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LOW CYCLE FATIGUE IN TURBINES

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16. Abstract

Behavior of certain components at low-cycle fatigue is a parameter related to the conditions of use of turbines, to the technology of engine production and to the precision of its regulation. The laboratory takes this into account using data from sophisticated tests and rigorous analyses. The production plan includes careful examination of possible causes of premature rupture. This parameter has motivated the metallurgy industry to develop new materials and new technology.

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LOW CYCLE FATIGUE IN TURBINES

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The author indicates the reasons for designating low cycle fatigue as a selective criterion for the materials of certain components by an examination of the conditions for use of a turbine. He then shows how this characteristic comes into play in the definition of the design, calculation of the service life, the concept of manufacturing and control. Finally, he raises the problem of developing new materials due to new requirements of engine makers. /42*

Introduction

Engine makers have recently added low-cycle fatigue behavior to the many criteria of selection of materials. Without dwelling on the new approach which could be discussed a good deal, the author wishes to present the reasons for use of this new parameter for various turbomachine parts and to show its implications in design, research and development, production and acceptance.

1. Generalities

1.1 Conditions of use

One cannot approach the problem of low-cycle fatigue in turbines without calling to mind the conditions for use of the latter:

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*Numbers in the margin indicate pagination in the foreign text.

--at constant load, temperature variations on a single component can be very high. In particular, this is the case for axles of the turbine or distributor of the turbine and even the turbine disk. This phenomenon can be increased by modern techniques of cooling;

--in a transitory state, establishment of unit stress and temperature has always had a certain phase lag. In the cold sections, the temperature can increase more rapidly than the unit stress, in the compressor this can be the inverse;

--the stress state of components depends on the typical cycle of operation of the engine. Let us recall that the external data played a role which is not negligible: for example, for an external temperature, there can be a variation from 15 to 45°C, the temperature in front of the turbine can increase from 150°C. In the case of the reactor, the examples are given in Plates 1 and 2. The typical cycles of a military and a civilian engine are very different. On the other hand, the service lives expected are from 3,000 to 10,000 cycles for the first and 40,000 to 80,000 for the second.

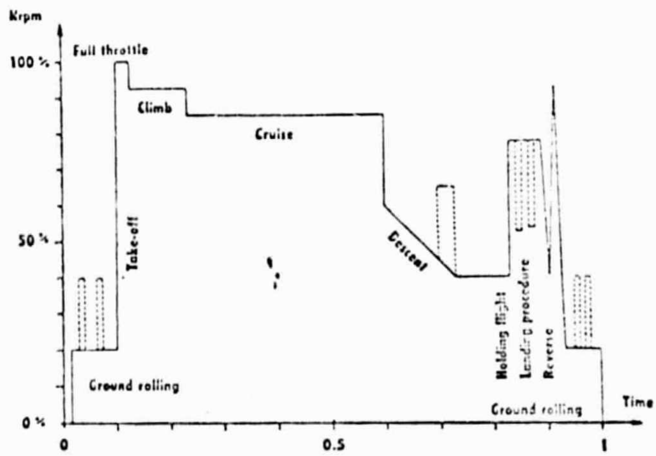

Plate 1. Civil engine: typical one-hour flight.

--For the helicopters, the situation is very complex because the conditions for use are variable from one to the other. One assumes that a typical cycle is

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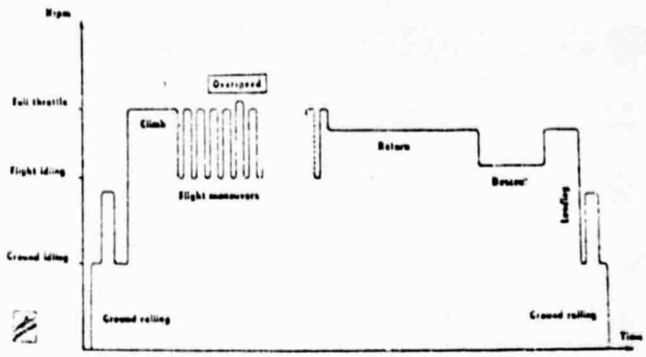
generally made up of:

- a starting phase (3 min) during which maximum power is required;
- a cruising phase requiring about 85% of maximum power. However, during this period, the helicopters can have to carry out different activities requiring maximum power; /43
- a descent phase requiring 30% of maximum power following;
- a phase of slowing flight (1 min).



