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MATERIAL VS STRUCTURE OF AIR CRAFT TURBINE ENGINES

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Abstract

The paper concerns the problems connected with the choice and application of materials in construction. Special attention was focused on the dependence of structure service cyclic life on material and technological properties as well as on material and product quality, which requires special focus to quality. The problem was presented with of the K-15 aircraft jet engine as example constructed at the Institute of Aviation and manufactured by PZL-Rzeszów. Basic parameters of materials applied in construction of aircraft turbines are: elasticity modulus, tension strength, mass density, elongation, reduction in area, corrosion resistance, fracture toughness - as functions of temperature. Technological parameters, on the other hand, include plasticity, machining and heat treatment, weldability, susceptibility to hardening, etc.

Introduction

Construction, technological and operational requirements for an aircraft turbine engine

Aircraft jet engines belong to the most sophisticated engineering structures. It is due to the fact that such engines must meet very high standards related to structure, technology and operational parameters. The said requirements can be divided into a number of basic elements, namely:

1. Achievement of the pre-set engine thrust,
2. Low mass per thrust unit ratio,
3. High degree of operational safety and reliability,
4. Relatively long service cyclic life,
5. Low fuel consumption,
6. Possibly small transversional dimensions, (slim line),
7. Relatively low cost of manufacture and operation.

Additionally, every type of turbine engine manufactured in Poland has to comply with Joint European Aviation Regulations JAR-E [1]. It obligatory implies observation of the requirements and the procedures concerning designing, testing and concluding set out in the said regulations.

Achievement of the pre-set thrust is a basic design requirement since it is the thrust which determines the flight parameters of an aircraft to which the engine will be build up. Moreover, the engine should have an appropriate acceleration and control dynamics.

Low mass per thrust unit ratio is obtained by proper selection of gas dynamic parameters and general configuration of the engine structural. Procedures leading to the mass reduction are, among others optimum forming of discs, shafts and other rotor elements. They also involve application of such technological and structural solutions, which do not require a big number of joining elements (e.g. flanges, bolts, washers, etc.). Welding of rotors is one example of the above mentioned solutions. Optimum forming of units and elements of an engine, especially a rotor, can be attained with the help of advanced methods of strength analysis, such as finite element method. Selection of suitable materials has also an essential influence on engine mass.

Safety is one of the crucial requirements for aircraft turbine engines. It can be seen especially in securing of quasistatic safety factors, resistance to emergency loading foreseen in JAR-E instructions for construction and considerable lowering of dynamic stress in these structure elements, which bear the biggest loading.

Ensuring adequate service cyclic life is closely connected with safety of the structure through appropriate safety factors of fatigue damage. Methods of determination of service cyclic life, safety factors, methods of concluding and scope of tests included in A JAR-E Supplement [1] determine proof procedures. Fatigue properties, closely connected to the technological process, play a main role in this case.

The rotor of engine, designed according to the requirements presented is mainly subjected to a low cycle fatigue originated from mass loading, which, in turn, result from maximum-to-zero rotation (max. number of r.p.m.) and from changes in temperature. Full loads, resulting from mass forces and heat as a full cycle as well as intermediate cycles, are counted by means of a rain flow method. Fatigue analyses leading to estimation of predicted cyclic life and service cyclic life, according to JAR-E, ought to be proved by stand testing or/and engine exploitation according to a determined procedure. Tests are performed on specimens, fragments of structure and whole engines (so called experimental engines in the test bed) and during flight test.

Costs of manufacture are related to design, manufacture technology and applied materials.

Requirements for the materials applied in rotor construction can be divided into:

structural requirements	- connected with safety and resistance to emergency loading as well as cyclic life,
technological requirements	- resulting by a possible technology of manufacture application,
operational requirements	- related to engine service conditions

Design features of materials used in aircraft turbine rotors one can enumerate first of all: elasticity modulus - $E(T)$, ultimate tensile stress - $R_m(T)$, yield stress - $[R_e, R_{0,2} = f(T)]$, mass density - $\rho\,(T)$, density to tensile strength ratio - ρ/R_m and density to yield strength ratio - ρ/R_e ratio, elongation - A, reduction in area - Z, fracture toughness - K_{IC}, impact toughness - U, as well as hardness - HB, HRC, HV and, coefficient of thermal expansion - $\alpha\ (T)$; as T temperature functions.

