

N18, A NEW HIGH STRENGTH, DAMAGE-TOLERANT  
PM SUPERALLOY FOR TURBINE DISCS APPLICATION

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Abstract

This paper deals with the main steps of the N18 alloy designed for application in high temperature turbine discs. Emphasis is put on the alloy chemistry and its selection to meet the engine manufacturer requirements. It is shown how a precise control of the grain microstructure may be obtained in this alloy through thermomechanical processing, using the Powder Metallurgy route. Therefore, N18 offers a unique combination of tensile and creep strength together with a high crack propagation resistance compared to other PM superalloys such as IN 100 or Astroloy.

1. INTRODUCTION

In the early eighties, SNECMA initiated a disc alloy development aimed at a material to be used in the hot section of its new engines. In its objectives, it stated explicitly the need for higher strength at medium temperatures as well as improved damage tolerance at 650°C. This programme was conducted with two research laboratories ONERA and CENTRE DES MATERIAUX ARMINES, and an alloy producer IMPHY SA. In 1986, it led to the invention of a new alloy N18 fulfilling all its objectives. After a short justification for this development, the main properties of N18 will be reviewed and compared to those of the existing superalloys.

2. THE NEED FOR A DAMAGE TOLERANT DISC SUPERALLOY

2.1. Evolution of operational requirements

Figure 1 presents an evolution of the operating conditions of engine discs designed by SNECMA over the last twenty years. The trend towards higher stresses and higher materials temperatures, clearly evidenced, reflects the constant drive for improved specific consumptions and higher thrust to weight ratios: it leads to temperatures at the rim of the last stage compressor discs (uncooled) or turbine discs (cooled) of the order of 650°C for the engines currently in development.

2.2. Evolution of materials

Most of present day disc alloys (Table 1) were derived from blade alloys (IN 100) or invented (Astroloy, René 95...), at a time when low-cycle fatigue was acknowledged as the preeminent degradation mode of engine disc materials; for rotating components, a Safe Life would be derived from a fraction of the number of cycles required to initiate an "engineering" crack. With the operational parameters which were then prevalent, that is stress levels, stress gradients, temperatures, it may be said that in most cases this approach warranted implicitly a slow crack

Table 1 - Compared composition of different disc superalloys with N18

Alloy	C	Ni	Co	Cr	Mo	W	Ta	Nb	Hf	Al	Ti	V	B	Zr	Fe
WASPALCOY	0.04	bal.	13.6	19.3	4.2	-	-	-	-	1.3	3.6	-	0.005	0.048	-
IN 718	0.04	bal.	-	18.6	3.1	-	-	5.0	-	0.4	0.9	-	-	-	18.5
IN 100 (LC)	0.07	bal.	18.6	12.4	3.2	-	-	-	-	5.0	4.3	0.8	0.2	0.06	-
MERL 76	0.015	bal.	19.0	11.9	2.8	-	-	1.2	0.3	4.9	4.2	-	0.016	0.04	-
RENE 95	0.08	bal.	8.1	12.8	3.6	3.6	-	3.6	-	3.6	2.6	-	0.01	0.053	-
ASTROLOY (LC)	0.023	bal.	17	15.1	5.2	-	-	-	-	4.0	3.5	-	0.024	<0.01	-
N 18	0.015	bal.	15.7	11.5	6.5	-	-	-	0.5	4.35	4.35	-	0.015	0.03	-
AF2D1A	0.35	bal.	10.0	12.2	3.0	6.2	1.2	-	-	4.6	3.0	-	0.014	0.12	-
AF 115	0.045	bal.	15.0	10.9	2.8	5.7	-	1.7	0.7	3.8	3.7	-	0.016	0.05	-

growth and therefore a certain damage tolerance capacity for the components thus designed.