Military engine : training flight

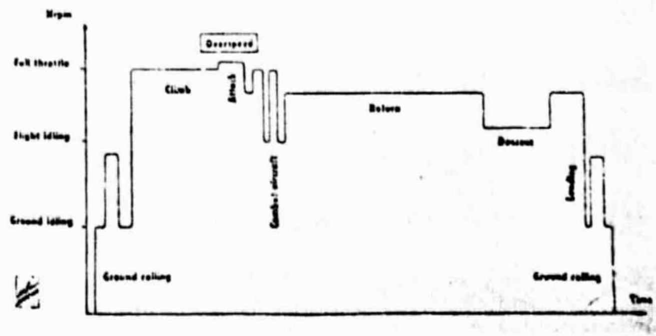


Plate 2. Military engine: typical interception and combat flight.

--for engines intended for use on the ground (for instance, turbo-trains) the movement on the gas control can be more frequent than in an aeronautical turbine engine. On the other hand, for industrial turbines, the cycle effect is negligible.

1.2 Effects on the Service Life of the Components

The components are subject then to cyclic stresses during each flight, the frequency of a cycle generally being somewhat raised. Those which are expressed by change in procedure and (or) temperature always show a variation in stress or deformation. The parts with the highest load are generally the following:

- disks of the compressors or axial and centrifugal rotors;
- the turbine disk;
- blades of the turbine and the turbine distributor;

- main shaft;
- high pressure housings.

The critical points are the zones of concentration of unit stress:

Disks: bleeding zones of the blades (dove tail, footing, etc.) orifices direct-drive dog clutch, calibers.

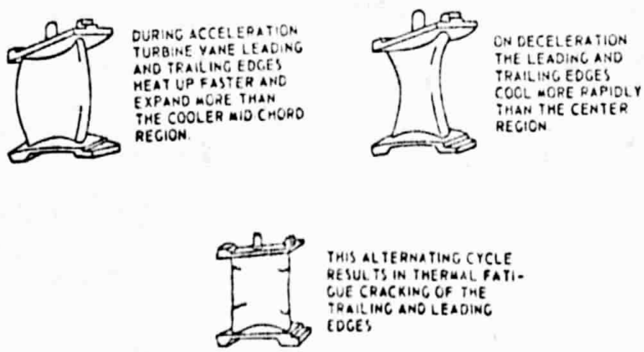
Shafts: variation of sections, grooves, holes, etc.

Housing: joining of flanges, periphery of bosses, etc.

The problems of the blades of the turbine and the distributor of the turbine are somewhat individual. These parts are subject to strong temperature gradients involved with cyclic variations of power. This stress involves dilations and contractions which are not uniform in which the alternate unit stresses of traction and compression (Plate 3) result in cracks in thin components (leading edge and trailing edge).

Cooling techniques often have a tendency to accentuate this phenomenon of thermal fatigue. Let us recall that the blades, in addition, are subject to creep. This set of problems is not actually new. The recent importance accorded to low-cycle fatigue strength of materials in turbines must be related to the tendency for increase in performance. This is accompanied by research into reducing specific consumption, the complexity of the engine and its weight, driving to rates of compression, temperatures and

THE BEHAVIOR OF SUPERALLOYS IN THERMAL FATIGUE



Sequence of events leading to the development of thermal fatigue cracks in an aircraft gas turbine component

Plate 3.

elevated speeds of rotation. Progress in the field of new materials was too slow after this; it has become imperative to increase the general level of unit stresses always looking for ways to decrease unevenness in shape. For certain engines, it is now permissible to operate certain areas in the plastic field, while the remainder of the components remain in the elastic field. In this case, due to the elastic reserve already set up, the zone considered is often subject to an imposed deformation.

As a result, behavior in low-cycle fatigue has become prevalent for certain components of the compression and turbine disks. Thermal fatigue can be compared to low-cycle fatigue.

2. Dimensionally, Service Life

The elements which we have discussed are generally vital components, that is to say, components in which breakdown involves major damage for the aircraft and the impossibility for the latter to carry out its mission. In addition, certain of these such as the compressor disks, the axial wheels, the centrifugal wheels, the turbine wheels, etc. have a maximum life defined by its manufacturer. For these reasons, they have become the object of particularly careful attention on the part of engine makers. The progress of their dimensionality is summarized in Plate 4.

