N18, P M SUPERALLOY FOR DISKS : DEVELOPMENT AND APPLICATIONS

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Abstract

The preliminary industrial development of a PM superalloy designated N18 for disc applications has been completed. This alloy is shown to exhibit good overall mechanical properties achieved after appropriate processing of the material. These properties have been determined both on isothermally forged and extruded billets as well as on specimens cut from actual parts.

The temperature capability of the alloy is about 700°C for long-term applications and approximately 750°C for short-term use because of microstructural instability. Further improvements in the creep and crack propagation properties, without significant reduction in tensile strength, are possible through appropriate thermomechanical processing that results in a large controlled grain size. Spin pit tests on subscale disks have confirmed that the N18 alloy has a higher resistance than the PM Astroloy and is therefore an excellent alloy for modern turbine disk applications.

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Introduction

A program on disk superalloy was initiated by SNECMA in 1984, in order to develop a new high strength material for compressor and turbine disks in modern aeroengines (1). The required specifications for mechanical properties were : a high yield strength up to 750°C, and high creep resistance associated with a very good damage tolerance capability up to 650°C, for long term use and up to 700°C for a limited duration. The outcome of this research program is a new patented PM superalloy, N18 (2) containing 55 % γ' strengthening precipitates, and exhibiting a high γ'solvus, i.e.1190°C. The objective of the initial development phase was to optimize the industrial processing of the alloy (3), in terms of powder production and consolidation, microstructural optimization through adequate thermomechanical treatments and to mechanically characterize the alloy at an intermediate scale on 170 mm outer diameter isothermally forged pancakes.

An industrial scale evaluation of the N18 alloy has been completed to confirm the excellent results of the first phase :

- manufacturing of full scale turbine disks according to the optimized route, detailed microstructural and mechanical characterizations on lab test specimens,
- exploration of temperature capability regarding thermal stability and possible improvement of high temperature mechanical strength through microstructural modifications,
- assessment of mechanical behavior by means of spin pit tests on subscale disks, subsequent to thermomechanical treatments representative of actual parts.

These three issues will be developed in this paper.

Full scale turbine disk characterization

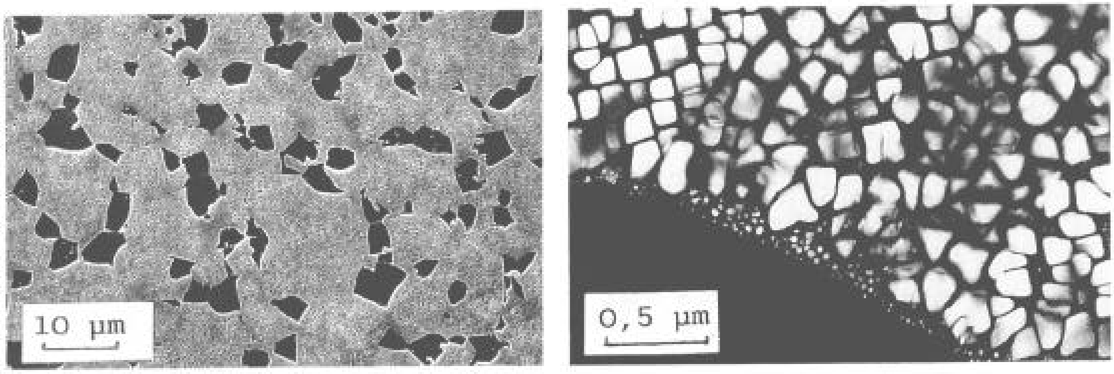
Manufacturing

480 mm outer diameter full scale turbine disks (average thickness 60 to 120mm) were isothermally forged at 1120°C from 200 mesh powder (-75 µm) 230 mm diameter extruded billets. Cleanliness control, achieved by water elutriation, revealed an acceptable ceramic inclusion rate (20 per kg within 65-75 µm range). The disks were finally heat treated as follows :

. 1165°C - 4 h solutioning + delayed oil quenching,
. 700°C - 24 h air cooling + 800°C - 4 h air cooling (aging treatments).