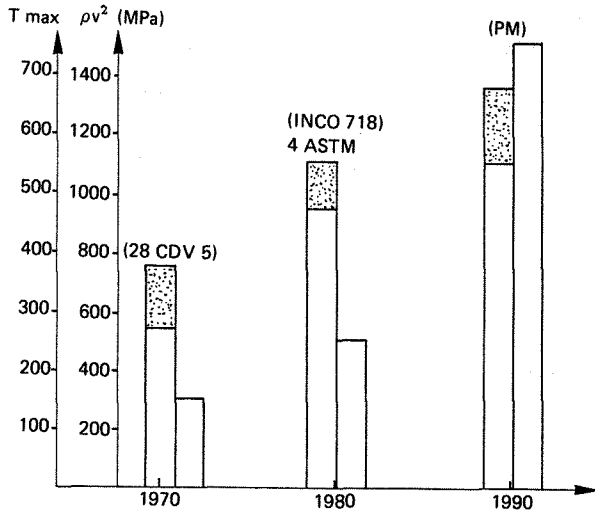


Figure 1 Evolution of temperatures and equivalent stresses within turbine discs for the three last decades

Materials developments and optimizations were conducted within the general framework of this "Lifing Philosophy". It naturally led to the development of more LCF resistant materials: the easiest path in that direction is a microstructural, and more specifically a grain size refinement and a strength increase via an increase in the overall content of hardening elements; the damage tolerance capacity of the engine discs made of these materials was therefore reduced under the double action: increase in operating stresses, decrease in crack growth resistance of fine-grain materials.

The situation was made even worse with the increase in operating temperatures of newer engines: it is now well established [1,2] that above around 550°C there is a noticeable interaction between cracks propagating under cyclic loads and oxygen rich environments. This phenomenon

is time dependent, and is activated by the temperature; two important materials parameters must be noted: alloy chemistry (two materials, low strength Waspaloy and medium strength Astroloy, behave favorably when compared with others) and microstructure. At 650°C, with inadequate materials and microstructures, cyclic crack growth under dwell time conditions may be increased by several orders of magnitude when compared on a frequency basis to 1 Hz cyclic crack growth: this leads to unacceptable damage tolerance for parts operating under such severe conditions.

### 2.3. Objectives

Within this context, SNECMA adopted in the early eighties ASTROLOY PM as a base for its discs development, considering it to present the best balance of properties, strength/damage tolerance, of all existing alloys; simultaneously a program was initiated to improve both properties, so as to reach an increase of 5% in yield strength and a decrease in crack propagation rate by a factor at least equal to three. Additional requirements were imposed upon the material:

- it should be processed by a powder metallurgy route, to insure microstructural homogeneity of the starting stock and good forgeability;
- powder consolidation and part shaping should be made via extrusion followed by isothermal forging, since it is the most reliable mean to impart the high plastic strains which minimize the deleterious effect of reactive inclusions [3]. Moreover, and equally important, it yields billets with excellent ultrasonic inspectability.

### 3. N18 ALLOY DEFINITION

A two phases programme was set up, the first phase being oriented towards the definition of the alloy composition and the second towards a study of the relationship between the microstructures obtained through the PM processing route [4] and the most critical mechanical properties, yield strength, creep and crack propagation resistance.

Table 2 - Main steps of the alloy development

Solid solution hardening of the $\gamma$ phase	Hardening and strengthening of $\gamma'$ phase	Influence of minor elements addition
Influence of chromium content: Ni --> Cr	Influence of the niobium content: Ni --> Nb	Influence of the carbon content (powder surface segregation -> consolidation)
Influence of cobalt content: Ni --> Co	Influence of the balance between Nb and Ta on the alloy's strength	Influence of the boron content
Influence of molybdenum content: Ni --> Mo	Influence of the Ti/Al balance on $\gamma'$ hardening capacity	Influence of zirconium additions
Influence of the balance between molybdenum and tungsten on the solid solution hardening	Influence of the Nb/Ti balance on the $\gamma'$ hardening capacity	Influence of hafnium additions (0 - 1%)
	Influence of the $\gamma'$ phase volume fraction on the alloy's strength	

### 3.1. Alloy chemistry

More than fifty heats were cast, atomized and densified at a pilot scale in order to carry out the alloy composition research work along the three following directions (table 2):

- i) a systematic study of the solid solution strengthening of the gamma phase ( $\gamma$ ) by the elements chromium, molybdenum and tungsten;
- ii) a study of the gamma prime phase ( $\gamma'$ ) hardening capacity of the alloy resulting from both the intrinsic  $\gamma'$  phase strength and its volume fraction. This was done by evaluating the influence of niobium, by substituting tantalum for niobium, by varying Ti/Al and Nb/Ti ratios;
- iii) the role of minor elements addition, such as carbon, boron, zirconium and hafnium. All these elements are required to insure a correct grain boundary strength - as well known, zirconium acts as a trap for sulfur and boron was shown to have a very strong effect on the crack propagation rate. Carbon is known to precipitate mainly under the form of chromium carbides within the grain boundaries, thus increasing their strength within certain limits.