2.1 Choice of Materials

The definition of performance obtained and conditions of use of the engine fix the aerodynamic and thermodynamic total data. Going from these, the choice of materials then requires the use of knowledge of the following metallurgical characteristics without omitting considerations of price, weight and space occupation;

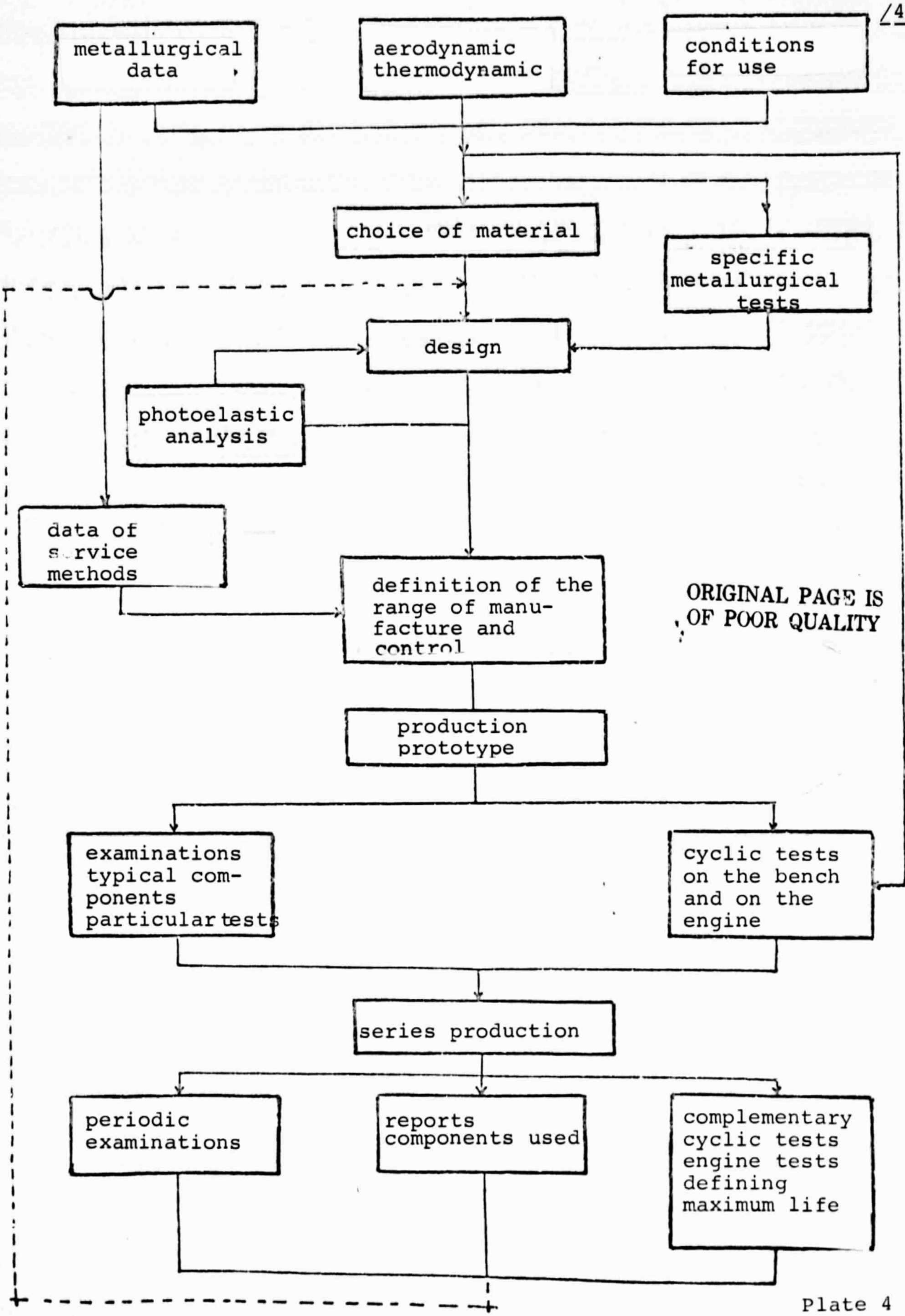


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Plate 4

- tensile strength R, yield point $R_{0.2}$, elongation (in the field of temperatures used); /43
- resistance to low-cycle fatigue on smooth and notched cylinders (in the field of temperatures used);
- resistance to crack propagation: K_{1c} $\frac{da}{dN}$
- creep characteristics.

