DEVELOPMENT OF LIFING METHODOLOGIES FOR HIGH RESISTANCE SUPERALLOYS IN AERONAUTICAL TURBOENGINES

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Both high resistance materials and up-to date lifing methods are essential to the development of modern turboengines. In addressing this need, recent breakthroughs in nickel base superalloys have been achieved, allowing operating conditions in turbines which would have been impossible without such materials improvement. Powder metallurgy and directionally solidified single crystal materials have been respectively developed for discs and blades manufacturing. However in both cases, due to the particular mechanical behaviour of these materials specific lifing methods have been found necessary for the design. Those two items are to be exposed in this paper illustrated by SNECMA military engine applications and discussed as regards civil engine requirements.

LIFING POWDER METALLURGY SUPERALLOY DISCS

Nickel base superalloys processed by powder metallurgy are currently used for the manufacturing of high pressure turbine discs in modern aircraft engines. It has been clearly evidenced that in such materials, non-metallic inclusions are favoured crack initiation sites and decrease the Low Cycle Fatigue (LCF) lives. Two actions have been undertaken to overcome this problem.

- Improvement of cleanliness of the material, through adequate sieving and associated quality control techniques.
- Validation of lifing methods taking into account the existence of inclusions as weak elements in the part.

Probabilistic lifing model

The effects of non-reactive inclusions on LCF resistance have been extensively studied for fifteen years in René 95 and Astroloy. The main conclusions of these studies can be summarized as follows :

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a) the LCF life is shorter (by a factor about 10) for crack initiation around surface inclusions versus internal ones. Two populations of lives are statistically shown, which means that the lives do not follow the classical log. normal distribution.

b) due to the cleanliness level of the material, the occurrence of large inclusions at the surface of a part (and a specimen) is very faint and strongly depends on the total loaded surface of the structure (de Bussac (1)). This phenomenon is considered as scale effect : the number and sizes of the inclusions are correlated to the stressed surface/volume. In order to get experimental data on lab specimens representative of discs, seeded P.M materials have been used (de Bussac (1)). The issues of the studies are that the failure probability and life time distribution in a P.M disc are dependent on the probability that it contains a comparatively large inclusion in a region of high stress and on the probability that the crack is initiated from that inclusion. These considerations have led to propose probabilistic models for life prediction in PM alloys. In SNECMA, a probabilistic model has been developed (de Bussac (1)) to predict the size of surface inclusions which initiate LCF cracks from the inclusion distribution. Numerous LCF tests have been performed on lab specimens machined in N18 discs, a PM superalloy developed in France and used in modern military engines (Guédou (2)). The predicted and experimental probabilities versus crack sizes fitted quite well (fig.1) and the model adequately simulates the scale effect (fig 2) : in lab specimens, 30/40 μm size particles are found to be the most probable sites for LCF crack initiations while 80 μm inclusions, which are quite scarce in lab specimens, are expected to be responsible of disc failure.

<u>Lifing methodology</u>

The principle of the LCF lifing model for PM discs is the following :
- for a given critical zone in a part, which means a given uniform loaded surface (or volume) size, and a given risk of failure, the critical defect size is established. Then a life diagram, where lifetimes against defect size are drawn through crack propagation calculations, is used and delivers the predicted life as shown in figure 3. In actual situations this simple methodology cannot be used just as it stands. Non uniform loadings and life scatter corresponding to a given defect size are to be taken into account but the principle of the previously described methodology is still applied. The lifetime evolution with the failure probability of a part is determined that allows to deliver the predicted life corresponding to the appropriate risk.Validation of this methodology has been made on seeded and unseeded lab specimens and on subscale discs. The method appears fully appropriate for short LCF lives (< 2.10^4 cycles). Additionnal experimental studies are however necessary to assess the relevance of the concept for long LCF lives (up to 2.10^5 cycles) as concern civil engines.

LIFING SINGLE CRYSTAL SUPERALLOYS BLADES

Nickel base single crystal superalloys, because of their superior high temperature properties have attracted considerable interest for blades manufacturing in gas turbine engines. The first basic need for the design of such components is the development of a model to describe the inelastic constitutive behaviour of the material and to predict the stress-strain dependance according time and temperature at the critical locations. Such models have been developed and sucessfully applied to classical equiaxed alloys. For single crystals, anisotropy introduces additional difficulties and distinct modeling approaches have to be identified. This will be developed in the following chapter. The second point of concern is life prediction. Different damage mechanisms are operating in turbine blades especially in the airfoil. The mechanical stresses induced by centrifugal loading are cause of creep damage. Moreover, the temperature variations both in time and in the part itself, generate cycled gradients which bring about thermal fatigue mechanisms with the additional influence of environment (oxidation). Those phenomena need to be accounted for in the designing codes and damage models have to be developed. Thermomechanical tests on lab specimens have been implemented in order to assess such models that will be described hereafter.

