718 SUPERALLOY FORGING SIMULATION : A WAY TO IMPROVE PROCESS AND MATERIAL POTENTIALITIES

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Abstract

In a forged condition, 718 superalloy is commonly used to manufacture some aircraft engine turbine parts severely loaded in service. The mechanical behavior of these parts depends on both thermo-mechanical conditions during flights and microstructural characteristics of the alloy.

As the microstructure is controlled by forging process, numerical models are developed to predict relevant microstructural data such as grain characteristics which are related to the processing parameters. Based on experimental studies, simulation tools allow to optimize a process range insuring its stability and the part quality in accordance with the required specifications.

Subsequently, these models will allow to describe the mechanical resistance of the forged part correlated with the flight thermo-mechanical data. For example, an empirical law was established to link grain size, temperature, strain range and low cycle fatigue (LCF) resistance. It has been introduced into a lifing software and validated by comparing experimentation and simulation. Thus, forging simulation models are implemented to take into account the process variability during the procedure which enable to get time, cost and quality savings.

Superalloys 718, 625, 706 and Various Derivatives
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Background

For long, Snecma Moteurs has been involved in improving its knowledge and expertise in turbojet engine discs manufacturing. As these parts are severely loaded in service environment both thermally and mechanically, permanent process control and improvement are always kept in mind by Snecma Moteurs manufacturers. To achieve this goal, several ways are possible and it can be reached either by a constant process control and/or by modeling.

Indeed, forged discs are among the most critical parts in engine. So, forging is the appropriate hot forming process to fulfill a rough matrix and to get the complex geometry of large semi-finished products like turbine discs or large fan blades with appropriate material flow.

The final objective is to get the desired metallurgical microstructure in terms of grain size, recrystallization rate, precipitation of hardening phases and resultant strength-hardening ... This can be achieved by one or more forging steps regarding the desired final deformation rate. The overall operations constitute what is commonly called the forging range.

As far as temperatures increase along the turbine axis, titanium alloys, which are of interest, regarding their low density and mechanical strengths, become inappropriate and must be replaced. Nickel base ingot processed superalloys such as INCO 718 alloy are widely used for aeronautical turboengine applications, both on forged parts (discs, blades, shafts, supports ...) and cast frame sections, due to their attractive mechanical properties up to 650°C [1]. Powder metallurgy grades, such N18 at Snecma Moteurs, are employed above 650°C.

Material and process overview

The initial billets are controlled before forging to assume exhaustive knowledge of the raw materials : chemical composition checking, initial grain size determination along diameter, phase transformation point determination, dimensional and finally US control [2].

As well, during forging, the process parameters are clearly identified and checked in order to guarantee reproducibility. The relevant process parameters are die speed related to energy under an hydraulic press, temperature of the mult along forging, tools and furnace temperatures, transfer and waiting time before and after forging, lubricant characteristics, quenching time in the selected fluids and transfer time between different quenching fluids. Finally, the resultant forged product is completely characterized with regards to macrographic and micrographic investigations. US control and mechanical characteristics are also performed both on attached ring and on a specific bulk part which is periodically selected for a more comprehensive characterization involving low cyclic fatigue behavior, creep resistance and tensile tests. As a result, the overall parameters presented in figure 1 are thoroughly well-known and they will be further used to supply with data as accurate as possible the simulation codes. Now, the simulation results can deliver quite valuable information on the parameters to control, allowing the improvement of the process stability and the work-piece quality.