However, the metallurgist must not forget numerous other criteria not directly used by the Bureau of Studies:

- ease of manufacture: founding or smelting, soldering, machining, thermal treatment, etc.;
- facility of acceptance;
- brittleness, transition temperature, sensitivity to cutting, resistance to corrosion and corrosion under stress;
- eventual resistance to thermal fatigue (in the case of the wheels and turbine blades);
- facility and independence of supply: in particular, for a military engine, the idea of strategic materials must not be forgotten;
- etc.

2.2 Defining the Design /45

The definition of the component as a function of flight cycles and minimum service life imposed, is complex and depends on the available data. A first design is obtained from conditions judged to be the most severe. Then, it is refined by more precise calculation according to the following general scheme:

- breakdown of different flight cycles into simple elementary cycles;
- determination of stress and temperature at each point of the component and extreme conditions of each elementary cycle assuming the operation conditions set up. The calculation must have taken into account centrifugal stresses and stresses

of thermal origin. In the zones of concentration of stresses, one makes the calculation in the elastic field, then one applies, if their is a plastic cycle, the Neuber theory preferably using the cyclic traction curve for the temperature used in the zone under consideration;

- determination o the parameters of fatigue at the beginning or at breakdown of the function of the temperature (Wohler diagram or Goodmann for deformation for stress impossed). It is desirable that the test conditions should be imposed by elementary flight cycles. Otherwise, the metallurgist must make more precise the limit of validity of use of the curves used. In parallel, one generally carries out the increases of the Paris curve $\frac{da}{dN} = C(\Delta K)^n$ for various temperatures;
- taking into account the frequency of appearance of these elementary cycles, one can in carrying out a summation of damage caused by the latter (Miner's law), define service life (in number of cycles).

Complementing the study of defining the component, a photoelastic analysis allows one to locate the zones with the highest load and to diminish concentrations of local stresses.

Remarks:

- In the case of components for which temperatures of function do not involve noticeable creep, one calculates assuming a constant temperature equal to the maximum value obtained during the cycle being used. On the other hand, if there can be creep, a more precise analysis is necessary in order to avoid excessive subdimensionality.
- Often one considers it most convenient to reduce all of the stresses to a single temperature T_o. The conditions $(\sigma_1 - T_1)$ and $(\sigma_2 - T_o)$ are called equivalent if they lead to the same number of cycles at rupture.
- Summarizing the effects of different cycles makes it possible

to make the stress conditions which are the most damaging to the service life of the components and the most critical zones more precise.

2.3 Discussion of Calculation Method

As a matter of fact, the approach which has already been made is particularly delicate and different parameters often must be taken into account more or less:

-- Speed of Propagation of Cracks

The curves of da/dN are indispensable and they act as a guide because the elevated level of stress can result in a speed of propagation which is too high, caused by efficiency of periodic tests of a component. On the other hand (1):

- they are very dependent on the conditions of the test (environment, frequency, type of cycle, $\frac{\sigma \text{ Max}}{\sigma \text{ Min}}$ etc.);
- their use necessitates the knowledge of the factor K in the zone where a crack is susceptible to propagation;
- they are traced in a case where the crack is transverse. But, we have brought up numerous examples of cracks in the bore of disks propagating to the interior of the part.

-- The Phenomena of Interaction of Fatigue and Creep

If there is creep during load, one must take into account the cumulative damage from fatigue and from creep, the law of Miner is not applicable. Different laws have been proposed, but they must be used with care. We must emphasize that the effect from time to time of maintenance under stress is not necessarily related to the phenomenon of simple creep. There is the case of certain titanium alloys where the effect of landing attributed to a blockage mechanism of dislocation by hydrogen, necessitates a low temperature (< 150°C). This "dwell effect" is practically impossible to take into consideration in the calculations. It must be made the object of special tests in the laboratory and on the bench.

-- Residual Stress from Manufacture

These are unforeseeable and difficult to measure.

-- Transitory Conditions

In reality, each change in flight conditions involves variations in temperatures and stress according to particular laws.

The fashion in which the new system of stresses and temperature are established, as well as the following order in which the different systems follow, play a role which cannot be ignored in the service life.

These transitory conditions are impossible to predict at the level of the preliminary project, are difficult to analyze and depend on regulation. Nevertheless, modern methods of testing and calculation make it possible now to incorporate them as well as possible into a complete evaluation of the load case.

