information about the used materials. Their analysis will essentially serve to obtain qualified knowledge about this type of the product, and will serve as the basis for adequate decisions during the repair, reconstruction and modification for conditions in which the device is assumed to operate.

The study was focused on the following parts: combustion chamber casing, flame tube, turbine rotor blades and turbine outer ring, shown in Fig 2.

a) b) c) d)

Fig. 2 Analysed parts: a) combustion chamber casing, b) flame tube c) turbine blade d) turbine outer ring

3. Experimental methods

Following methods for material analysis were applied:

In the first place, all of the four parts were subjected to the EDX analysis of the basic chemical elements using a scanning electron microscope. The analyses were extended to a number of areas on the surface with the consistently recorded results. In some cases, for the verification of the results, AES (Atomic Emission Spectroscopy) chemical analyses were carried out at a certified laboratory in the U. S. Steel Košice – Labortest, Ltd. Also the metallographic – microscopy analysis of the structure by the light microscope / SEM microscope was performed to confirm the chemical analysis, and to assess any structural abnormality.

If it was possible due to the size and shape of the examined component, mechanical properties on the basis of the static tensile strength tests were evaluated. If it was impossible, the test of hardness and the relevant conversion tables were used [4]. In all of four cases, we tried to find a match with materials either based on the Russian standards (GOST) or with the available Slovak technical standards (STN). Some results have been already published by authors in [2].

3.1. Combustion chamber casing

Chemical analysis was performed in three places of the outer surface of the plate after the removal of the brown coloration. The inner side of the plate differs in grey colour, therefore a part of the coloration was left on the surface and the analysis was performed also on the area where the coloration has not been removed, see Fig. 3. The analysis in the point of the coloration (spectrum 7, see Fig. 4) has shown that aluminium and zinc were present, probably in the actual coloration. It was possible to remove the coloration by an acetone diluent. Although the origin of the coloration or its purpose is not known precisely, in our first approximation it is considered to be a paint applied for corrosion protection, for both electrochemical and chemical ones (in the former USSR "alitation" was frequently applied to aviation equipment).

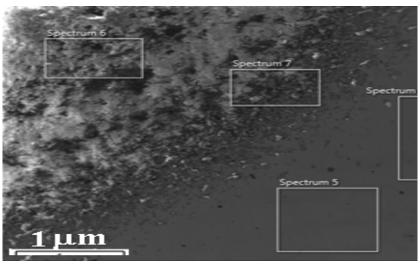

Fig. 3 Coloration appearance

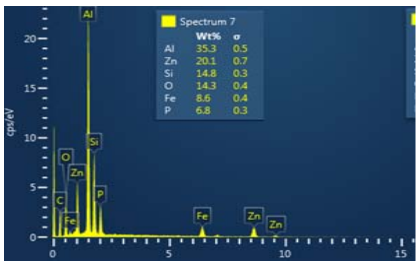

Fig. 4 Analysis of coloration – spectrum 7

The quantitative analysis performed in accordance with the ASTM E 415-08 standard by the atomic emission spectrometry (AES – at the certified laboratory in the U.S. Steel Košice – Labortest, Ltd.) reveals chemical composition summarized in Tab. 1.

As it is a product made in the former Soviet Union, the possibility of the confrontation with the GOST standard is available. This type of the steel is designated as "chromansil" and corresponds to the 25CrMnSiA (25KhGSA) GOST steel [5]. Also the STN standards cover the group of the structural manganese-silicon-chromium steels. The best match with the STN 41 4331 standard steel was observed. The chemical composition as prescribed by this standard is also overviewed in Tab. 1.

Tab.1 Chemical analysis comparison of casing material and standard steel

	C [wt. %]	Si [wt. %]	Mn [wt. %]	Cr [wt. %]	S [wt. %]	P [wt. %]
AES	0.26	1.09	0.96	0.99	0.004	0.017
STN	0.28÷0.35	0.80÷1.10	0.90÷1.20	0.80÷1.10	0.004	0.017

The metallographic analysis of the casing material has shown that the structure is consistent with the chemical composition. It may be said that it is a ferritic-pearlitic structure with globular pearlite and well spheroidized carbides, see Fig. 5. It is apparent that the material was isothermally annealed, due to the fact that this product is operating mostly at slightly higher temperatures. Isothermal annealing was performed at temperatures in such a way that the subsequent long-term affecting the environment at adequate temperatures does not cause structural changes in the material, which would decrease its mechanical properties. In other words, annealing took place at higher temperatures than is the operating temperature of the combustion chamber casing.