#### 3.1.1. Solid solution strengthening

Molybdenum was shown to be a better solid solution strengthener as compared with tungsten, as far as the specific properties of the alloy are considered. Moreover, substituting tungsten for molybdenum leads to a detrimental effect on notched creep properties (figure 2) [5,6]. As a high hardening of the  $\gamma$  phase was needed, the molybdenum content of the alloy was pushed up to 6.5 wt%.

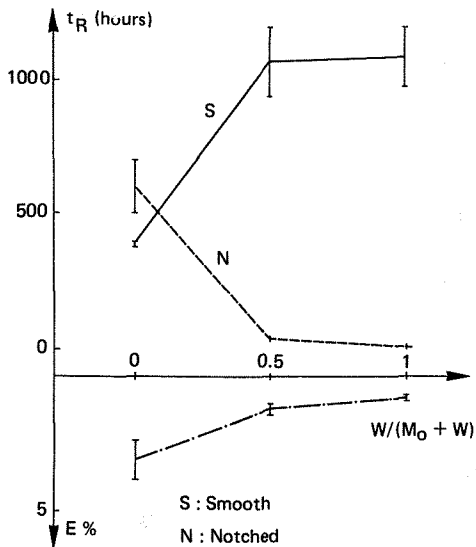


Figure 2 Relative influence of tungsten and molybdenum on smooth and notched creep properties (650°C/1000 MPa)

Cobalt content increase was shown to have an action on both phases ( $\gamma$ ,  $\gamma'$ ) and the microstructure of the alloy: it is the well known lowering of the Stacking Fault Energy (SFE) of the  $\gamma$  phase on one hand, and the change of  $\gamma'$  phase composition and morphology on the other hand. As far as mechanical properties are concerned, it was shown that the influence on strength remains limited, while the creep properties dropped down when the cobalt content falls below 6-8 wt% [7]. On the opposite, a too high cobalt content ( $\approx 18\%$ ) leads to low properties in creep/fatigue tests [8], so that the best cobalt content was shown to lie within the range 15-16 wt%.

The influence of chromium content is illustrated on figure 3, which shows a sharp increase in the 0.2% proof stress with the chromium content from 5 to 15%. However, the chromium content of the alloy was fixed to 11.5 wt% [5,6] for the two following reasons:

- it has a deleterious effect on notched creep rupture strength at 650°C/1000 MPa for contents around 15 %;
- due to the high molybdenum content of the alloy, chromium content has to be limited to insure thermal stability relative to TCP phase formation.

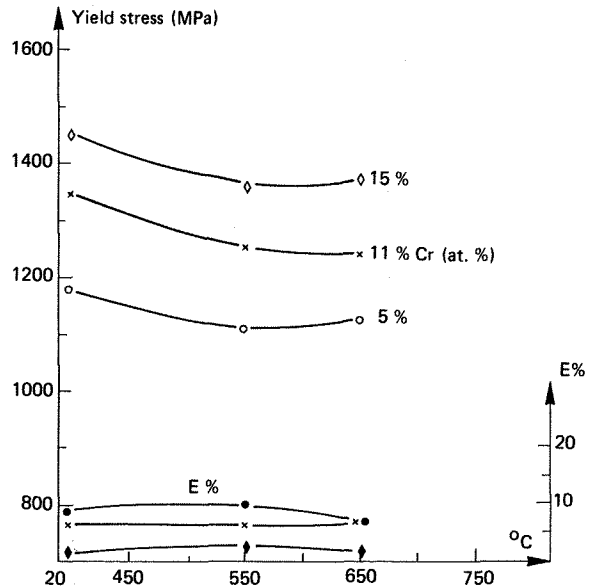


Figure 3 Variation of elongation to rupture and 0.2% yield stress with temperature as a function of the chromium content of the alloy

#### 3.1.2. Gamma prime phase hardening

Substitution of titanium for aluminium has a strong effect on the 0.2% yield stress since replacement of about 4 at% of aluminium by 4 at% of titanium leads to an increase of 150 MPa at 550°C [9].