-- The Effect of Graduation

In the zones of stress concentration, the volume most strongly solicited is most often very weak and localized in superficial zones. This is why durability is, in general, higher than predicted in theory. In fact, instead of the factor in the form of K_T, it would be more appropriate to consider fatigue as a graduation factor such as the gradient of stress or deformation (1), (2).

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-- The Environment

It is recognized that this parameter plays a very important role in the cold parts. Its effect is connected to the level of the stress applied and the form and frequency of the cycle(4).

-- Thermal Fatigue

There do not exist actual per hour values obtained from the Laboratory tests which can be used by the Bureau of Studies. The footings of the blades or the wheels of the turbine of certain engines are, however, severely subject to this stress.

2.4 Optimization - Service Life

2.4.1 Prototype Phase

Going from the design of the finished piece, the Methods Service in combination with the Metallurgical Service determine the shape of the "crude" components. The scale of manufacture during elaboration up until assembly of components on the engine is the object of particular attention of the latter which is in parallel with the drawing up of the technical documents. (Test memoranda, instructions for thermal treatment, specifications, etc.) One part of the first components made are used for metallurgical tests, and the other parts for cyclic tests.

-- Metallurgic Tests

Dissection of typical components: measurement of principal characteristics (R, $E_{0.2}$, A, creep, K_{1c}, low-cycle fatigue, etc.) in order to qualify the component and to evaluate the minimum values which they can attain.

Particular Tests:
- complements of low-cycle fatigue tests and speed of propagation of cracks as a function of the cycle used;
- specific tests: dwell effects, effect of the frequency and form of the cycle, etc., measurement of residual stresses;
- macrographic and micrographic analyses.

-- Manufacture and Control Tests

Machining, soldering, thermal treatment, shot peening, ultrasonic control, radiograph, etc.

-- Cyclic Tests on the Bench

In fact, the insufficiency of available data, lack of time, the difficulty of assessing parameters of manufacture and shape, the complexity of the problem make bench tests and tests of the motor on actual pieces the only ones which make it possible to optimize the solution and result in a more precise estimation of service life. One must then evaluate, among the conditions of use, the point of functioning which causes the most fatigue, taking into account the probability of its appearance. Its definition is related not only to the profile of flight cycles, but also to performance of the engine (a sensitivity and technique of regulation, mounted in operation, etc.). Not being able to cycle the temperature on the bench, one carries out tests at a temperature which is constant but variable in a part and applies the rule of equivalency of stress defined in 2.2. Stress is governed by speed of rotation.

If the number of cycles before the crack is defined as X, the sure life predicted (VSP is from $\frac{X}{n}$) in general n is equal to 4 in order to take into account the dispersion factor. If one desires to gain time, one can carry out tests for higher stress. One often assumes that the ratio of 4 for life service is equivalent to a ratio of 1.3 for applied stress. But this depends strictly on the gradient of the curve of low-cycle fatigue in the field of the number of cycles considered.

The authorized service life (VAS) [vie autorisee en service, authorized service life] at the beginning of use is $\frac{VSP}{2}$ to $\frac{VSP}{3}$ in order to take into consideration the variations between tests on the bench and the actual conditions of flight.

Conversion of the number of cycles authorized to the number of flight hours is delicate. It is the object of agreement

between builder and the user.
The bench test is often pursued until complete rupture. It also makes it possible not only to localize the critical zones, but also to gain information on the direction and speed of crack propagation.

Remarks:

Carrying out short cycles on the bench in an effort to gain time, one cannot take into account the effects of landing. If these latter are of well known importance, specific tests are launched in parallel.

-- Series Phase

The results of metallurgical tests, tests on engines on the bench, having made it possible to define components conforming to the objects intended, optimization is pursued in the same way in series by

- Metallurgical Tests

They are made up essentially of periodic dissections of components or parts of components in order to:

- inspect the quality of manufacture;
- detect eventual anomalies which did not show up in the preliminary phase;
- evaluate variation of parameters and to reduce them to the minimum.

In addition, special tests related to problems encountered are carried out.

- Cyclic Tests

One could arrive at VAS = VSP by a particular procedure at each engine and as a function of regulation strength. This depends on the actual service life obtained and on the results of cyclic tests on the components having already had a certain potential on the engine.

-- Reports of Component Use

This set of factors leads, either to a better definition of a maximum life or to a modification of design.