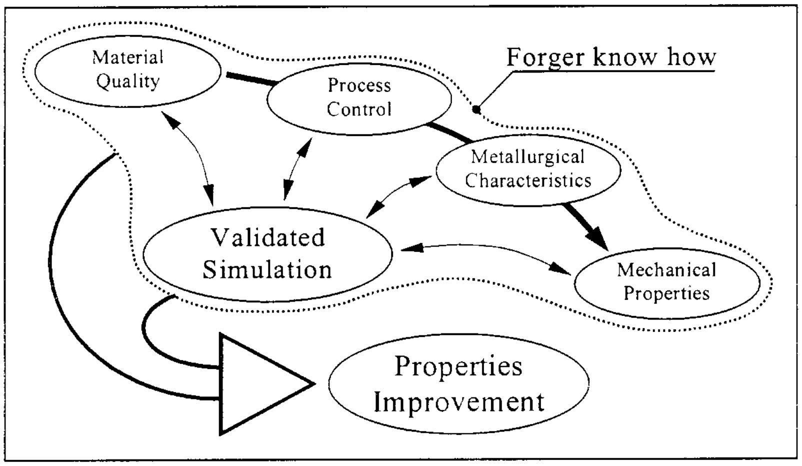


Figure 1: Control and simulation of forging process scheme

Simulation

Modeling tools have been developed to account, as accurately as possible, of the physical phenomena operating during the deformation process. The models are mainly based on the description of microstructural and metallurgical evolutions [3] on one hand and on mechanical or thermo-mechanical strengthening laws on the other hand. If the mechanical and thermal algorithms have been used for long, the implemented metallurgical laws are more difficult to establish and have to be fitted to a large number of experimental data, describing a wide range of process conditions. Such models are intrinsic to the corresponding alloys and are available at Snecma Moteurs for all the forged alloys used for discs. They are implemented in computer software as post-processing codes. Hence, the predictive models can be run for any kind of work-pieces during the whole process.

The mechanical properties are obtained by further models based on experimental relationships with metallurgical characteristics. In the following, we will describe the applied method to correlate the LCF behavior of the 718 superalloy to the thermo-mechanical deformation it undergoes in service and to its microstructural characteristics.

Prediction of INCO 718 LCF Resistance

Experimental Procedure

For more than 10 years, it has been commonly established that fine grain microstructure is related to better LCF resistance even if this trend is associated with a huge scatter of LCF results especially when the grain size decreases.

In the present study [4], we will propose a new model based on a large number of data : more than 2750 specimens have been investigated after strain controlled test, in the range of temperature from 200°C to 650°C and of strain range between 0.48% and 1.24%. All the fatigue tests have been performed on machined and polished cylindrical specimens. The applied strain controlled fatigue cycle is sinusoidal with a frequency of 1 to 2 Hz. The loading ratio is zero and only an axial load is applied.

On figure 2, we can notice that a grain size of ASTM 10 microstructures lead from several thousands to three million cycles. From this consideration, Snecma Moteurs has developed some numerical models which allow to predict LCF resistance resulting from the microstructural parameters and in service conditions. Moreover, this microstructure depends on the forging conditions in itself.

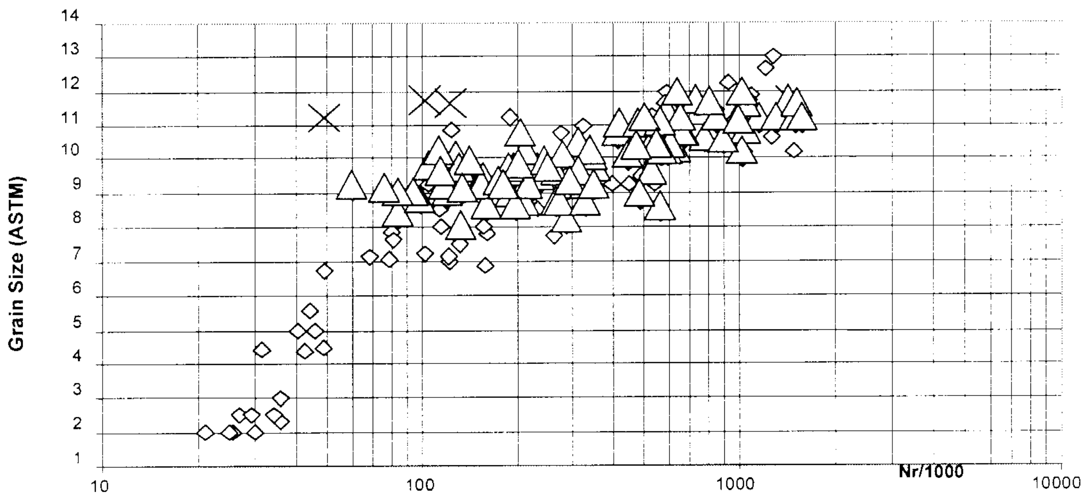


Figure 2 : Variation of experimental fatigue life rupture time with the microstructure. LCF tests achieved at 350°C on INCO 718, at low frequency (1Hz) and under R=0 load ratio for strain controlled loading (between 0.52 and 0.60%)

◇ : Experimental data : crack initiation site not identified

Δ : Crack initiation located on grain

× : Crack initiation located on carbide

Sometimes, this trend can be held up considering extremely low results. These abnormal points were identified to be due to the LCF initiation phase and more precisely to initiation sites on carbides (figure 3a) when located on the sample surface.