Niobium has a still stronger effect, since an increase in the niobium content (in replacement of aluminium) from 1.1 at% to 3.8 at% yield a 200 MPa rise in the 0.2% proof stress at the same temperature [9]. As the alloys with a high niobium content were shown to have a rather poor crack

propagation resistance, the substitution of tantalum for niobium was studied despite the increase in density which follows. In fact, the gain in crack propagation rate remained limited, and at 650°C the static properties appeared to be slightly lower [5].

Substitution of niobium for titanium was shown to give a sharp increase in yield strength, but unfortunately a drop in ductility which was far below the specifications at high temperatures (figure 4). It was then decided that, if any niobium should enter the alloy, its content would remain below 1.5 at%. In fact, N18 alloy was designed without niobium.

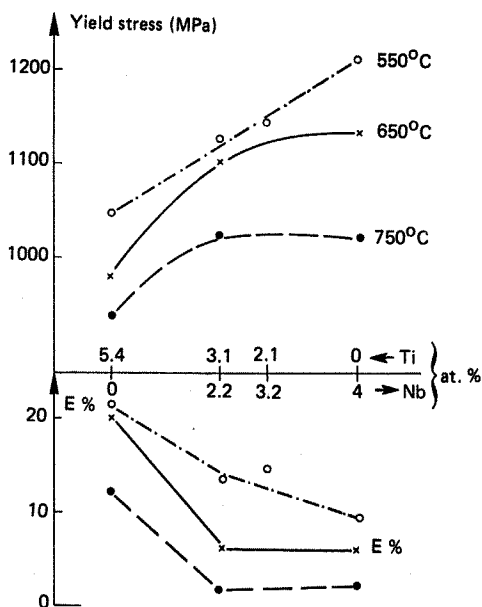


Figure 4 Influence of the substitution of niobium for titanium on the tensile properties as a function of temperature

Finally, the influence of the  $\gamma'$  phase volume fraction was studied in the range 47-60%. High  $\gamma'$  volume fraction alloys were shown to exhibit higher strength but lower ductility, so that the  $\gamma'$  volume fraction of N18 was finally restricted to 55% as compared to 47% in the case of Astroloy.

Table 3 - Compared physical properties of N18 with some other PM superalloys

	$\gamma'$ fraction	$\gamma'$ solvus	Density (g/cm <sup>3</sup> )	N <sub>v</sub>	M <sub>d</sub>
IN 100	61 %	1185°C	7,9	2,471	0,928
MERL 76	64 %	1190°C	7,95	2,591	0,941
RENE 95	48 %	1155°C	8,27	2,217	0,915
ASTROLOY	45 %	1145°C	8,0	2,357	0,926
N 18	55 %	1190°C	8,0	2,361	0,932

\* Some of these alloys were equally processed using the PM route.

### 3.1.3. Minor elements addition

Four minor elements were given some particular attention, i.e. carbon, boron, zirconium and hafnium, in order to optimize the grain boundary properties.

The studies performed on different heats clearly showed that the optimized contents of each of those elements are:

- 300 ppm for carbon;
- 100 ppm of boron for its beneficial effect on all mechanical properties [10];
- 300 ppm of zirconium for its already mentioned ability to suppress grain boundary sulfur segregation;
- 0.5 % hafnium for its positive influence on both static and dynamic mechanical properties.

The completion of all these studies lead to the optimized N18 alloy [11] composition reported in table 1 with some other conventional alloys\* for comparison sake. In table 3 are reported some physical properties of N18 together with those of some currently available PM superalloys. It is worth mentioning the relatively low density of N18 (8 g/cm<sup>3</sup>) as compared to the other alloys.

### 3.2. The grain structure control using the powder metallurgy (PM) processing route

#### 3.2.1. Processing route

The progressing route retained for N18 [12] was aimed at creating a grain structure favourable to damage tolerance and to control it with accuracy within a normal thermomechanical treatment window realistic from an industrial point of view:

- i) powder production is performed using argon atomization followed by a screening down to 106  $\mu$ m (140 mesh) so as to limit exogen particles size;
- ii) densification is done using hot extrusion so as to produce large size billets with a small grain size (3-4  $\mu$ m) > 12 ASTM very well fitted

for subsequent isothermal forging. It should also be pointed out that the fine grain structure allows a smaller size of exogen particles detection by the Ultra Sonic Non Destructive Testing Technique;

- iii) near net shape parts are obtained using the isothermal forging technique: N18 presents a wide range of superplastic behaviour and an excellent forgeability [13];
- iv) final heat treatments are performed so as to develop both the desired grain and  $\gamma'$  particle sizes.