Testing of the above features should be possibly carried out with specimens cutted from parts or semi-finished products, thermally treated together with the element from which they have been taken. Special attention should be paid to the place from which the specimen is taken out. It should be selected according to stress in finished product and anisotropy resulting from production technology. Such conditions sometimes cannot be met in production line because of technological limitations and cost of manufacture. The problem, however, should be analysed in detail at the stage of designing of a new structure, and also at every modification related to the design, technology or material change.

The above properties of material make it possible to evaluate the safety in pseudo-static states and a strength in failure case. In Fig. 1, a diagram of specimen tension is shown. The specimen is made of N18K9M5TPr alloy. The diagram created on the base of results of the axial compressor rotor of K-15 engine has been applied to an elasto-plastic displacement and stress analyses.

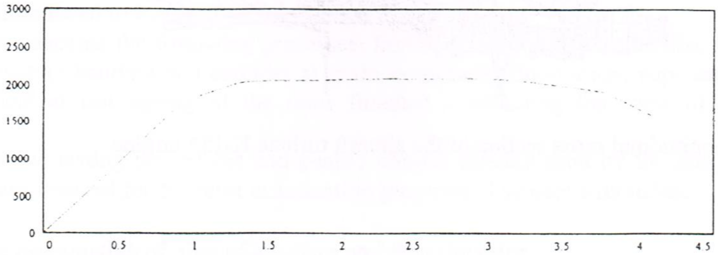

Fig. 1 Result of a static tension test performed on N18K9M5TPr alloy specimen, T=20°C (*too small elongation has to be noticed*).

The above properties are not sufficient full evaluation of usefulness of the material. Also a high long-term strength of material at elevated temperature ranges, fatigue limit, and first of all behaviour of the material at low cyclic fatigue range. Fatigue low cycle properties of material are determined during the low cycle fatigue tests, or on the base of the formulae proposed by *Manson* [2]. Those take into account the values obtained during a static tension test. Low cycle tests make it possible to determine the curve of cyclic strain at ε = *constant* or/and at σ = *constant* including an influence of asymmetric loading, overloading cycles, frequency of loading, etc. The tests, similarly as in static conditions case, should include an influence of individual technological processes - mainly anisotropy of properties and residual stresses.

Technological properties include several features of material, such as the possibility to obtain a uniform and repetitive structure, plastic and machining workability, surface treatment and good weldability. In rotors of aircraft turbine the applied materials ought to reveal a low heat expansion factor, high resistance to temperature (thermal shocks) and materials with low residual stress (initial stress), being either a natural property or during the thermal treatment process obtained.

Service properties of material including its resistance to an environmental impact, i.e. fuel and products of its burning, all kinds of corrosion, fretting at joints, wear, etc.

So it can be concluded that a modern designing of aircraft turbine engines results from technologies of manufacture of individual engine units, and its rotor in particular. The latter is closely connected with the accessibility to materials of suitable properties. Hence, not only structural and material solutions but also technological and material innovations are the most safeguarded secrets of every engine manufacturer.

The examples of problems connected with introducing of a new material to the rotor of K-15 engine[1] compressor (Fig. 2) are presented below.

[1] The designer of the engine Mr Julian Falecki, M.Sc., Eng. is now at Institute of Aviation.

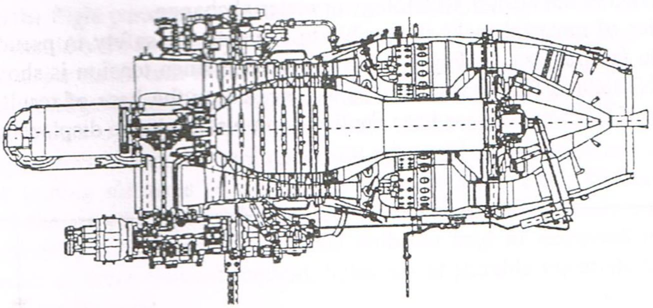

Fig. 2 Longitudinal cross section of the aircraft turbine K-15* engine

Selection of new material

Justification of the material choice

There are numerous highly resistant materials, which comply with the constructor's requirements accordingly to the strength level. However, owing to technological properties, the choice is actually restricted to two material groups, i.e. titanium alloys and age hardened, martensitic steel, commonly known as „managing These materials have a specific property, namely a possibility to creating structures welded with „ready-made" elements (assembles need no mechanical treatment).