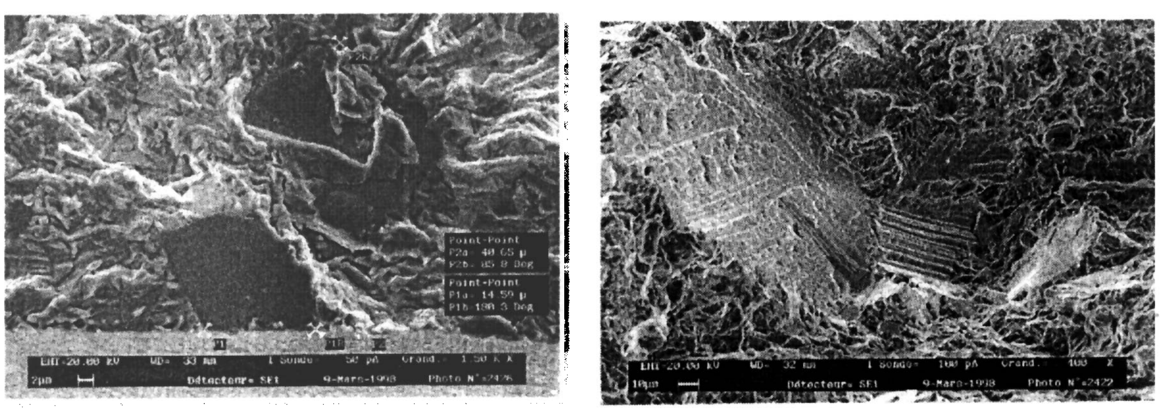


Figure 3: Fractographs of fatigue crack initiating sites

(a) Machined specimen : Fatigue crack initiated from a carbide on the specimen surface

(b) Machined specimen : Fatigue crack initiated from a grain

In the studied range of temperature and deformation, test-pieces exhibit two different rupture mechanisms. On one hand, initiation on carbides systematically makes the lowest fatigue life when they are on the surface of the sample and when they become as large as the grain structure (i.e. : grain size of about ASTM 7-8). Considering that the average size of a carbide is measured between 20 and 40 microns, we can guess that according to the thermo-mechanical solicitation conditions, competition can occur between carbides and grains in regards to fatigue crack initiation when the microstructure become the same order of magnitude than the carbide size [4].
On the other hand, initiations on grains (figure 3.b) induce higher fatigue lives especially as grain size is finer and as they are situated far from the test-piece edge. Some failures on carbides have been observed near the surface or inside the test-piece, but they are associated with longer lives. This behavior can be explained by different initiation mechanisms such as carbide cleavage, "intrusion-extrusion" on the surface grains, ...
By distinguishing the fatigue initiation element effect and the discrepancy between two microstructure measurements, the scatter in low cycle fatigue results is reduced. In this paper, the carbide rupture mode will not be considered further on.

Fitting Procedure

Korth [5], considered the effects of various parameters applied during LCF tests on alloy 718 and presented a mathematical law relating imposed strain range, temperature and fatigue life. This model corresponded to a polynomial law with 5 parameters and not less than 12 constants but with no links to the physical phenomena.
Taking into account the experimental data available for each applied condition (temperature and strain controlled loading), all the other parameters being kept fixed as described above, we can get an average curve relating microstructure to fatigue life (see Figures 2 and 4). As a result, the fatigue behavior of alloy 718 can be described by an empirical equation over the entire range of available data.

