

N18, Powder Metallurgy Superalloy for Disks: Development and Applications

J.Y. Guedou, J.C. Lautridou, and Y. Honnorat

The preliminary industrial development of a powder metallurgy (PM) superalloy, designated N18, for disk applications has been completed. This alloy exhibits good overall mechanical properties after appropriate processing of the material. These properties have been measured on both 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 creep and crack propagation properties, without significant reduction in tensile strength, are possible through appropriate thermomechanical processing, which results in a large controlled grain size. Spin pit tests on subscale disks have confirmed that the N18 alloy has a higher resistance than PM Astroloy and is therefore an excellent alloy for modern turbine disk applications.

Keywords
microstructure, gamma prime; microstructure, grain size; microstructure, inclusions; overaging; powder metallurgy; spin tests; superalloy; turbine disks

1. Introduction

A PROGRAM on disk superalloys was initiated by SNECMA in 1984 to develop a new high-strength material for use in compressor and turbine disks for 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 limited use. The outcome of this research program was a new patented PM superalloy, N18, containing 55% γ' strengthening precipitates and exhibiting a high γ' solvus, i.e., 1190 °C.[2] The objective of the initial development phase was to optimize the industrial processing of the alloy,[3] in terms of powder production and consolidation and microstructural optimization through adequate thermomechanical treatments. It was also desired 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 laboratory 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 article.

2. Full-Scale Turbine Disk Characterization

2.1 *Manufacturing*

The 480-mm outer diameter full-scale turbine disks (average thickness 60 to 120 mm) 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 the 65 to 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)

2.2 *Microstructural Investigations*

A homogeneous microstructure was observed in the inner zone of the disk (7 to 10 μm) (Fig. 1), whereas slightly coarser grains were observed 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.

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/min), whereas the finer sizes (0.20 μm) can be correlated to the highest cooling rates (170 °C/min). A diagram plotting γ' size versus quenching rate (up to 1000 °C/min) 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 sensitivity

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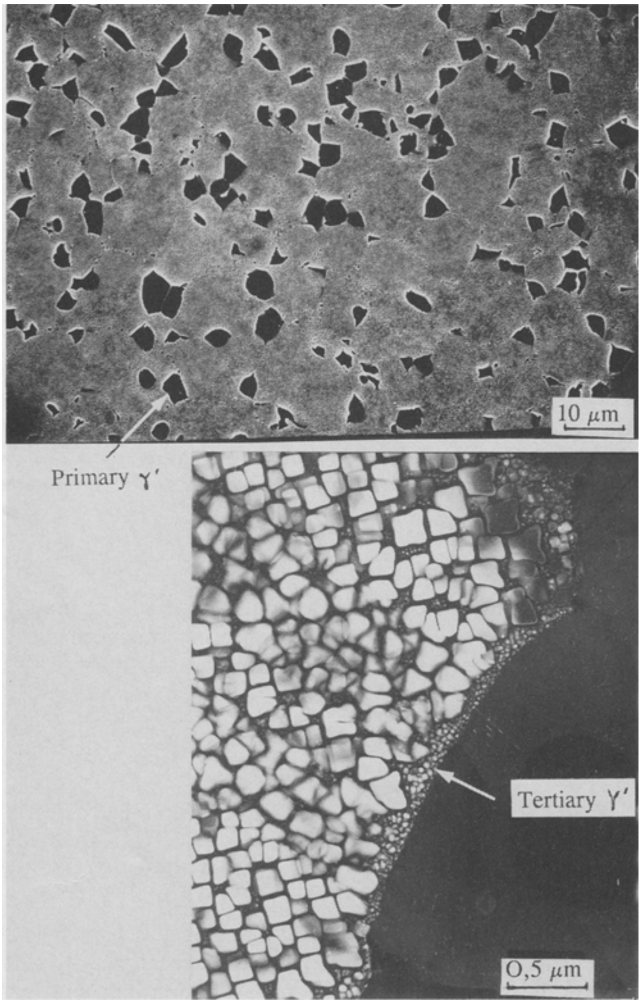

Fig. 1 Microstructure of N18. (a) Grain size and primary γ' population. (b) Secondary and tertiary γ' population.