Since Polish titanium alloys are not available, N18K9M5TPr steel was chosen. Domestic managing steel production was initiated at the end of 1970's as the result of the aviation industry requirements. It should be noted that it is one of a few examples of a totally new material being introduced in construction.

Steel N18N9K5TPr is high strength hardened martensitic steel of resistance Rm. ~ 2000 MPa. At the above strength level the steel has also satisfactory ductility: elongation A ~ 8 ÷ 10%, reduction i area Z ~ 50% and fracture toughness $K_{IC} \sim 60 \div 70$ MPa m $^{1/2}$. However, the biggest advantage of this material are its unique technological properties: perfect weldability (welded joint strength equals to the strength of welded material) and practically unlimited hardening capacity. Negligible changes in dimensions and shape occurring during the final heat treatment - ageing allow for mechanical treatments of parts at superquenched (softened) state and, afterwards the hardening heat treatment of a finished part. The resistance to corrosion of the material one can to compare to 1H13 grade stainless steel.

Technology ·f ·otor manufacture

Specificity of technological process concerns:

- manufacture of rotor discs,
- welding of rotor,
- the of hardening heat treatment procedure,
- application of particularly strict procedure of material and rotor quality control examination in the production process course.

Technology of forging of billets[1] from which the discs are forging was developed so as to reduce up to the minimum a mechanical anisotropy. As the result of optimum properties in the direction of maximum working stress in the rotor were obtained. The previous original smith forging being one of the sources of large discrepancies in properties of a individual forgings was rejected and the die forging process has been applied instead[2].

Electron welded structure of the rotor required to develop an electron beam welding technology, which had not been used in Poland before. It was developed at the Institute of Aviation and introduced to PZL-Rzeszów Aviation Plant.
Heat treatment concerns the following processes: homogenising treatment of disc forging – removal of structure banding and carbides at grain boundaries dissolution; supersaturation - austenitizing and at last ageing of the rotor finished - obtaining the rotor of the final properties.

Non-destructive testing procedures and quality control already used by the manufacturer were preliminary selected for the rotor examination purposes. The above includes:

- magnetic examination of, first of all, discs and then the rotor,
- X-ray examination of the rotor welded joints,
- penetrating examination of whole rotor,
- electromagnetic examination of the rotor joints.

The analyses and tests performed have shown that the critical from exploitension point of view areas of the rotor are the sockets the blade locks and the welded joints.

Prototype testing; structure and technology adjustments

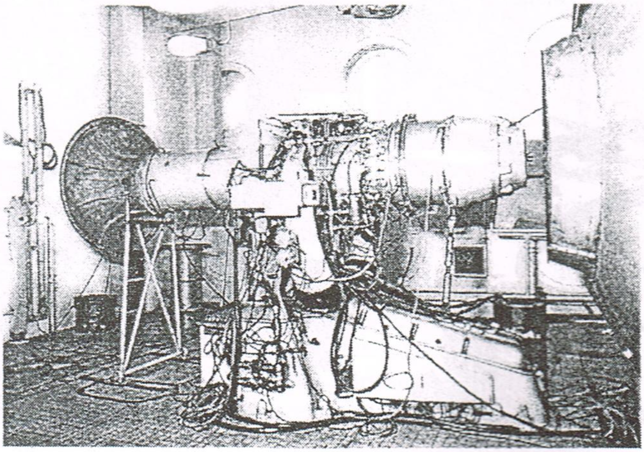

Fig.3. K-15 engine at the engine test bed.

[1] Technology was developed by Mikrohuta - Strzemieszyce Steel Works and the Institute of Aviation.
[2] Jawor Forging Plant, Stalowa Wola Steel Works and the Institute of Aviation developed technology.

A series of prototype rotors was manufactured and, they were underwent strength and durability testing, which made it possible to verify the design, the material and, technology (e.g. Fig. 3 and Fig. 4). As the result of the tests, structural and technological modifications were introduced. The most important are as follows:

- redesigning of the locks of the compressor first-stage,
- redesigning of the welded joints,
- change of the blade material,
- change of quality examination methods and verification of the technical requirements.