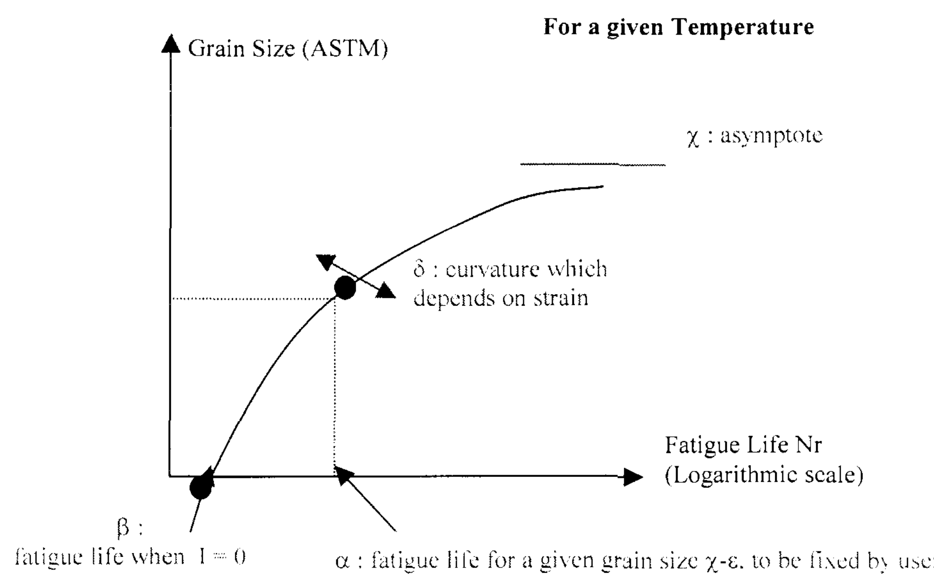


Figure 4 : Schematic representation of the fatigue life curve

Analysis of the test data consisted of empirical curve fitting using the equation below, where Nr_{moy} is cycles to failure, I is an average grain size describing the microstructure and α, β, χ, δ and ε are constants. An hyperbolic formula correlates rather well Nr to I when temperature and strain loading are fixed. We further refer to the one parameter law taken as :

$$\mathbf{Nr_{moy}}\,(\mathbf{I}) = \beta + \frac{\alpha - \beta}{(\frac{1}{\varepsilon})^{\delta} - (\frac{1}{\chi})^{\delta}}\left[(\chi - I)^{-\delta} - \chi^{-\delta}\right] \qquad (1)$$

Curve fitting was performed separately for each lot of data, where a lot is defined as continuous cycling test at a single temperature and a given strain range, around an average specified value, from various specimen with evolving grain size for the low cycle tests. Based on experimental results, for any given conditions, we get χ=13 and δ=3.
When temperature and strain loading are changed, we get a linear evolution of Nr_{moy} which can be further described by :

$$\mathbf{Nr_{moy}}\,(\mathbf{I}) = f_1 + f_2 * \left[(13 - I)^{-3} - 13^{-3}\right] \qquad (2)$$

Where f_1 and f_2 are function of temperature and strain loading.
Considering the influence of temperature (see Figure 5), we can establish that the temperature has nearly no effect on fatigue life.

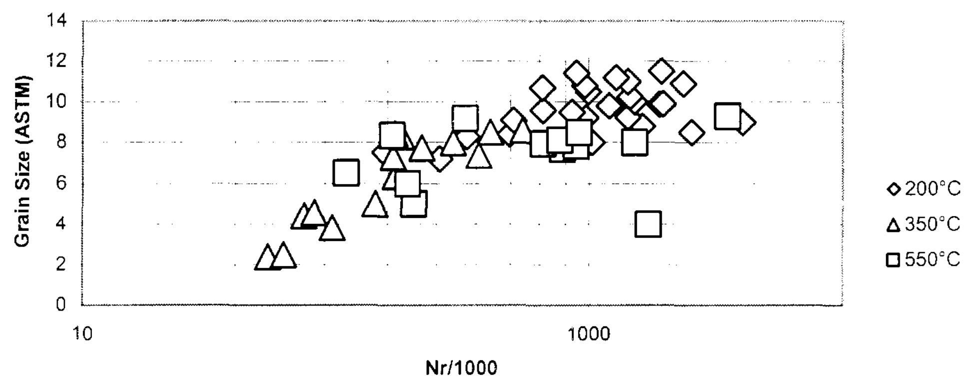


Figure 5 : Effect of temperature for a given strain range on fatigue life
Experimental data, based without fatigue crack initiation on carbide. Average curve for a strain loading 0.48%