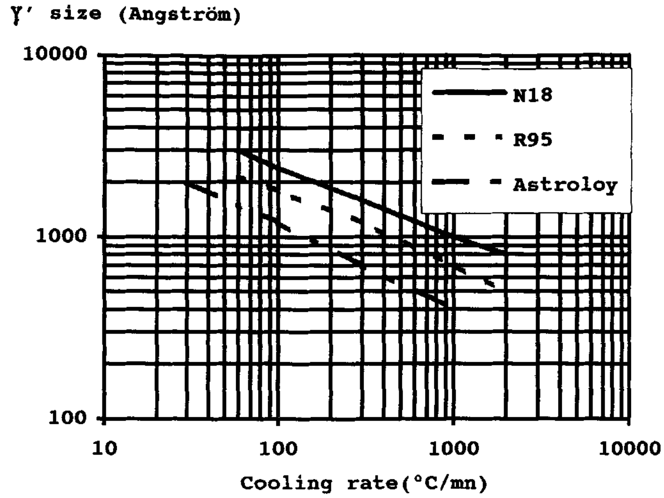

Fig. 2 Effect of cooling rate on the mean size of the secondary population.

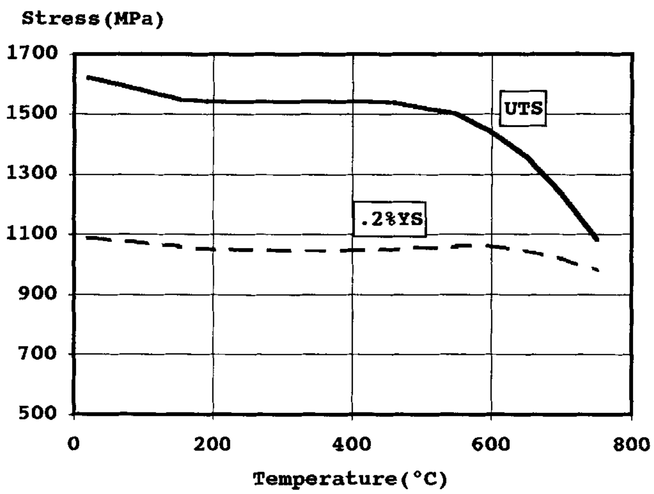

Fig. 3 Variation in tensile strength of N18 with temperature.

to cooling rates. Moreover, Fig. 1(b) shows the presence of very fine tertiary γ' precipitates of about 0.02 μm.

2.3 *Mechanical Characterization*

Numerous specimens were cut from several disks to perform laboratory tests for mechanical properties such as tensile, creep, low-cycle fatigue (LCF), and crack propagation, data which are mandatory for design purposes.[5]

2.3.1 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).

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

2.3.2 Creep

Good creep resistance, which was a requirement of the alloy specifications, was 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 noted that the stress-rupture elongation was close to 10% for the above-mentioned temperatures.

2.3.3 Low-Cycle Fatigue

In modern turboengines, service life is generally limited 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 to 650 °C by numerous strain-controlled LCF tests (about 300). Cylindrical specimens (10 mm in

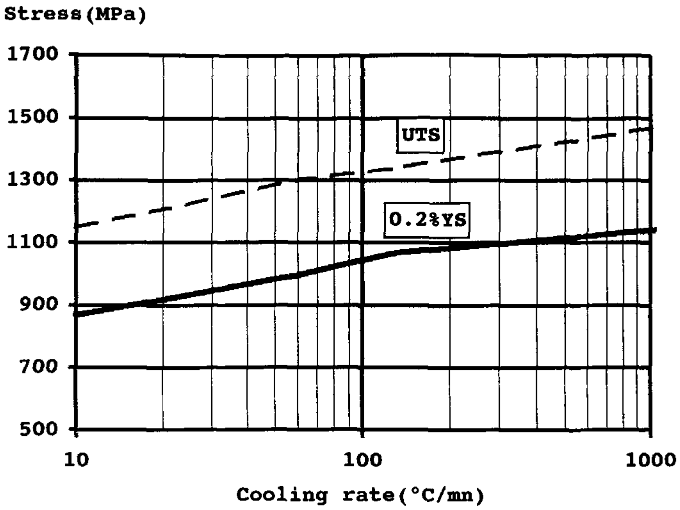

Fig. 4 Effect of cooling rate on tensile strength of N18 at 650 °C.