Microstructural investigations

A homogeneous microstructure is observed in the inner zone of the disk (7 to 10 µm) (Fig. 1) while slightly coarser grains are revealed in the external zones (10 to 15 µm). The size of the secondary γ' varies from 0.15 to 0.30 µm, the smaller sizes are found in the outer part of the disk.



a) b)

Fig.1-Microstructure of N18
a) grain size and primary γ' population
b) secondary and tertiary γ' population

Cooling rates after solutioning treatment were measured by thermocouples located at the bottom of holes drilled in different areas of the disk, and the results are quite consistent with microstructural investigations : the coarser sizes (0.30 µm) are associated with lower cooling rates (65°C/mn) while the finer ones (0.20 µm) can be correlated to the highest cooling rates in the considered locations of the disk (170°C/mn). A diagram plotting γ' size versus quenching rate (up to 1000°C/mn) has been drawn (4) and compared to two other PM superalloys (Fig. 2). A nearly constant slope is observed for all materials which indicates a similar sensivity to cooling rates. Moreover, examination of figure 1b highlights the presence of very fine tertiary γ' precipitates of about 0.02 µm.

Mechanical characterization

A large number of specimens were cut from several disks to perform lab tests for mechanical properties such as tensile, creep, low cycle fatigue and crack propagation, data which are mandatory for design purposes (5).

Tensile properties The ultimate tensile strength remains quite high (> 1500 MPa) up to 550°C and then decreases down to 500 MPa at 900°C. Similarly, the yield strength is almost constant, about 1050 MPa up to 700°C and then decreases, to 450 MPa at 900°C (Fig. 3).

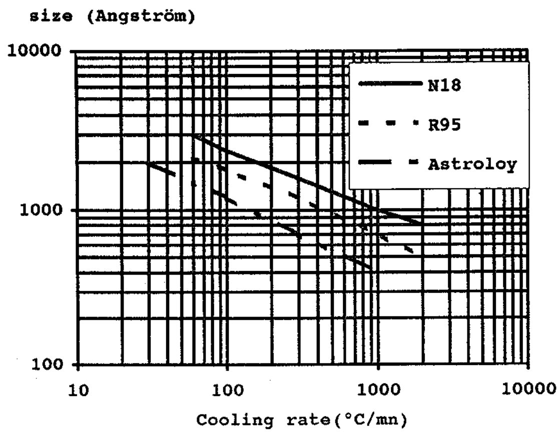


Fig.2-Effect of cooling rate on the mean size of the secondary γ′population

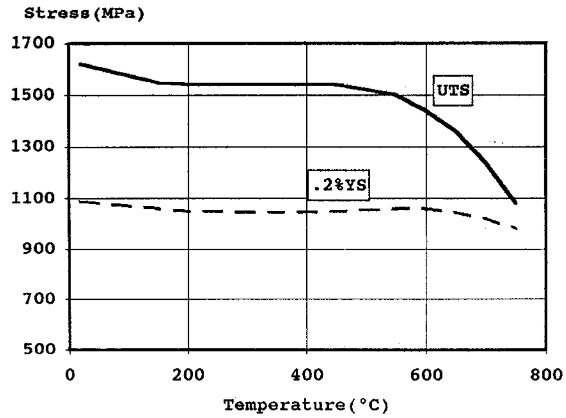


Fig.3-Variation of tensile strength of N18 with temperature

A correlation has been established between the quenching rate (and consequently, the secondary γ′ size) and the monotonic mechanical properties : between 65 and 170°C/mn, corresponding to the γ′size evolution from 0.30 to 0.20 µm, a limited increase in both yield and ultimate stress (about 10 %) is recorded for N18 (Fig. 4). Such tendencies are commonly observed on superalloys (6).

<u>Creep</u> The good creep resistance, which was a requirement of alloy specifications, has been confirmed at 650, 700 and 750°C (Fig. 5). A comparison with reference alloys, such as INCO 718 and Astroloy, clearly shows the advantage of N18 (Fig. 6). It should also be noticed that the stress rupture elongation is close to 10 % for the above considered temperatures.