### 3.2.2. Grain structure control using heat treatments

The  $\gamma'$  phase solutioning heat treatments realized in the temperature range 1100-1180°C leads to a large variety of grain size ranging from 4  $\mu\text{m}$  (> 12 ASTM) to 60  $\mu\text{m}$  (5-6 ASTM). This precise grain size control ability over a quite large temperature range, resulting from the solutioning properties of its  $\gamma'$  phase (figure 5), is indeed one of the main advantages of N18 as compared to Astroloy. Figure 6 illustrates two typical grain structures obtained from the following heat treatments:

- i) a fine grain structure (4-5  $\mu\text{m}$ ) (> 12 ASTM) obtained with the 1110°C solutioning treatment results from the presence of a relatively high volume fraction of coarse  $\gamma'$  particles ( $\approx 30\%$ );
- ii) a medium grain size (12-15  $\mu\text{m}$ ) (9-10 ASTM) obtained with the 1165°C solutioning treatment owing to a much lower coarse  $\gamma'$  volume fraction (10-15%).

All the blanks were submitted after solutioning to a quench at a controlled cooling rate (100°C/mn) followed by a two step standard ageing treatment 700°C/24h AC + 800°C/4h AC.

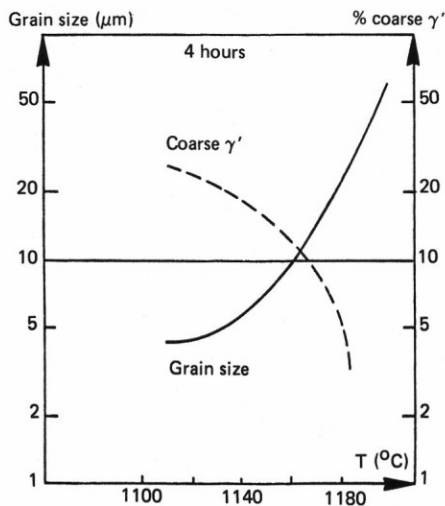
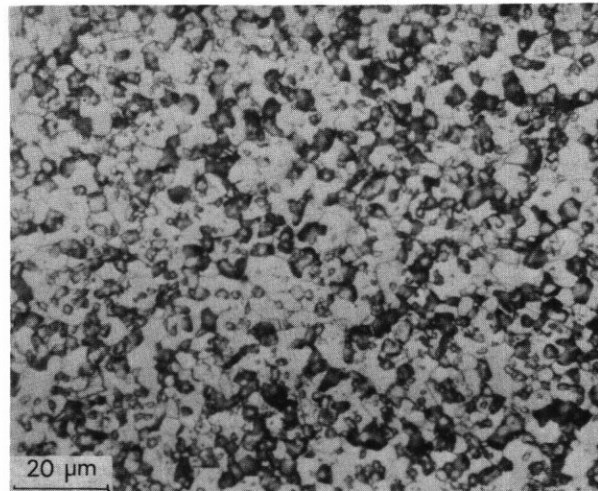
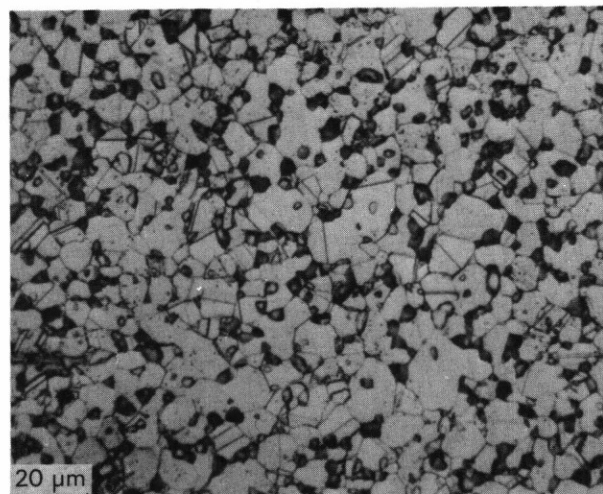


Figure 5 Influence of the solutioning temperature on the residual coarse  $\gamma'$  volume fraction and grain size of N18 alloy



1110°C - 4 h



1170°C - 4 h

Figure 6 Two typical grain structures obtained by isothermal forging at 1110°C and 1165°C respectively

## 4. MECHANICAL PROPERTIES AND THERMAL STABILITY

The mechanical properties of N18 alloy [12] have been evaluated both under static and dynamic loading conditions and compared to those of fine grain Astroloy.