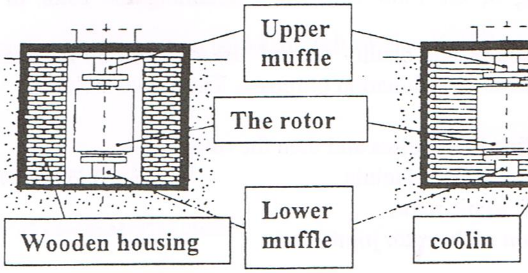

Fig. 4 Test stand for rotor low cycle fatigue testing under low pressure.

The fir-tree root locks in the first-stage of the compressor were replaced with dove tile_root locks in order to increase service cyclic life. The design change was also due to structural, technological and mass reasons (fatigue cracking of lock foot of a blade resulting from a structural notch, difficulties with adequate surfaces smoothness - class and also high loading with a mass force of the blade).

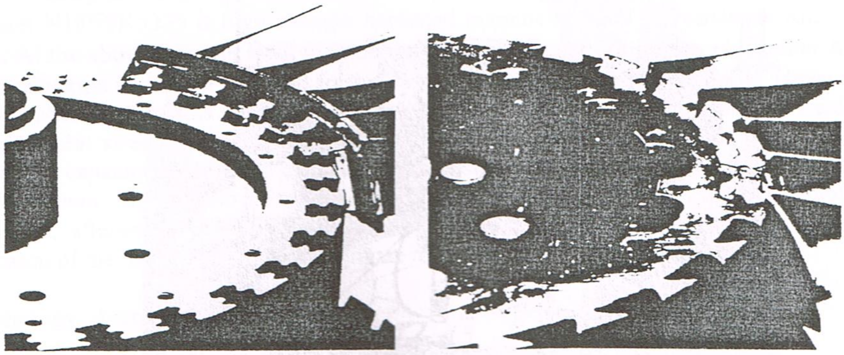

Fig. 5 Blade lock a - former fir-tree design, and b) new dove tile type.

Change in structure of welded joints is a consequence of implemented modifications of welding technology, in particular cooling conditions and removing of technological overlap.

Previous design of the joint caused blistering at the bottom of a joint, which became initiators of fatigue cracks, Fig. 5 and 6.

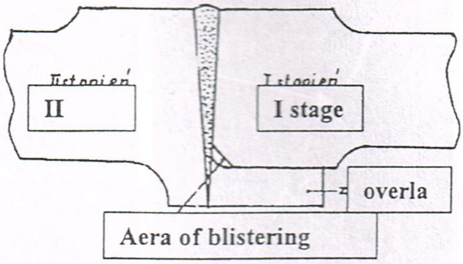

Fig. 6 Joint welded with an overlap

Material of the rotor blades of EI961 grade steel was replaced with WT-3 grade titanium alloy in order to reduce stress level at the blades.

Quality control of a rotor was modified as the result of structural and technological changes and stricter technical requirements. The latter, resulted from tests and structural experiments. According to the data, with nominal stress (σ_{nom} = 600 ÷ 900 MPa) and local stress (σ= 1500 ÷ 1750 MPa), the quality of rotor surface is a decisive factor for fatigue crack initiation in the sockets.

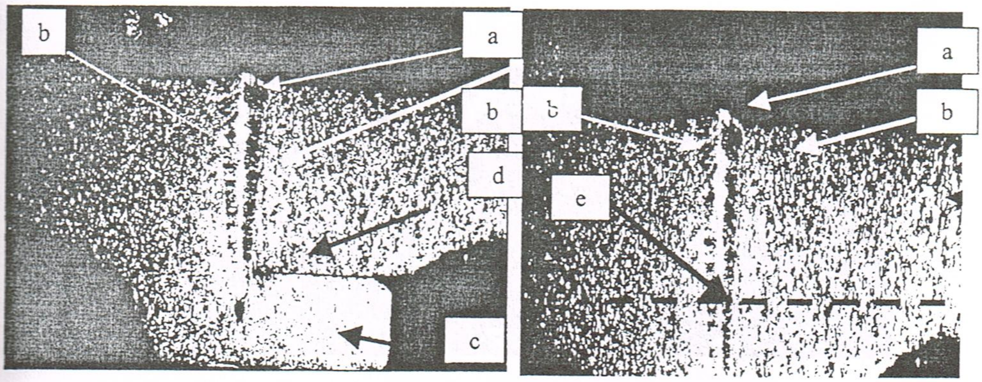

Fig. 7 Microstructure of a joint, A – previous design, B - modified joint: a - weld, b – weld affected zone c - overlap, d - area of blistering, e - line of the overlap removal.