Anisotropic viscoplastic models for single crystals

The monotonic and cyclic anisotropic behaviour of AM1 single crystal, a french patented alloy used in SNECMA military engine M88 (Bachelet (3)), have been characterised for elastic and viscoplastic loadings. The influence of the crystallographic orientation on the shape of the stabilized hysteresis loop is shown for example in fig. 4. Two approaches have been considered to modelize the mechanical behaviour of AM1 single crystal :
- a macroscopical phenomenological concept, using an anisotropic yield criterion (Nouailhas (4)).
- a micro-macro deformation based model (Méric (5)) where the constitutive equations are introduced at the slip level. The physical mechanisms are taken into account through the classical Schmid law.

In both cases, the models have been implemented in finite elements codes and the coefficients of the laws have been identified. Experiments and theory were found in good agreement (Hanriot (6)) not only in terms of stress-strain response at a macroscale level (fig. 5) but also as concern the activated slip systems at a microscopic scale.

In order to fully characterize the mechanical behaviour and the actual damaging processes of single crystal blades in realistic conditions, a thermomechanical fatigue (TMF) methodology has been developed (Guédou (7)). In such tests, both strain and temperature evoluate simultaneously on a volume element specimen (tubular which allow cycles quite representative of critical areas in turbine airfoils (fig. 6). The TMF behaviour revealed to be strongly dependent on crystallographic orientations due to large elastic modulus differences (factor about 2,4 between E <001> and E <111>) and to quite different plastic deformation capabilities. The anisotropic constitutive 3D models have been validated in anisothermal conditions (fig. 7). The damaging mechanisms have been investigated and on uncoated materials, the life is mainly spent in crack growth regime. In that case, a creep-fatigue interaction model appears quite appropriate. However, the above conclusions are altered when coated specimens (aluminide coatings) are considered, which are representative of cooled turbine blades which are always coated in turboengines. The damaging mechanisms are modified since the resistance of the coating plays a predominant role in the life of the component. On bare alloys, cracks always initiate on casting defects (microshrinkages, porosities...) whereas on coated ones, oxidation and cracking of coatings are involved and the ductile-brittle transition temperature needs to be carefully determined. More complex models are to be developed and validated under isothermal LCF conditions, and obviously with TMF tests which are the most relevant as regard actual operating conditions.

CONCLUSION

The noticeable increase of component resistance in modern aeroturboengines is partly due to the development of high performance materials, but this issue could not have been achieved without joined improvement of materials processing and designing methods in which the mechanical concepts are closely related to the operating physical mechanisms. On that way, a strong collaboration between people in materials and in mechanics teams is mandatory . This are led to the predominant role of a new engineer specialist in the materials mechanics domains.

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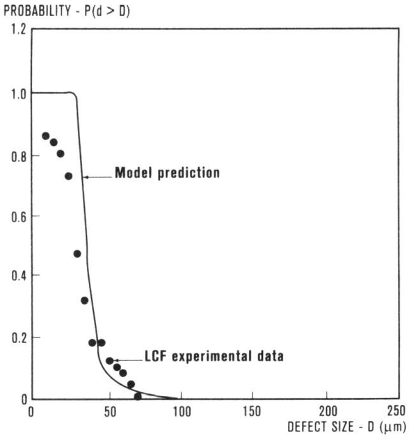