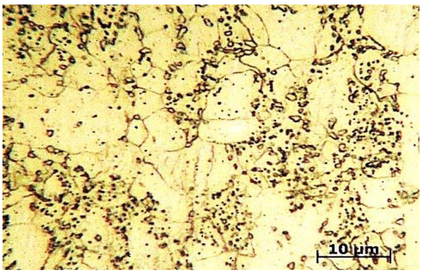

Fig. 5 Feritic-pearlitic structure with globular pearlite

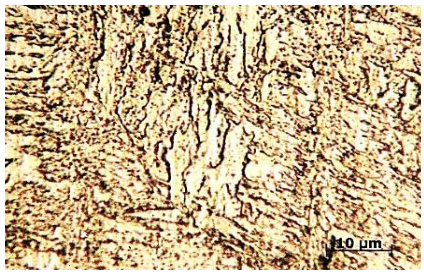

Fig. 6 Widmansttäten-type structure inside weld

The combustion chamber casing contains also well-made welds, with no visible defects. The structure inside of the weld is essentially given by the way of the casing production. Welding is followed by a rapid cooling, which, according to the low carbon content in the matrix, causes the typical acicular Widmansttäten-type structure, without a clear incidence of carbides, see Fig. 6. The micro-hardness measurements have shown that the hardness HVm 0.05 in the weld was about 300 units versus 240 at the outside positions. This type of the structure is visible even after several years of the thermal exploitation. That is a proof that the material operates at temperatures lower than the tempering temperature of the steel.

Measurement of the mechanical properties of the casing material was performed by the conventional static tensile test. The test results obtained together with the values prescribed by the STN standard are given in Tab. 2.

Tab. 2 shows that the measured values are consistent with the prescribed values of the standard steel STN 41 4331.

Tab. 2 Mechanical properties of casing material and standard steel

	$R_{p0.2}$ [MPa]	R_m [MPa]	A_{10} [%]	Hardness HV 10
casing material	460	587	15.8	253
STN 41 4331	min. 345	490÷780	15	*

*STN Standards do not prescribe hardness after annealing

3.2. Flame tube

The materials used in the production of a flame tube are usually the nature of nickel alloy of the Nichrome type which belongs to the non-treatable alloys. They can be characterized as heat-resistant (temperatures up to about 1 200 °C). The qualitative analysis by the EDX was carried out in two steps. The first step involved mainly the surface analysis. The result of this analysis in comparison to the GOST standard material EI 435 is given in Tab. 3. The second step involved the inclusion or precipitate sites, respectively.

Tab. 3 Chemical composition of flame tube material and nickel alloy EI435

Material	Ni wt.%	Cr wt.%	Si wt.%	Mn wt.%	Ti wt.%	Fe wt.%	C wt.%
Flame tube material	75-77	22	1	0.5	0.5	0.9	0.1
EI 435	70-77	22	<0.8	<0.7	0.35	<6	<0.12

The chemical analyses of the chosen precipitates are given in Table 4. As it is clear from the results, there is a small difference between the precipitate composition and the average surface analysis. The difference is in the increased content of the Ti particles. Presumably, they are the TiC-based ones.

Tab. 4 Average chemical composition of precipitates

	Ni wt.%	Cr wt.%	Si wt.%	Ti wt.%	N wt.%	Al wt.%	Ta wt.%
Precipitates	65.3	19.4	0.5	12.6	9.8	0.3	1.4

The metallographic-microscopic analysis revealed that the examined Ni-Cr heat resistant alloy shows a structure shown in Fig. 7 and Fig. 8.