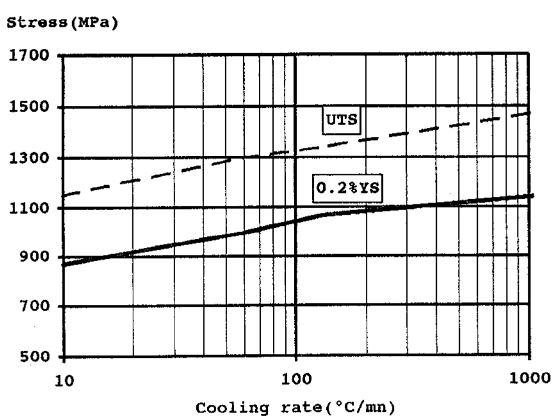


Fig.4-Effect of cooling rate on tensile strength of N18 at 650°C

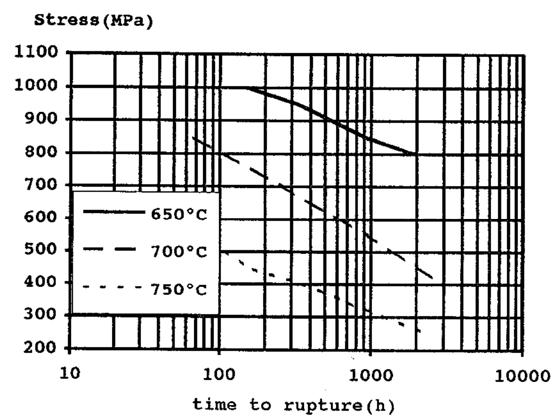


Fig.5-Mean stress rupture properties of N18 at different temperatures

<u>Low cycle fatigue</u> In modern turboengines lives are generally limited, in service, by cyclic damage associated with high loading amplitude variations at low frequencies due to

operating conditions. Therefore, the low cycle fatigue resistance of N18 was characterized in the temperature range 200-650°C, by a large number of strain controlled LCF tests (about 300). Cylindrical specimens (10 mm in diameter, gage length 20 mm) were tested using a sine wave (0.5 Hz) under repeated strain controlled ($R\epsilon = 0$). A large scatter in lives is recorded, which is commonly noticed in PM superalloys (7) (Figure 7).

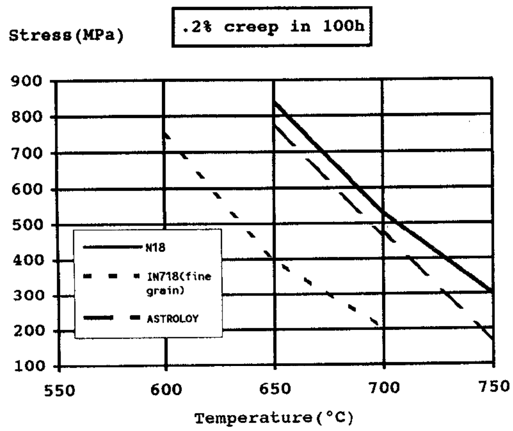


Fig.6-Comparison of creep resistance of N18 with reference alloys

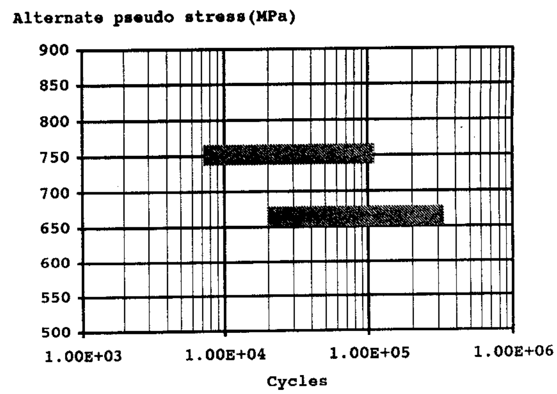


Fig.7-LCF scatter at 550°C

Fractographic SEM investigations on failed specimens have shown that in almost all cases, the crack initiation sites are metallurgical defects regardless of the test temperature, i.e. ceramic inclusions or porosities :

- at high loading levels, surface defects appear to be the most detrimental for 70 % of crack initiation sites. Surface crack initiations occur even around quite small size defects (down to 30 µm). A large amount of crack initiations around porosities (85 % of surface initiations) indicate that these defects are statistically much more numerous than ceramic inclusions, due both to the significant improvement of powder cleanliness and to the high solutionning temperature which causes the coarsening of the argon bubbles entrapped inside the powder particles during atomization.
- at low loading levels, large internal inclusions, up to 200 µm, are mainly the cause of crack initiation (80 % of crack initiation sites) with scarce subsurface small inclusions or porosities.