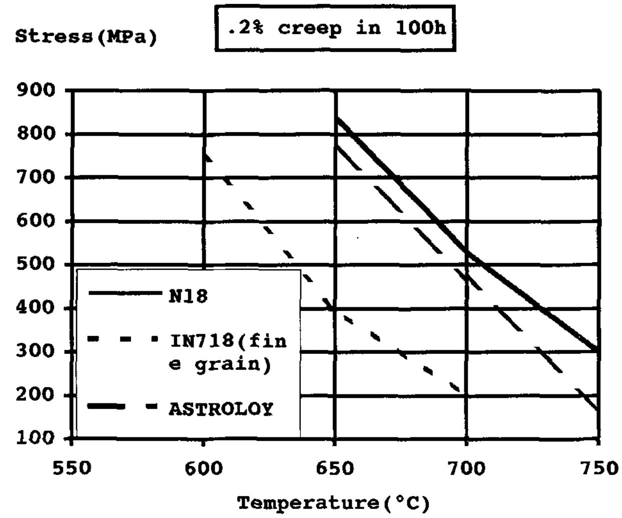

Fig. 6 Comparison of creep resistance of N18 with reference alloys.

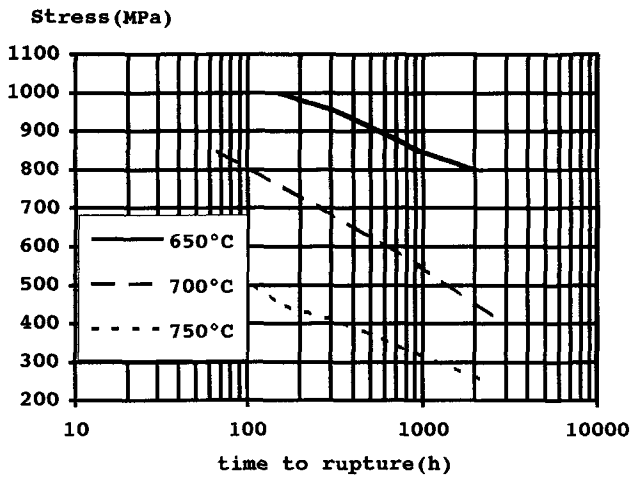

Fig. 5 Mean stress-rupture properties of N18 at different temperatures.

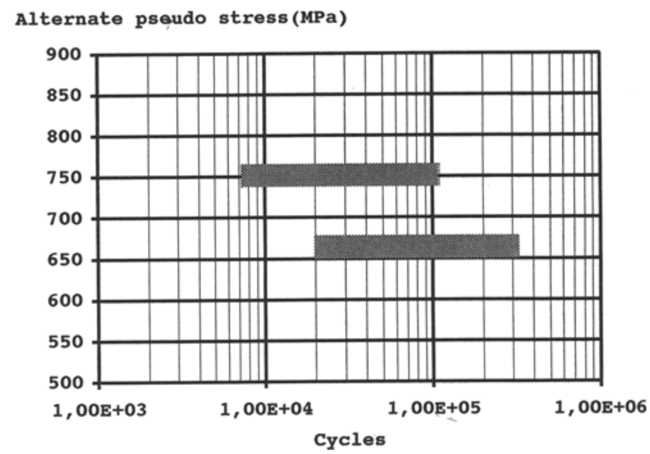

Fig. 7 Low-cycle fatigue scatter at 550 °C.

diameter; gage length, 20 mm) were tested using a sine wave (0.5 Hz) under repeated strain control ($R\varepsilon = 0$). A large scatter in service life was recorded, which commonly occurs in PM superalloys[7] (Fig. 7).