Figure 1 - Comparison between predicted and experimental probabilities

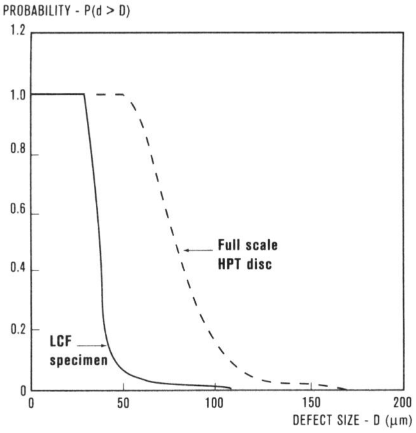

Figure 2 - Scale effect illustration for N18 superalloy

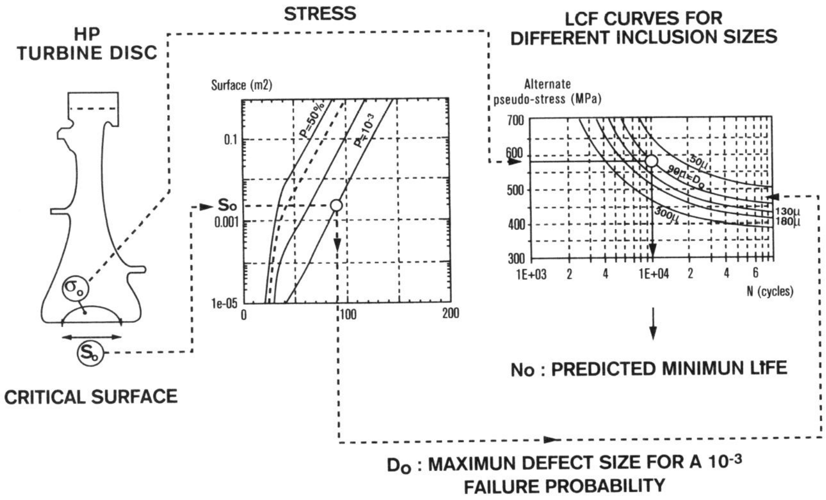

Figure 3 - Schematic representation of lifing methodology for Powder Metallurgy Superalloy discs

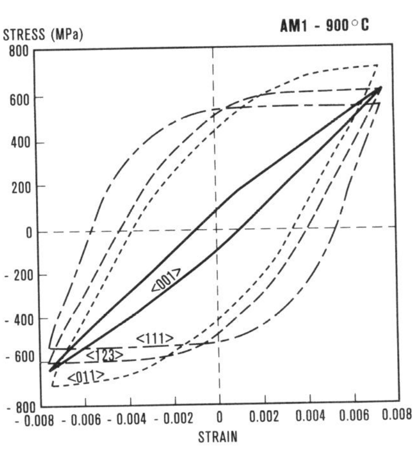

Figure 4 - Influence of crystallographic orientation on stress-strain behaviour

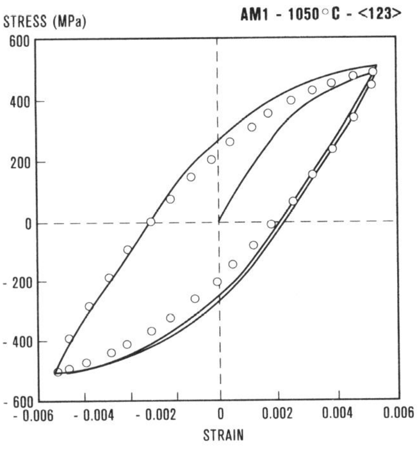

Figure 5 - Comparison between experimental and predicted fatigue loops

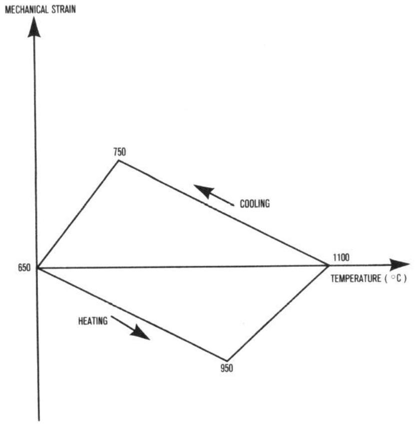

Figure 6 - TMF cycle definition

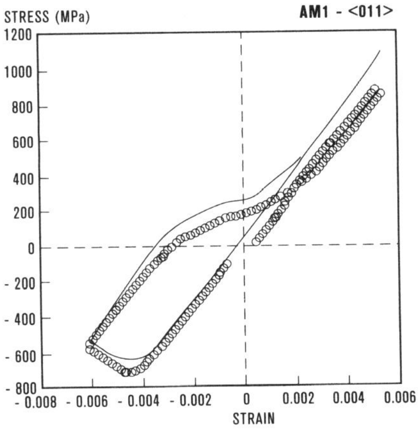

Figure 7 - Comparison between experimental and predicted TMF loops