3. Metallurgical Consequences

The problems of low-cycle fatigue and thermal fatigue have many attributions at the level of the metallurgist. We will cite those which concern the studies and tests at the Laboratories, the concept of the scale of manufacture and control, research on materials and new technology. /47

3.1 Studies and Tests at the Laboratory

Experimentation

The outline of the curves of low-cycle fatigue (cycling under stress or deformation), cyclic traction and speed of propagation of the cracks, the necessity for complex instrumentation, are all delicate and onerous. In particular, the conventional fatigue machines have been replaced with new electrohydraulic instruments which are relatively sophisticated.
In addition, the importance of thermal fatigue problems, the absence of definite and adapted tests have led each laboratory to develop a particular methodology which permits rapidly characterizing the alloys as to this parameter (3).
Finally, the Bureau of Studies demands an increased precision in results of the Laboratory for classical characteristics of traction (yield point at 0.1 to 0.05%, cold-hardening coefficient, true stress at rupture, etc.). We recall that the knowledge of low-cycle fatigue curves is the basis for the dimensionality of certain critical parts and the determination of test conditions on the bench which make it possible to establish their service life.

Studies

Tests for fatigue and speed of propagation pose numerous other problems which must be examined with care: choice of the test piece, definition of machining, shape and frequency of the cycles, etc. In parallel, the microfractographic analysis of the rupture facies of the test pieces is indispensable. The attribution of a rupture as a phenomenon of a low-cycle fatigue or thermal fatigue is often difficult particularly if the functioning temperature of the component in the examination zone is elevated for the constituent material (photos 18-19 [photos 18-19 were not included for translation]). In addition, for the blades, a crack which has once begun can propagate rapidly due to the vibration phenomenon. This is why the thoroughest examination of it or of the zones of its origin is necessary. One usually considers that low-cycle fatigue ruptures begin at the surface like conventional fatigue. However, due to the load level of the component piece, accidents of structure (segregations, inclusions, etc.) or an elevated local level of residual stress can be responsible for premature initiation. In this case, the latter can perfectly well be in the interior of a part (photos 5, 6, 7).

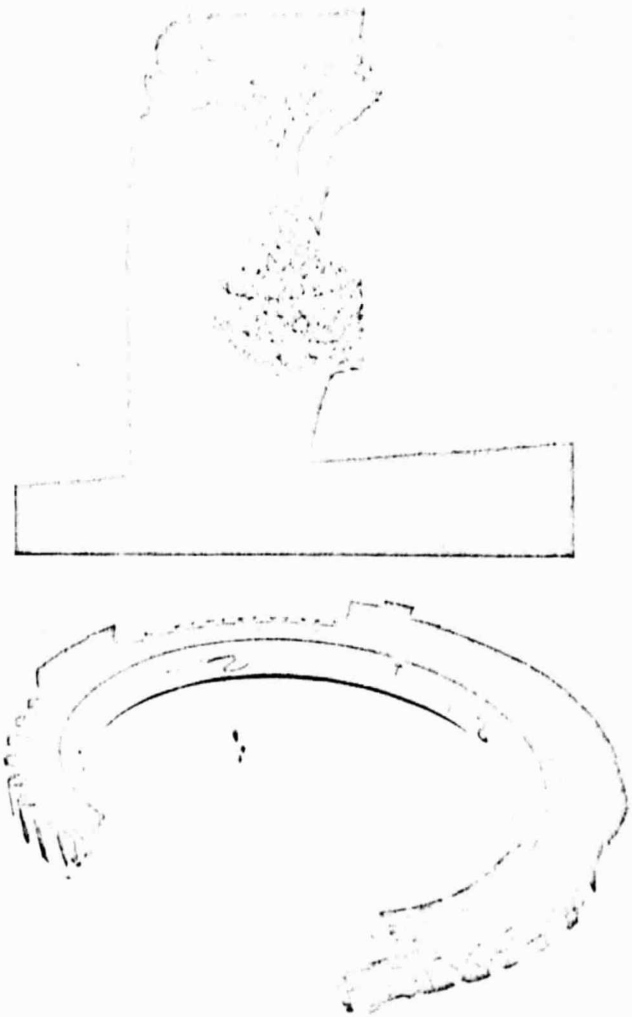

Photo 5: Back view \ secondary crack.