Fractographic scanning electron microscopy (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 defects (down to 30 μm). Numerous 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 solutioning 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 primarily the cause of crack initiation (80% of crack initiation sites), with scarce subsurface small inclusions or porosities. Such qualitative observations have been previously reported for PM Astroloy.[8] In this case, the minimum fatigue life was observed for surface crack initiations, and it is found that the crack nucleation period was reduced dramatically. The experimental fatigue lives are in good agreement with crack propagation calculations.

2.3.4 Crack Propagation

The above comments clearly indicate that use of fracture mechanics concepts will be necessary for life predictions in PM superalloys.[9] Therefore, detailed crack propagation characterization has been carried out on N18, using short crack speci-

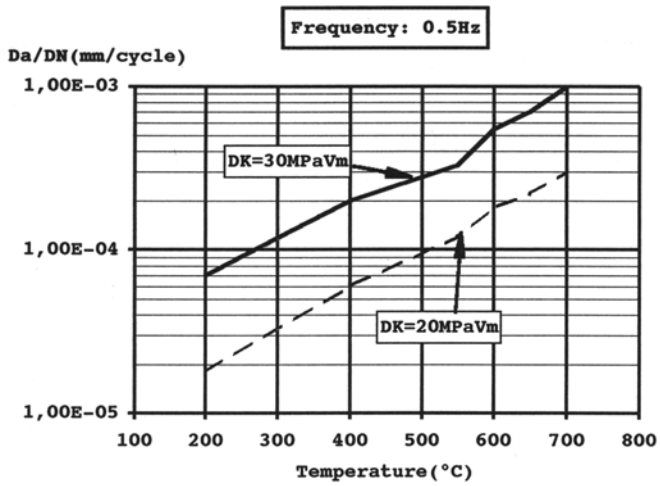

Fig. 8 Variation in crack growth rate of N18 (frequency, 0.5 Hz) with temperature.

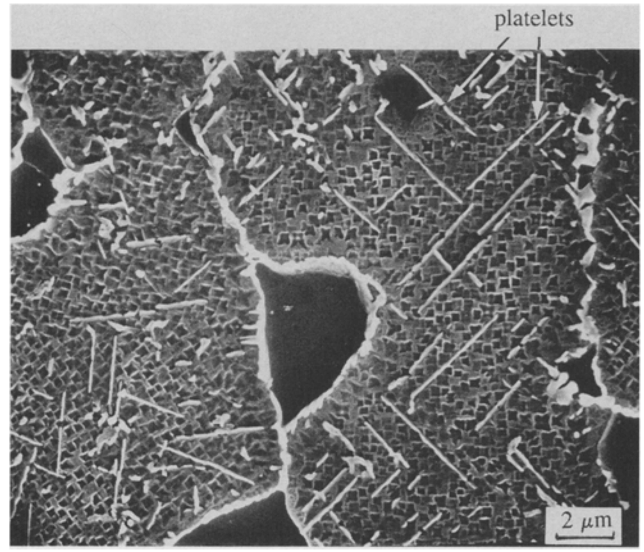

Fig. 10 Microstructure of N18 after aging.

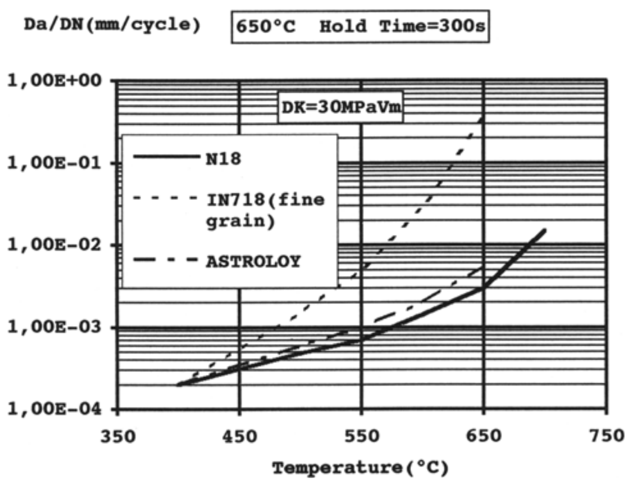

Fig. 9 Comparison of crack growth rate of N18 (650 °C, hold time 300 s) with reference alloys.