Such qualitative observations have been previously made on PM Astroloy (8). In this case, the minimum fatigue lives are observed for surface crack initiations, and it is noticed that the crack nucleation period is dramatically reduced : the experimental fatigue lives are in good agreement with crack propagation calculations.

Crack propagation The above comments clearly indicate that the fracture mechanics concepts will be necessary for life predictions in PM superalloys (9). Therefore, a detailed

crack propagation characterization has been carried out on N18, using short crack specimens (8), considering temperature and frequency variations of 400 to 700°C and 3.10^{-3} to 5.10^{-1} Hz, respectively.
At 0.5 Hz, the crack growth rate increases by a factor 3 to 4 between 400 and 650°C, but only by a factor of about 1.5 between 650 and 700°C (Fig. 8). At 650°C, no frequency effect is evidenced up to 10^{-2} Hz, but an increase of a factor about 3 is noticed for the crack growth rate at 3.10^{-3} Hz. Such effects are commonly observed in superalloys (10) but it should be emphasized that N18 is much less sensitive to dwell time at high temperature than reference alloys such as INCO 718 and PM Astroloy, (Fig. 9).

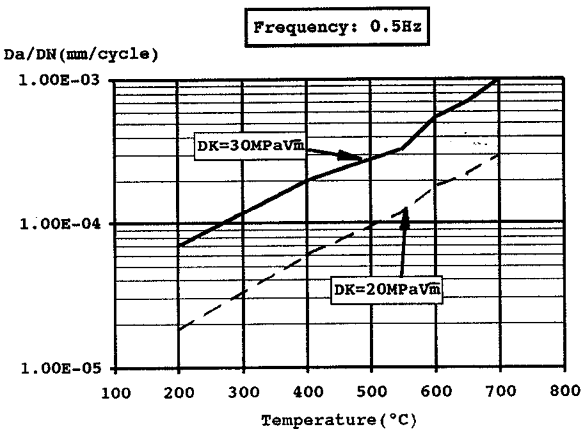


Fig.8-Variation of crack growth rate of N18 with temperature

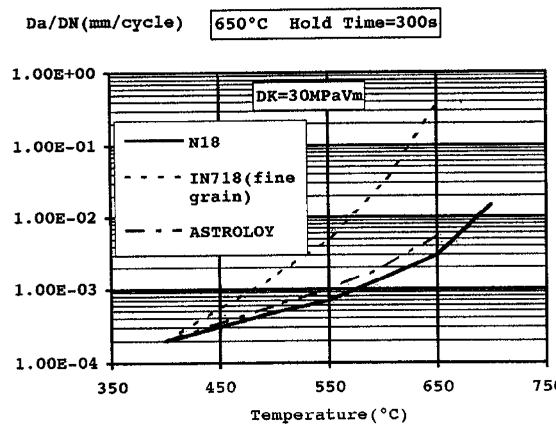


Fig.9-Comparison of crack growth rate of N18 with reference alloys

The fractographic investigations on failed specimens indicate a totally transgranular propagation mode up to 550°C, a mixed mode at 600-650°C and 0.5 Hz frequency, and an intergranular mode at lower frequencies ($\leq 10^{-2}$ Hz) and/or higher temperatures : the mechanisms responsible for these different modes require careful and detailed analysis in relationship with the microstructure and the chemistry of the alloy.