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No 10 x 800 Engraved detail No. 9

No 9 x 400 Area of stria on the main lug

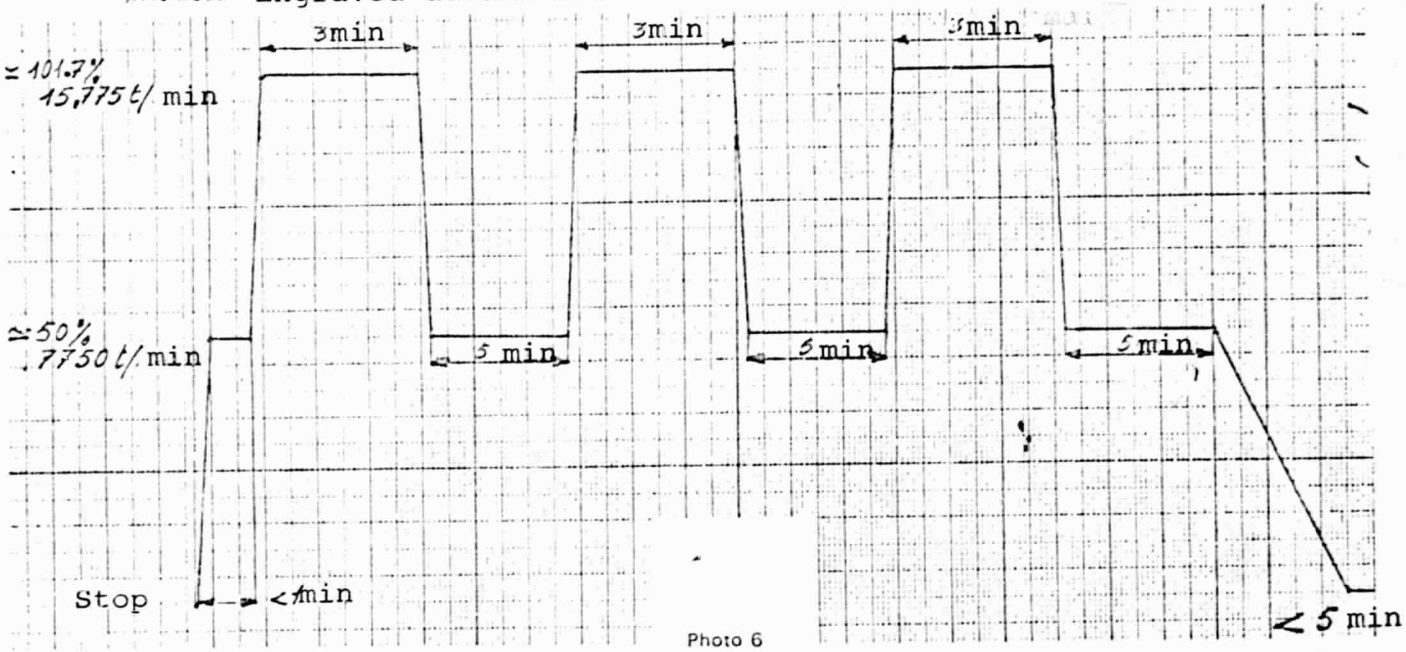
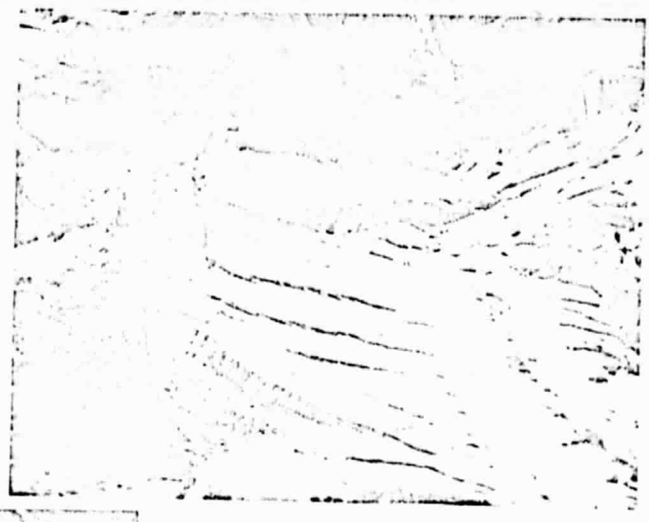
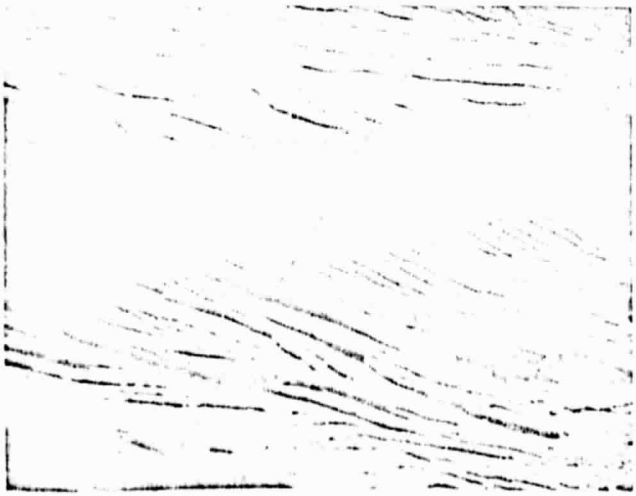