On the contrary, the strain controlled loading at a given temperature seems to be a prominent parameter regarding fatigue life [4]. As a result, the effect of strain loading can be described by :

$$f_1\,(\Delta\varepsilon_{lt}) = 3.10^{6} * e^{-8.9\Delta\varepsilon_{lt}} \qquad (3)$$

$$f_2\,(\mathbf{T}, \Delta\varepsilon_{lt}) = T * 5.10^{7} * e^{-12.9\Delta\varepsilon_{lt}} \qquad (4)$$

where $\Delta\varepsilon_{lt}$ is the total strain range (in percent). The effect of temperature and strain range are defined before fitting the linear expression and the chosen values represent a compromise that gives the best correlation of fit.
When replacing equations (3) and (4) into (2) and after optimizing and adjusting to experimental data, we get a general equation, referred as the three parameters law, which links

the 3 evolving parameters Temperature T, strain loading $\Delta\varepsilon_{lt}$ and the microstructure I with fatigue life taken as :

$$\mathbf{Nr_{moy}\ (T,\ \Delta\varepsilon_{lt},\ I)} = 3.10^{6} e^{-9.4\Delta\varepsilon_{lt}} * \left\{ 1 + 10^{-2} * e^{-4.1\Delta\varepsilon_{lt}} \left[\left(1 - \frac{I}{13} \right)^{-3} - 1 \right] \right\} \qquad \mathbf{(5)}$$

Validation and discussion

We have to keep in mind that this last formulation is based on an empirical method and is available only on the settlement domain where it has been established, typically a working temperature between 200 and 650°C and a strain rate between 0.5% and 1.25%. To validate this model, we have first compared it with the experimental data. On figure 6, the predictions agree well with the experimental data.

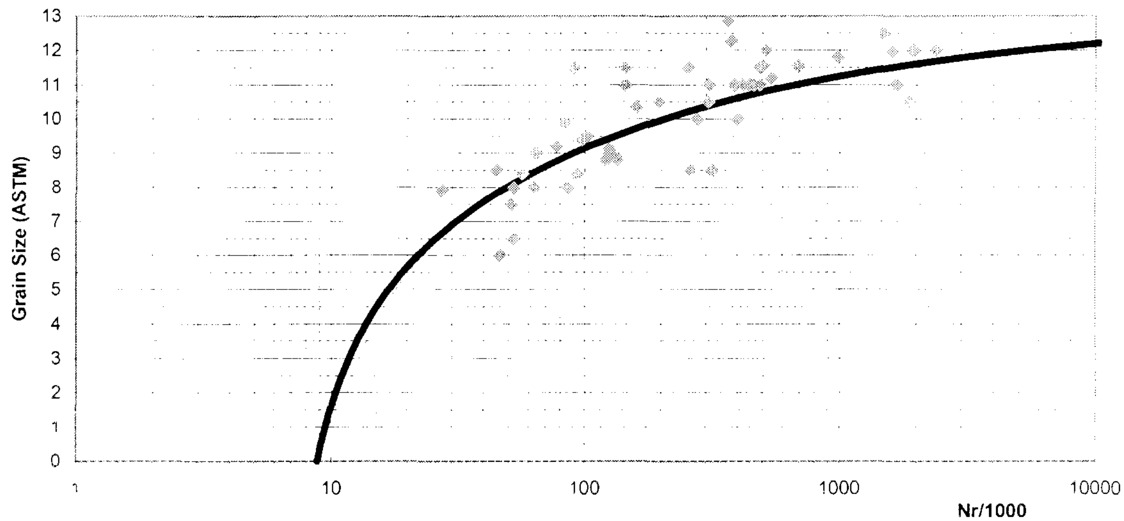


Figure 6 : Life cycle fatigue behavior, based on experimental data, without taking into account crack initiation on surface carbide

Loading conditions : T°=350°C and $\Delta\varepsilon$lt. = 0.62%

◆ Experimental data

------- One parameter law

▬▬ Three parameters law

Then, we used the mathematical model to overwrite the calculated fatigue life to the Wöhler curves used in designing new parts. Once again, we notice a good agreement (figure 7), even though we observe some discrepancies for very fine microstructure and high strain or stress loading. We notice also some discrepancies for coarser loading where experimental data are not very tremendous.