Exploration of N18 potential

Temperature capability

Although the alloy is designed for continuous application up to about 700°C (1-3), the overaging behavior of N18 was assessed after the following post-heat treatment conditions :
① 700°C - 2000 h ② 750°C - 500 h
Microstructural investigations revealed that neither the grain size nor the primary γ' size (3-5 µm) are modified by such overaging treatments.
The secondary γ' size remains unchanged after overaging ①, but increases to 0.3 - 0.35 µm for overaging ②. As expected, both post-heat treatments lead to numerous precipitates of

intergranular carbides ($M_{23}C_6$ type) and platelets, which could be M_7C_3 type carbides or σ phase (Fig.10). A stability diagram has been established (Fig. 11), showing that the platelets are observed after 1000 h dwell time at 700°C, and only after 300h at 750°C, but an intergranular carbide coalescence is noticed for shorter times.

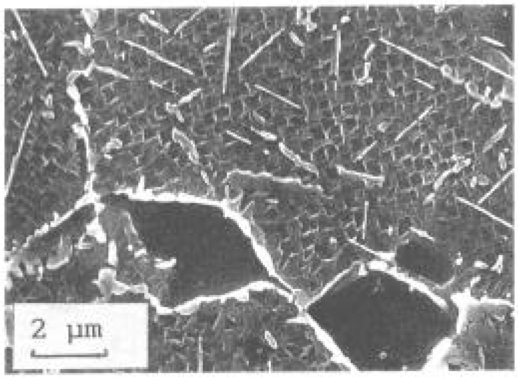


Fig.10-Microstructure of N18 after aging (10.000h at 700°C)

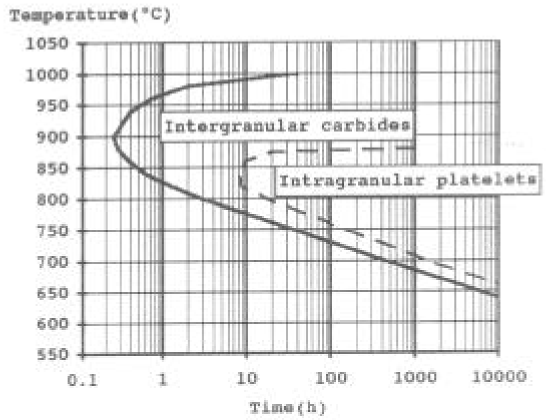


Fig.11-Stability diagram of N18

The influence of such phases on mechanical properties has been studied. The tensile strength is not significantly affected for both overaging treatments ; however, the ductility at room temperature is strongly reduced (20 -> 10 %). This may be due to the starting TCP precipitation (11). The creep resistance at 650 and 700°C diminishes significantly : the time for 0.2 % elongation is reduced by a factor 3 to 8, and times to rupture by a factor less than 2.

On the contrary, the crack propagation tests at 650°C (frequency 3.10^{-3} Hz) show a small decrease in crack growth rate, possibly related to the intergranular carbide precipitation.

The above results clearly indicate that the operating temperature must be limited to 700°C in N18 disks, with possible short time excursions up to 750°C.

Grain size effect

An improvement of high temperature (650 - 750°C) mechanical properties can be expected especially in creep, by modifying the grain size. Coarse grained N18 microstructures have been achieved through a supersolvus solutioning treatment (1200°C) followed by slow cooling to 1165°C.

Heterogeneous grains sizes (50 to 300 µm) are observed. The microstructure exhibits serrated grain boundaries, with large intergranular primary γ' (Fig.12). The mechanical tests indicate that the tensile properties at 650 and 750°C are slightly lowered (5 to 8 % in stress) while the ductility is much more affected (10 to 30 % decrease). At 700 and 750°C, the creep resistance is dramatically improved, by a factor of

5 to 30, in terms of lives (Fig. 13). The same effect, as expected (12), is observed for the crack propagation rate, which diminishes by a factor of about 5 to 10 at 730°C - frequency 3.10^{-3} Hz.
Nevertheless, long dwell times at such high temperatures are not allowed because of the stability considerations. Therefore, even if the above results appear to be quite promising for high temperature properties improvement, the mechanical resistance at lower temperature (especially fatigue resistance) needs to be assessed. Moreover, an appropriate thermomechanical treatment has to be developed to allow a controlled grain size increase in large parts.