### 4.1. Static properties

Tensile properties of N18 alloy clearly exhibit a net gain relative to those of Astroloy, as illustrated in figure 7, both for the yield strength and the stress to rupture; the elongation to rupture of N18 alloy, which is of the same order of magnitude than that of Astroloy up to 650°C drops above 700°C, but still remains at an acceptable level ( $\approx 10\%$  at 730°C). N18 tensile properties do not appear to be dependent upon the formerly reported solutioning treatments i or ii.

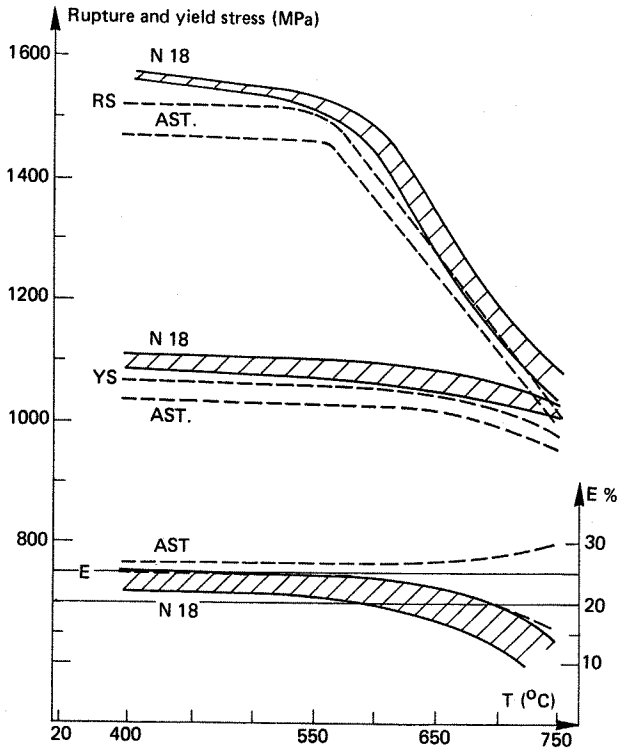


Figure 7 Compared tensile properties of N18 and Astroloy as a function of temperature

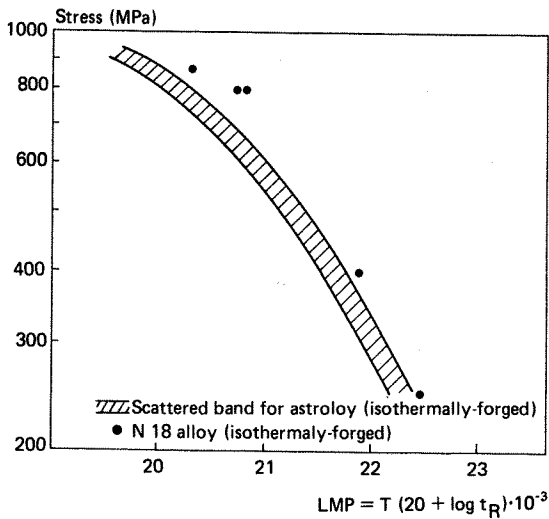


Figure 8 0.2% creep properties of N18 and Astroloy (LARSON-MILLER diagramme)

Creep properties are strongly dependent upon the solutioning treatment as may be expected. Generally speaking, creep rupture lives are equivalent to those of Astroloy in the case of the low temperature solutioning treatment, and above those of Astroloy when the solutioning treatment of N18 is performed at 1165°C, whatever the test temperature in the range 650-750°C. This better creep resistance of N18 as compared to Astroloy results both from the grain size and the  $\gamma'$  phase precipitation, which still remains to be optimized through the aging treatments. Moreover, with the above mentioned heat treatment, i.e. 1165°C/4h/

quench 100°C/min + 700°C/24h/AC + 800°C/4h/AC, the time to reach an 0.2% elongation at 650°C under a stress of 800 MPa for N18 alloy is twice that of Astroloy; the 0.2% elongation creep properties of the two alloys are illustrated in a LARSON-MILLER diagramme in figure 8. It is also worth mentioning that neither Astroloy nor N18 exhibit any notch sensitivity at 650°C.