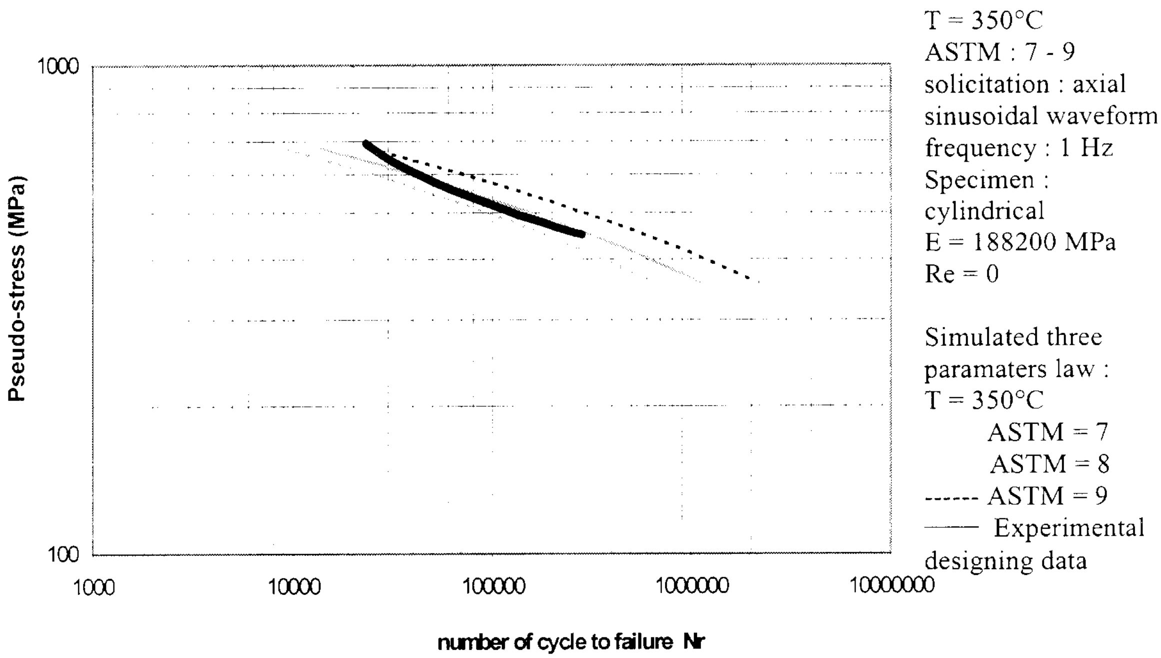
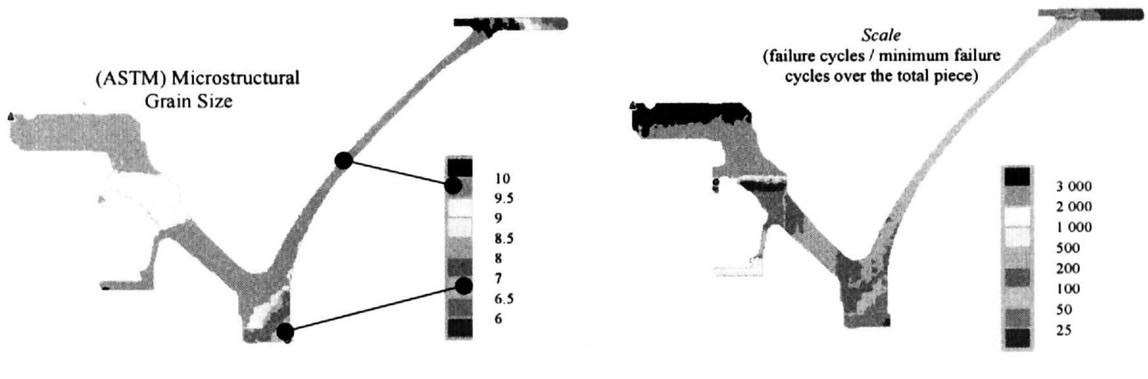


Figure 7 : Comparison of experimental data with simulated fatigue life for a given microstructure (ASTM 7-9) and a given temperature