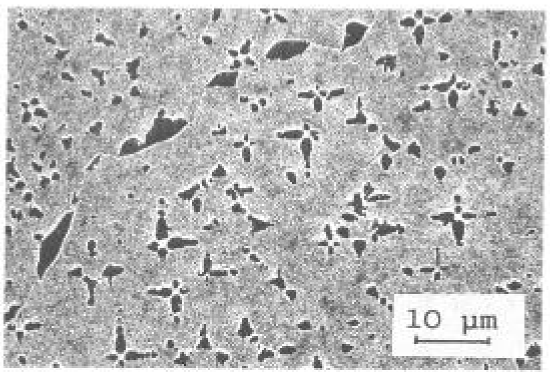


Fig.12-Microstructure of coarse grain N18

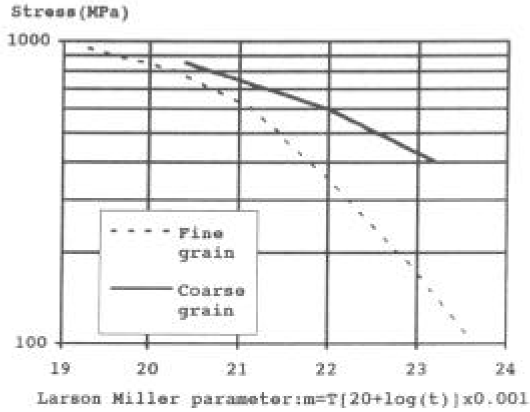


Fig.13-Improvement of N18 creep properties by grain size coarsening

Spin tests

The N18 mechanical characterization on lab specimens has been complemented by bench tests on subscale disks, which allow to assess the behavior of the alloy in conditions, representative of large scale processing and production of disks : machining and surface conditioning, complex stress state. For PM materials, these tests are all the more attractive since they enable to take into account the scale effect, which is suggested by the large scatter in low cycle fatigue lab tests. In fact, a subscale disk involves a critical loaded volume equivalent to 50 - 100 times a fatigue lab specimen volume. Finally, spin pit tests contribute to get invaluable data for design methodology development (13,14). Disks with a 170 mm outer diameter have been isoforged from 200 mesh powder extruded bars, and then heat treated and machined following industrial practice. Bench cyclic tests have been performed at 600 and 650°C. The loading cycles are imposed through rotation speed variations in 90 seconds, so that at maximum speed, a large volume (≈ 50 %) of the disk is stressed at very high level of stress over 1000 MPa. Previous tests on PM Astroloy disks, with comparable processing, manufacturing and loading conditions, have been performed to allow a comparison between the two alloys in conditions representative of engine disks. The results are presented in Table I :

Table I - Spin tests results

Temperature	Maximum rotationnal speed	Life to rupture Astroloy cycles	N18 cycles
600°C	Low (47.700 RPM) High (53.000 RPM)	5500 to 45000 1000 to 2000	> 20.000 3000 to 5000
650°C	Low (47.700 RPM)	4000	10000 to 12000

It is clear that longer lives are observed for N18 compared to Astroloy (a factor 2 to 3 improvement). Fractographic investigations revealed a transgranular propagation mode for N18, at 600 and 650°C, while in Astroloy, a mixed mode is observed at 600°C and a pure intergranular failure at 650°C : those results confirm the data obtained on lab specimens, and corroborate the improved crack propagation resistance of N18 over Astroloy.

Conclusion

N18 PM superalloy for disks has been investigated in detail for mechanical properties evaluation in order to carefully validate the potential of this material. Lab tests on specimens cut from turbine disks have totally confirmed the excellent resistance to creep and dwell time crack propagation up to 700°C of this alloy, while keeping high tensile properties. The low cycle fatigue lives are closely related to the presence of certain defects, mainly ceramic inclusions or porosities, as is the case in all PM superalloys.

The temperature capability of the alloy in service for a few thousand hours has been determined to be 700°C, and about 500 h maximum at 750°C because of the microstructural stability. Possible improvement of mechanical resistance at 700 - 750°C have been clearly evidenced, by modifying the grain size and morphology. Finally, spin pit tests on subscale disks validate the good mechanical properties determined in lab tests over reference PM superalloys. N18 has thus proved to be an excellent alloy for turbine disks operating up to 700°C, exhibiting a weak dwell time sensitivity which is very favourable to Fracture Mechanics concept application for design.

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