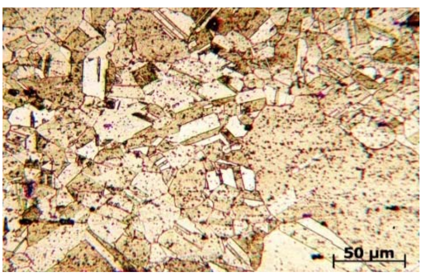

Fig. 7 Microstructure of flame tube

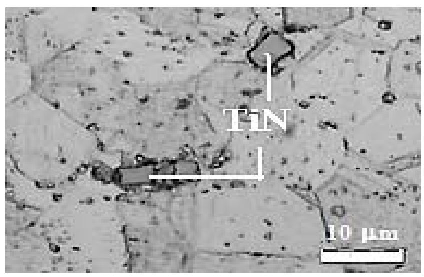

Fig 8 Precipitates – carbides and TiN

The structure is quite irregular. In the outer boundary, the layer has a typical austenitic character and on the other side it is a fine-grained polyhedral [6]. These two forms also differ in hardness. The micro-hardness of the coarse-grained part was 218 HV_{m} 0.05 and of the fine-grained part it was 242 HV_{m} 0.05. However, it should be noted that the flame tube is made of the sheet metal with a thickness of about 1 mm. The temperature inside the flame tube may achieve even 1 000 °C, while the outside is being cooled down with a relatively cold air from the compressor. In a base matrix structure, fine precipitates were formed. According to the chemical composition, these precipitates may be carbides (tiny particles) and nitrides (rectangular formations), see Fig. 8. In addition, a substantial part of the hardening precipitates is formed in the γ' phase – Ni_3 (Al, Ti). Its appearance will be similar to the one presented in turbine blade section.

It is possible that this alloy belongs to the group where disperse strengthening is achieved by the treatment of the material during the operation. This is evidenced by the value of ductility, which will decrease from 40 % just after manufacturing to 16 % after the exploitation causing disperse strengthening. The mechanical properties of the flame tube material were determined on the basis of static tensile tests as well as hardness tests. The test results are shown in Tab. 5. From materials within the GOST standards, the alloy designated as EI 435 is closest to the investigated alloy.

Tab. 5 Mechanical properties of the flame tube material

	$R_p\,0.2$ [MPa]	R_m [MPa]	A_{10} [%]	HV/HV_{m}	HB
Flame tube	394	630	16	216 /242	205
EI 435	170-270	610-780	38	-	-

3.3. Turbine blade

The microscopic analysis of the blade material microstructure type has been realised for the purpose of material identification. According to the first assumption, the blade was manufactured by casting [7]. This assumption appears to be right, as the microstructure shows a high level of dendriticity, see Fig. 9.

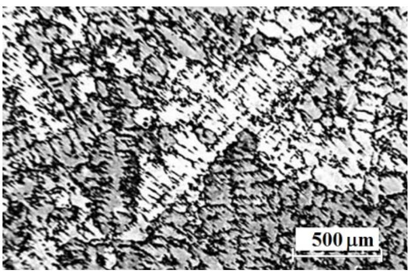

Fig. 9 Dendritic structure of blade

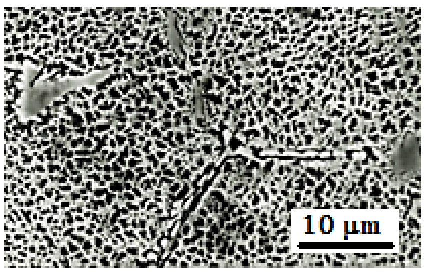

Fig. 10 γ' phase

Final properties of this cast material are reached by aging under specific conditions. This is evidenced by the (remained) dendritic structure and its high tensile strength induced by aging described later. In most cases these types of the nickel-based superalloys consist of the following main phases: γ phase, γ' phase, see Fig. 10, carbides (MC, $M_{23}C_6$ and M_6C) and adverse phases (σ, μ, G – phases, Laves phases and ε – phases) that was already described in detail in [8, 9].

The EDX qualitative chemical analysis of the material has been made in a cut plane rectangular to the blade axis in the blade root nearby its tree-type connection, see Fig. 11, and reveals the result stated in Tab. 6 in comparison to the standard Ni-Co superalloy. After the material analysis in the blade, basic elements as Ni, Cr, Co, Mo, W, Al, Ti and C as well were detected.