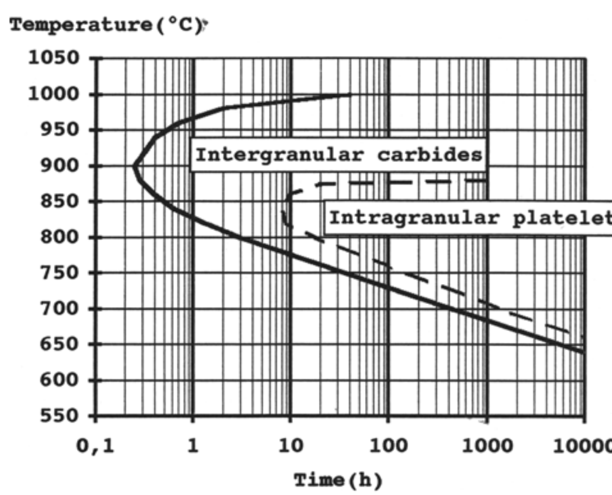

Fig. 11 Stability of critical phases in N18.

mens,[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 increased 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 was evidenced up to 10^{-2} Hz, but an increase of a factor about 3 was 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 temperatures than reference alloys such as INCO 718 and PM Astroloy (Fig. 9).

The fractographic investigations on failed specimens indicated a totally transgranular propagation mode up to 550 °C, a mixed mode at 600 to 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.

3. Exploration of N18 Potential

3.1 *Temperature Capability*

Although N18 is designed for continuous application up to about 700 °C,[1-3] its overaging behavior was assessed after the following post-heat treatment conditions: (1) 700 °C, 2000 h; and (2) 750 °C, 500 h. Microstructural investigations revealed that neither the grain size nor the primary γ' size (3 to 5 μm) were modified by such overaging treatments.

The secondary γ' size remained unchanged after overaging treatment 1, but increased to 0.3 to 0.35 μm for overaging treat-

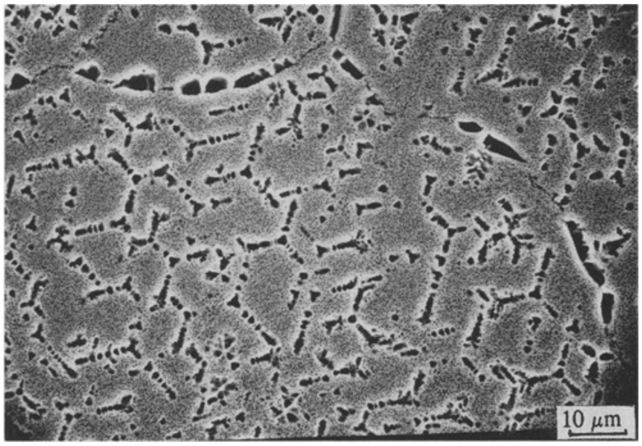

Fig. 12 Microstructure of coarse-grained N18.

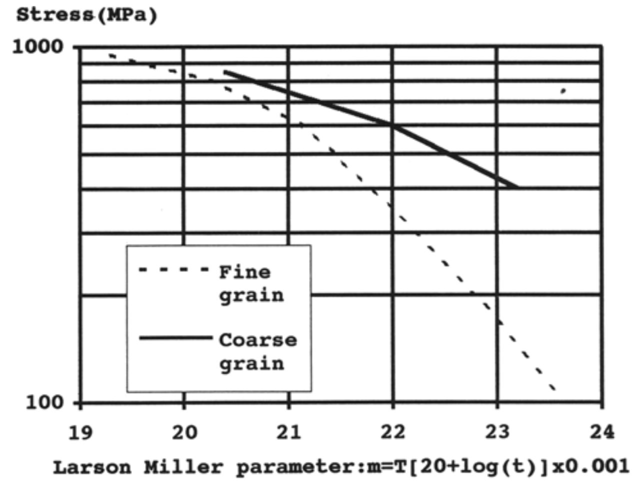

Fig. 13 Improvement in N18 creep properties with grain size coarsening.

ment 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 were observed after 1000-h dwell time at 700 °C and only after 300 h at 750 °C, but an intergranular carbide coalescence was observed for shorter times.