A new methodology of blade lock sockets surface examination was developed. It consists 100% examination of the sockets magnetic-luminescence-microscopic and with eddy current methods. The examination is performed in order to localise the surface defects and to evaluate the state of the roots (micro-cracking, fretting, corrosion, etc.) in the course of service. In Fig. 7 a, b, c a microscopic, magnetic-luminescence image of root surface is shown, and in Fig. 8 – micro-cracking.

The 100% of welded joints examination with eddy current method of the weld, and weld affected zones.

The structural and technological changes led to a longer service cyclic life of the rotor namely from 700 to 12600 full test cycles. Now the intensive research takes place for further increase of rotor service cyclic life.

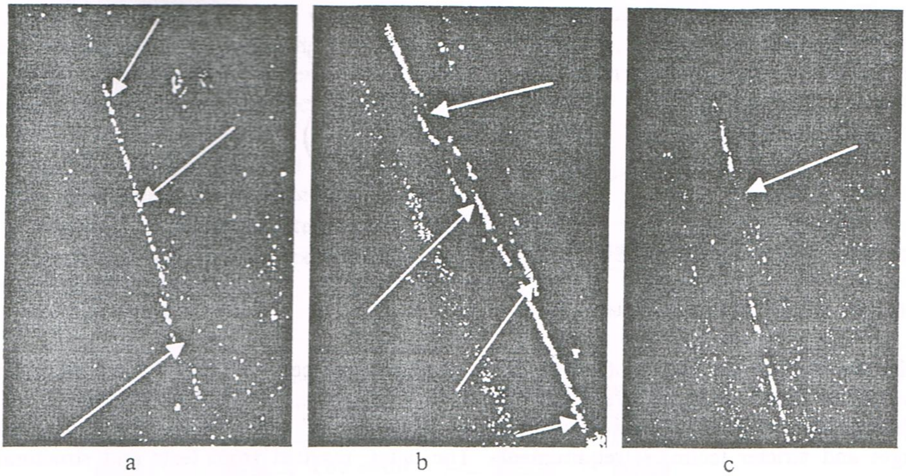

Fig. 8 Micro-cracking occurred after 12300 cycles of low cycle fatigue tests. Visualisation has been done with magnetic-luminescence-microscopic method. Cracking is non-continuous. The arrows indicate discontinuity of cracking in the root surface, caused by a multi-focal initiation.

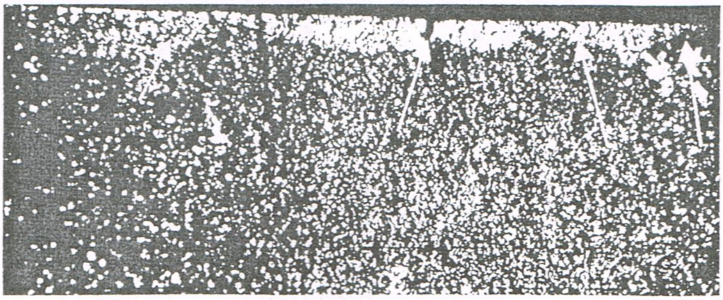

Fig.9. Multifocal fractures at lock cracking area. Arrows indicate origin of the fatigue.

Concluding remarks

The problems with the introduction of a new material procedure, i.e. N18N9K5TPr grade steel to the structure rotor of compressor in of K-15 engine, indicate difficulties and costs related to this procedure. General requirements for turbine engines of modern aircraft must meet, and which are briefly outlined at the beginning of this paper, make the constructors increase the nominal stress level in all elements of a rotor. So, the materials applied so far are often useless and must be replaced with new ones, of higher strength and create an opportunity to new technologies application. Long-term process of implementation of a new material requires extensive testing, verification of elements and whole structures, development of manufacture technologies and methodology of quality examination. As it results from the paper, the choice of material depends on many of its properties, and therefore, the procedure of material replacement on the base of identical chemical composition only, which is well known practice, is unacceptable.

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