Tab. 6 Comparison of chemical content of investigated material and standard ZhS-6K

Material	Ni [wt. %]	Cr [wt. %]	Co [wt. %]	Mo [wt. %]	Al [wt. %]	Ti [wt. %]	W [wt. %]	C [wt. %]
turbine blade	~64	~12	~11.3	3.4	3.6	2.5	3.2	~0.1
ZhS-6K	~67	11.5	4.5	4	5.5	2.8	5	0.16

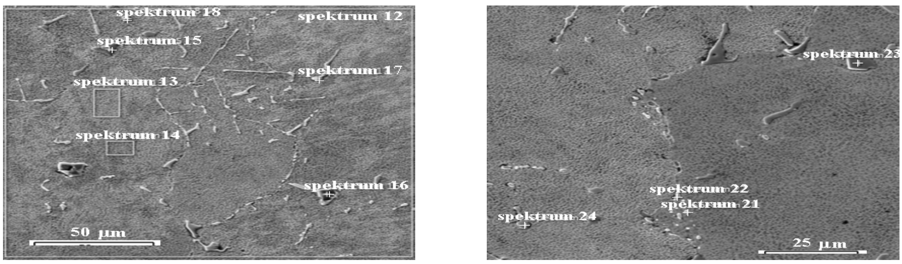

Fig. 11 EDX analysis areas

Based on the analysis we can say that the turbine blade material is a Ni-Co-Cr superalloy, which belongs to hardenable heat resistant superalloys. On the basis of the aforementioned facts and taking into account the chemical composition, it can be stated that Gamma phase – γ forms the matrix, in this case it is a solid Ni-Cr solution, where a part of the Ni is replaced by the elements such as Al, Co, W, Mo. Phase gamma prime – γ' causing precipitation strengthening can be identified by a transmission electron microscopy. The character of the carbide phase can be inferred also by the EDX analysis. This was performed on randomly selected precipitates, see Fig. 11, spectra identified as 15, 17, and 18 and spectra 21, 22, 23 and 24. The analyses of precipitates are shown in Tab. 7. The precipitate from the spectrum of 15 has been compared with the composition of the matrix, and it has been found out that the content of Ti, Mo, W was several times higher, which raised the presumption that the precipitate is of nitridic nature. The same presumption was applied to the spectrum of the precipitate 16 having the same shape and the size. According to [9, 10] in the Ni alloys composition the carbonitrides of M(C,N), Ti (C,N) or $M_{23}(C,N)_6$ type were found. Precipitates from the spectrum 17 and 18 differ in shape and size, compared to the previous precipitates, and they vary the composition. These precipitates are difficult to identify accurately without a precise analysis by transmission electron microscopy. In the first approximation with respect to the Cr content, it could be MC carbide (Ti, Mo, W) or $M_{23}C_6$ carbide (Cr, Mo, W, Ti) [10].

As the results for the precipitates 21-24 show, there are differences in the chemical composition again. The precipitates 21 and 22 have the supporting element of Mo, while in precipitates 23 and 24 it is Ti element. Therefore there is a great probability that they are carbides with the high levels of Cr and W.

Tab. 7 Chemical content of the chosen precipitates

Element	Ti [wt. %]	Mo [wt. %]	W [wt. %]	Ni [wt. %]	Cr [wt. %]	Co [wt. %]	Al [wt. %]	Sr [wt. %]
Spectrum 15	53.5	28.0	16.6	1.9	–	–	–	–
Spectrum 17	37.7	22.6	32.5	3.7	3.5	–	–	–
Spectrum 18	46.3	25.2	23.2	2.8	2.5	–	–	–
Spectrum 21	1.7	54.0	13.4	6.5	21.8	2.6	–	–
Spectrum 22	1.9	47.4	14.3	12.1	20.2	3.4	0.7	–
Spectrum 23	47.7	25.9	20.4	2.3	2.2	–	–	1.5
Spectrum 24	39.4	22.7	31.0	3.3	3.5	–	–	–

Metallographic analysis that preceded the chemical identification of individual structural components pointed to the following facts. As it is apparent also from Fig. 12, the material shows a clearly dendritic structure. Fig. 13 shows the basic grains referred to the solid solution – γ phase (Ni-Cr), which contains precipitates of intermetallic phases. The carbide phase is seen in Fig. 13. Carbides precipitated as the grain boundary network, mostly as $M_{23}C_6$ carbides. Carbides within the grains may be of MC nature with dissolved elements as Mo, V, Zr or of the carbonitride TiC(N) type.