This model have advantages and disadvantages. First, this model is realistic since the parameters can be physically interpreted in relation to the grain size – life curve. But this model has been established for a given set of specimen tested in low cycle fatigue conditions for precise geometry, frequency rate and surface finish. It has not been validated for extrapolated conditions such as beyond parameters covered by the test data and can therefore predict unrealistic behavior where the fitting suffer a lack of data or where fatigue crack initiation on carbides become prominent and can not be neglected anymore.
Strain range appears to be the independent variable that have the largest effect on cycle life of alloy 718, whereas temperature has little effect on the strain life behavior. The grain size affects also the fatigue behavior of alloy 718 and larger grain sizes consistently show a reduction in cycle life, as already demonstrated by Pieraggi and Uginet [6].
Finally, surface finish has been considered in another study, which is not reported in this paper in order to see its impact on fatigue life behavior. If US peening can considerably increase the number of cycles to failure on smooth specimen, reverse results can be observed on notched samples according to the scratch tolerance and also at which temperature the test is performed [7].

Over 2750 data points were used to perform the curve fitting analysis and lead to describe the fatigue life as a function of strain range, temperature and grain microstructure. The main conclusions of this work can be summarized as follows. A fatigue life model set on experimental data has been developed and predicts successfully in the determination range the number of cycles to failure with good accuracy for standard fatigue initiation on grains. This model has been introduced in FORGE2 and is used to predict the fatigue life according to the microstructure induced by the deformation process. An example is given below, as an application of the law in the simulation codes (figure 8), for a low pressure turbine driving cone.



(a) (b)

Figure 8 : FORGE2 simulated application for a low pressure turbine driving cone
(a) : Calculated microstructural grain size map
(b) : Deduced LCF prediction map (normalized scale) as a function of grain size, temperature and strain controlled loading during in service conditions

Application and perspectives

Short-term benefits of numerical simulation

Numerical simulations enable to get direct cost saving by helping to identify causes when production problems occurs in existing process. Such tools are also very powerful to optimize new processing routes in relation with required metallurgical criteria, without being obliged to test each proposed range. Manufacturers thus gain in rapidity without wasting test pieces. In the same way, the process can be optimized, regarding the mechanical properties in the development step, with a reduced risk, and it creates a real concurrent engineering between designers, manufacturers and quality controllers.

Long-term benefits of numerical simulation

The use of such simulation models also helps to always better understand which physical mechanisms are involved in the materials during deformation and to better control the phenomena by defining the most relevant parameters. Consequently, this is a precious tool to acquire rapidly the know-how and to reinforce our expertise in forging. Secondly, when changing a process parameter (forging temperature, initial billet diameter, final work-hardening rate), simulations can help to settle a new forging range with the final expected parameters and also help to confirm the reliability of the operating ranges (confidence interval on the in and out parameters, expected matrices filling ...). This helps to define the robustness of new forging processing routes and to evaluate the limit of existing ones.
Considering the mechanical properties maps with the expected ones, we can be led to modify easily the process in order to improve an average mechanical property, to reduce a scatter or to adjust a local value to the local future loading. These simulated data can be further used by designers to stress new discs due to expected mechanical properties. This can imply reduction

in weight, life time increase for existing engines, as well as increase of allowable strains, thus of total overload with an equal estimated life time.

Conclusion

As the relationship between microstructure and low cycle fatigue is widely established, the grain initiation results have been used to propose a behavior law relating thermo-mechanical engine data (temperature, stress-strain), grain size and LCF life. Other parameters such as frequency or strain ratio are fixed. This mathematical law can be used in a large scale of temperature and deformation ([200°C ; 650°C] & [$\Delta\varepsilon_{lt}$ = 0.48% ; $\Delta\varepsilon_{lt}$ = 1.24%]) and predict successfully the number of cycles to failure with good accuracy. Some points need more studies and will be considered later. For example, a law could be introduced to formulate the edge carbide initiation behavior by a probabilistic approach.

After the metallurgical study and the settlement of the mathematical law, the result is submitted to the Research Department and the Quality Laboratories or Methods Sections. As an application, the mathematical law relating microstructure with LCF life is introduced in the forging simulation program named FORGE2. Before manufacturing engine parts, the software delivers a LCF life prediction, according to the microstructure induced by the deformation process. Thus, the Methods Sections and the Research Department can communicate with the same simulation tool. The tasks to make the metallurgical data suitable for the FORGE2 metallurgical variables are finished and the way to extract thermo-mechanical data from the Research Department software is currently studied. Here and now, some low cycle fatigue life maps can be seen on the CFM56-5A engine low pressure turbine driving cone.

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