The influence of such phases on mechanical properties has been studied. Tensile strength was not affected significantly for both overaging treatments; however, ductility at room temperature was strongly reduced from 20% to 10%. This may be due to the starting TCP (topological close-packed phases) precipitation.[11] Creep resistance at 650 and 700 °C decreased significantly. The time for 0.2% elongation was reduced by a factor 3 to 8 and time to rupture by a factor of less than 2.

However, crack propagation tests at 650 °C (frequency, 3×10^{-3} Hz) revealed 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 excursions up to 750 °C.

3.2 *Grain Size Effect*

An improvement in high-temperature (650 to 750 °C) mechanical properties can be expected, particularly 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-grain sizes (50 to 300 μm) were observed. The microstructure exhibited serrated grain boundaries, with large intergranular primary γ′ (Fig. 12). Mechanical tests indicated that the tensile properties at 650 and 750 °C were lowered slightly (5 to 8% in stress), whereas ductility was affected much more significantly (10 to 30% decrease). At 700 and 750 °C, creep resistance was improved dramatically, by a factor of 5 to 30, in terms of service life (Fig. 13). The same effect, as expected,[12] was observed for the crack propagation rate, which decreased by a factor of about 5 to 10 at 730 °C and 3×10^{-3} Hz.

Table 1 Spin test results

Temperature, °C	Maximum rotational speed, rpm	Life to rupture, cycles Astroloy	N18
600	Low (47.700)	5500-45,000	>20,000
	High (53.000)	1000-2000	3000-5000
650	Low (47.700)	4000	10,000-12,000

Nevertheless, long dwell times at such high temperatures are not feasible because of stability considerations. Therefore, even if the above results appear to be quite promising for high-temperature property 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.

3.3 *Spin Tests*

The mechanical characterization of N18 laboratory specimens was complemented by bench tests on subscale disks, which assessed the behavior of the alloy under conditions representative of large-scale processing and production of disks: machining and surface conditioning and complex stress state. For PM materials, these tests are all the more attractive, because they take into account the scale effect, which is suggested by the large scatter in low-cycle fatigue laboratory tests. In fact, a subscale disk involves a critical-loaded volume equivalent up to 50 to 100 times a fatigue laboratory specimen volume. Finally, spin pit tests garnered invaluable data for design methodology development.[13,14] Disks with a 170-mm outer diameter have been isoforged from 200-mesh powder extruded bar and then heat treated and machined following industrial practice.

Bench cyclic tests were performed at 600 and 650 °C. The loading cycles are imposed through rotation speed variations in 90 s, so that at maximum speed a large volume (~50%) of the disk is stressed at a very high level of stress of over 1000 MPa.

Previous tests on PM Astroloy disks, with comparable processing, manufacturing and loading conditions, were performed to allow comparison of the two alloys in conditions representative of engine disks. The results are presented in Table 1.

It is clear that longer lives are observed for N18 compared to Astroloy (an improvement of two to three times). Fractographic investigations revealed a transgranular propagation mode for N18 at 600 and 650 °C, whereas in Astroloy a mixed mode was observed at 600 °C and a pure intergranular failure at 650 °C. These results confirm the data obtained on laboratory specimens and corroborate the improved crack propagation resistance of N18 over Astroloy.

4. Conclusion

Use of PM superalloy N18 for disks has been investigated in terms of mechanical property evaluation to carefully validate the potential of this material. Laboratory tests on specimens cut from turbine disks completely confirmed the excellent resistance to creep and dwell time crack propagation up to 700 °C of this alloy, while maintaining 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 several 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 to 750 °C has been clearly evidenced by modifying the grain size and morphology. Finally, spin pit tests on subscale disks validate the good mechanical properties determined in laboratory 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 favorable to the fracture mechanics concept application for design.

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