Fig. 12 Microstructure of the blade

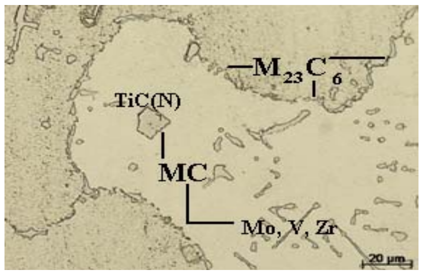

Fig. 13 Carbides distribution

Due to the small size of the turbine blade, it was not possible to make a relevant sample for the static tensile test. So only the hardness tests were performed to approximate the determination of the material strength, according to the EN ISO 18265 standard, using conversion tables [4]. The measured hardness values were HV 10 = 380 and HV_{m} 50 = 513 → HB = 360 → R_m = 1220 MPa. As shown in the results, the material exhibits high strength, which corresponds to the Ni-superalloy. After comparing this material with other known Ni - alloys from castings made in the former USSR as structural materials for the aircraft turbines, it can be assigned to a standard type of alloy – the ZHS-6K [11].

3.4. Turbine outer ring

The turbine outer ring is a part of the engine design, attached to the combustion chamber casing. Its task is to define the clearance between the casing and the tip of the blade. It is not mechanically stressed but subjected to elevated temperatures in the range from 600 to 700 °C. The qualitative chemical analysis was performed using the EDX analysis and by AES – results are in Tab. 11. Fig. 15 shows the areas where the analyses were performed.

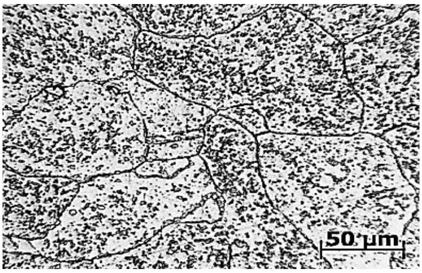

Fig.14 Outer ring material microstructure

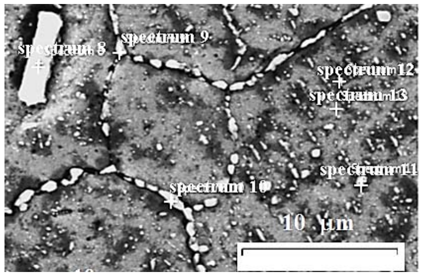

Fig.15 Areas of EDX analysis

Different spectra were used to identify the precipitates considering the secondary particle as indicated in Fig. 15 – spectra 8. The analysis revealed that the majority element in this type of particle is Nb, together with other elements such as V, Cr, Ti and B. It is assumed to be MC carbide with Nb as the major component, see Tab. 8.

Tab.8 Quantitative analysis of particles

Element	Nb [wt. %]	V [wt. %]	B [wt. %]	Fe [wt. %]	Cr [wt. %]	Mn [wt. %]	Ni [wt. %]	Ti [wt. %]
Spectrum 8	76.1	4.9	15.9	2.6	1.4	0.5	0.4	0.4

Another group of carbides consists of particles present on the grain boundaries – e.g. spectra 9, 10. Their chemical composition is shown in Tab. 9. The priority element of these particles is pure iron. They are assumed to be a complex-type of carbides $(Fe,Cr,V,Mo)_xC_y$ [12]. A similar character has been shown by particles identified on spectra 11 and 12.