#### 4.2. Dynamic properties

##### Fatigue behaviour

Both stress and strain controlled low cycle fatigue tests have been performed on N18 and Astroloy for comparison sake. The results obtained with a high peak stress level of 1200 MPa using a sine shape loading curve with a frequency of 0.5 Hz show no net difference between the two alloys. This result simply indicates that, due to its high stress level, this test was more related to the inclusion content of the alloys - almost identical for both Astroloy and N18 processed by the PM route - than of their intrinsic fatigue resistance.

##### Crack propagation behaviour

Crack propagation behaviour of N18 alloy is illustrated on figure 9 with and without a dwell time of 300 seconds at the maximum stress together with the form of the loading cycle. This figure clearly evidences the net gain of N18 with a relatively fine grain structure over fine grain Astroloy, the crack growth rate of N18 being two to three times lower than that of Astroloy, known as a very good damage tolerant disc alloy. The advantage of N18 over gathorized IN100 is still better, the crack growth rate of N18 being one order of magnitude lower than that of IN100.

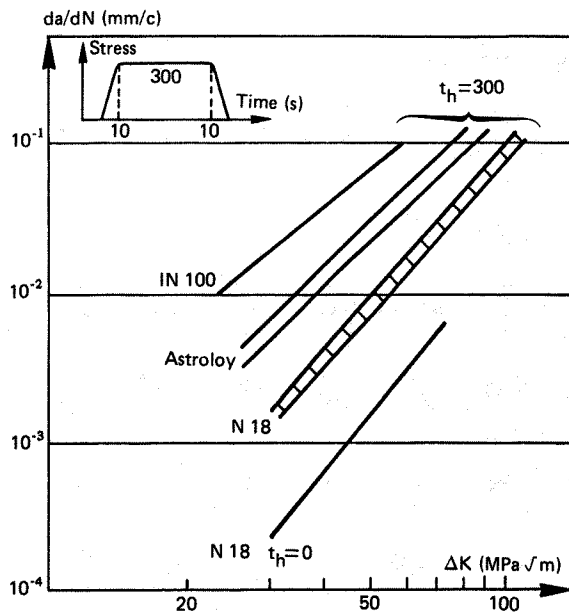


Figure 9 Comparison of the crack propagation rates of N18 alloy, Astroloy and IN 100 as a function of the stress intensity factor

#### 4.3. Thermal stability of N18 alloy

Thermal stability of N18 alloy has been given some more care due to both the high  $\gamma'$  volume fraction and solution hardening elements content of this alloy. The Nv and Md values for N18 are compared in table 3 with those of some currently available PM superalloys. To assess N18 thermal stability, twenty different alloys [14,15] conveniently chosen and several heats with chromium and molybdenum contents lying around that of N18 were then submitted to long term holds (up to 900 hours) at high temperatures (700 and 750°C), with and without an applied stress.

Two main structural modifications were observed after long term ageing:

- i) an increase in the intergranular chromium carbide precipitation with both temperature and holding time;
- ii) formation of limited amounts of small size ( $\approx 1 \mu\text{m}$ ) plate shape precipitates originating from either bulk or grain boundaries chromium carbide particles, which might be identified either as modified chromium carbides or TCP phases.

The amount of these phases was very limited, so that TEM techniques have to be used to evidence them. Another feature which is worth mentioning is that molybdenum appears to be more deleterious compared to chromium, in that sense that raising the molybdenum content by 1 at% leads to a relatively higher level of plate shape precipitates than raising the chromium content of the alloy by the same amount. It was further demonstrated that none of the mechanical properties were modified by that precipitation.

Finally, long term ageing - over 2500h at 700°C - performed at SNECMA further demonstrates the good thermal stability of N18 alloy [13].

#### Conclusions

The new high strength damage tolerant superalloy N18 exhibits a unique combination of several features which makes it particularly suited for application to the discs of modern gas turbine engines operating up to 700°C; this was obtained through:

- a balance of hardening elements which gives it higher static and creep properties than in alloys currently in use such as INCO 718 and Astroloy;
- a chemical composition associated with a medium grain size microstructure, which leads to an excellent damage tolerance capacity at 650°C;
- an excellent processability by powder metallurgy using an extrusion plus isothermal forging route which insures an excellent ultrasonic inspectability of both the billet and final part, as well as a precise control of the microstructure by normal industrial practice.

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