Photo 6

Zone of origin



Cleavages and depths



Detail of the plate below

Plate 7

3.2 Concept of Manufacture and Control

Metallurgists must examine the process of manufacture and control with particular care in order to:

- eliminate all causes for premature initiation or increase of the rate of propagation of cracks;
- detect eventual defects;
- guarantee a certain level of the characteristics at all points on the parts.

Let us recall by way of example, the problems encountered on titanium alloys; HID (High Interstitial Defect) and heavy inclusions related to elaboration techniques, elevated residual stresses in relation to the range of machine and thermal treatment, weakening of the low-cycle fatigue characteristics and increase in the rate of propagation of the cracks in relation to rate of welding in the β or $\underline{a}$ - β phases and the structure. Consequently, the complete range is studied with a good deal of attention in close collaboration with suppliers and clients: production conditions (refusal on opening or delivery is general), conditions of conversion, machining, thermal treatment. The acceptance of the range proposed is related to results of examination of typical components and for components at maximum life in the result of bench tests on the engine. A definite time is fixed and made the object of a written document. It cannot be modified without agreement between the supplier and the client.
In addition, the constancy of manufacture is inspected by periodic examination of the components in a crude state. The control techniques and very complete, precise and adapted to possible hazards: macrographic, ultrasonic, radiographic control, by eddy currents, etc.
Individual adjustment exists which permits determining the position in the ingot, of the piece which is to become the component and to /48
follow the different phases of its manufacture (the batches of

matrix alloys, the mold batch, the forge batch, the thermal treatment bath, etc.); this makes it possible to eliminate the group of doubtful components in a case of occasional irregularity in manufacture.
We must not forget, finally, that control of the elements of the engines after partial functioning on the bench or on the engine itself is done with a particular procedure often lengthy and involving difficulties due to the configuration of the parts (form, accessibility.

3.3 Study of Materials and New Technology

The existence of the Bureau of Studies causes the metallurgist to turn toward new solutions. Research into new materials is always constant. Recently it has resulted in the development of alloys on a titanium base for high temperature (TASZr D - 5522 S) and certain super alloys on a nickel base (Inco 718 - various modifications of alloys from smelting in order to increase ductility in heat).
While it seems at the present time that traditional metallurgy does not allow one to hope for spectacular progress, the launching of a new slight difference is an excessively lengthy and costly operation. In addition, one must recognize that the range of available alloys, notably on nickel bases, is already impressive.
This is why it seems that research into new technologies is the most promising method. The purposes envisaged are the following:

- to increase the performance of slightly different products already known. This is the case of guided solidification and to some degree isothermal forging;
- to cause the creation of new and slightly different products with increased characteristics; powder metallurgy seems to promise the best approach;

- to increase the level of general quality of the components; the HIP (Hot Isostatic Pressure) in stopping porosities, can bring new progress to precision founding;
- to cut down the cost price. Great hopes are founded on powder metallurgy, the components being used in a crude state of compacting.

Conclusions

Behavior at low-cycle fatigue of certain components which are heavily loaded is a characteristic related to the conditions of use of turbines (deformation and frequency of use of typical missions), to the technology of the engine and to the precision of its regulation.

Taking this into account by calculation is required at the Labor- /49 atory with adapted and sophisticated tests and a most rigorous analysis of the dispersion of characteristics obtained for the actual component. A thorough examination of possible causes of premature rupture ensues in the production plan: this is done by strict imperatives on the operation, a precise and careful definition of the range of manufacture and control.

Finally, this characteristic is the motivation of a certain evolution of metallurgy by the use of new technology.

Acknowledgements

We wish to thank SNECMA for the information furnished and for their advice.

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