Tab.9 Chemical content of particles on grain boundaries

Element	Fe [wt. %]	Cr [wt. %]	Mn [wt. %]	Mo [wt. %]	Ni [wt. %]	V [wt. %]	Si [wt. %]
Spectrum 9	45.9	32.9	7.8	4.6	4.5	4.0	0.4
Spectrum 10	49.1	28.8	7.7	4.0	5.5	4.5	0.4

Tab.10 Chemical content of particles inside grains

Element	Fe [wt. %]	Nb [wt. %]	Cr [wt. %]	Mn [wt. %]	Ni [wt. %]	V [wt. %]	Si [wt. %]	Ca [wt. %]	Mo [wt. %]
Spectrum 11	40.7	29.8	14	5.9	4.2	5.1	0.3	–	–
Spectrum 12	62.6	–	15.9	8.4	7.2	1.7	0.5	0.2	2.1

As it is clear from the analysis, the material of this component is the classic Cr-Ni alloyed austenitic steel, the one of the so-called “cost-effective type”. The development of these steels was caused by the lack of nickel in some period of time. That was the reason why nickel was replaced by manganese. However, they are technologically more difficult to produce. Currently they are replaced by conventional Cr-Ni steels [13]. The microstructure of these steels appears to be simple, see Fig. 14. The matrix is made up of a solid solution with segregated intermetallic and carbidic phases.

Analysis of the mechanical properties was performed only by measuring the hardness. Hardness by *HV* 10 has shown the value of 230 and by *HRB* method a value of 97.5. These values correspond, according to the EN ISO 18265 standard, to the conversion between hardness and strength to the tensile strength of about 760 MPa.

It can be concluded that the studied turbine outer ring material is the chrome-nickel-manganese steel, which can be identified according to the GOST standards as a material designated as EI 481 (4Kh12N8G8MFB) [5]. The composition, as well as the comparison of its mechanical properties is given in Tab. 11 and 12.

Tab. 11 Chemical content comparison of investigated material and standard steel

Element	Fe wt.%	Cr wt.%	Mn wt.%	Ni wt.%	Mo wt.%	Nb wt.%	V wt.%	Si wt.%	C wt.%
EDX	67.2	13	8.3	7.5	1.25	0.6	1.6	0.55	–
Labortest	rest	12.6	8.45	8.4	1.07	0.32	1.45	0.52	0.43
EI 481	67	12.5	8.5	8.0	1.25	0.35	1.4	0.55	0.42

Tab. 12 Mechanical properties of ring material and EI 481 (4Kh12N8G8MFB)

	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]	*HV*10	*HRB*
Turbine ring	–	740	–	230	97.5
EI 481	700	1000	20	–	–

4. Conclusions

On the basis of the performed analyses of the selected MPM-20 engine parts combustion chamber casing, flame tube, turbine blade and turbine outer ring, the following conclusions can be drawn:

- Analysis of the elements contained in the combustion chamber casing material and its microscopic analysis have shown that it is made from the low carbon alloyed steel with a lower content of alloying elements. On the basis of the chemical composition, mechanical properties obtained by testing of the tensile strength and hardness measurement, it was possible to assign this combustion casing material to the standard steel STN 41 4331, respectively the Russian equivalent – "Chromansil" steel according to the GOST: 25CrMnSiA (25KhGSA).
- The flame tube material stressed by high temperatures in the process of the fuel combustion, according to the results of the basic element content analysis, can be assigned to the heat-resistant nickel superalloys with high chromium content. Based on the chemical composition, mechanical properties and hardness of the material, this material can be most likely assigned to the standard Russian nickel-based superalloy EI 435 intended for forming and reliably operating at temperatures up to 1 200 °C.
- Based on the analysis results, the turbine blade material is Ni-Cr alloy belonging to hardenable refractory superalloys. The fact is evidenced by the remained dendritic structure of this cast material and its high strength induced by aging. By comparing this material with the known Ni – alloys used for castings from Russia and found as structural materials in aircraft turbine engines blades, it is possible to associate it, with a high probability, to a standard alloy of the type ZhS-6K.

- As the turbine outer ring is also exposed to increased temperatures, it is clear from the analyses that the material used to produce this component is a classic Cr-Ni alloyed austenitic steel, so-called “cost-effective type”. This material can be identified in first approximation according to the GOST standards EI 481 (4Kh12N8G8MFB).

The acquired results are beneficial and form the basis for further structural modifications of the engine in the process of improvement of its operational capabilities.

Acknowledgement

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