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PROPERTIES OF NEW C&W SUPERALLOYS FOR HIGH TEMPERATURE DISK APPLICATIONS

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Abstract

The enhancement of efficiency in gas turbine engines requires the development of new superalloys capable of withstanding higher temperatures. The development of novel industrial cast and wrought (C&W) disk alloys with required combination of strength, creep and fatigue resistances at 700°C is particularly desired due to the expensive cost of powder metallurgy. In this context, new C&W disk alloys were recently developed to fulfill these requirements. TMW4 shows higher properties than the current C&W disk alloy despite an expensive cost due to its high cobalt content, where as 718Plus presents a moderate cost with restricted creep properties at 700°C compared to the current U720Li disk alloy. The new nickel base superalloys developed by Aubert & Duval were therefore designed to offer a better compromise between high temperature properties at 700°C and cost. This paper describes the alloys metallurgical features and the alloys design partly based on phase diagrams modeling. The study was firstly carried out on small ingots of 6kg to optimize the chemistry before forging by industrial processes 200kg ingots. The ability to be processed by the conventional cast & wrought route and the control of the highly expensive elements contents confer to the alloys an attractive cost comparable to that of 718Plus alloy. The high amount of gamma prime and the molybdenum-tungsten levels insure higher creep and tensile properties than those obtained with 718Plus. Tensile, creep, fatigue, long-term aging tests show that the new alloys have high mechanical properties up to 700°C. Based on these results, it should be possible to extend performance capabilities, in terms of cost and mechanical properties, of most current C&W superalloys for turbine disks.

Introduction

The latest design of high-efficiency engines has high requirements for the mechanical properties and temperature capability of the key components, especially the first stages of disk where the the stress and temperature are the highest. Alloy development for turbine disk with high properties up to 700°C is consequently crucial in order to improve the thermal efficiency in gas turbine engines. 718 alloy which is extensively used for turbine disk is not capable of withstanding temperatures higher than 650°C due to the coarsening of gamma double prime [1-3]. The U720Li, which is strengthened by γ' phase, has a greater temperature capability and can be processed by the conventional cast & wrought (C&W) route [4-5]. This ability to be processed by the conventional route confers to this alloy a moderate cost compared to superalloys produced by powders metallurgy as René88DT, N18, RR1000. However, U720Li is difficult to fabricate by the C&W route due to its high γ' prime content (45%) and can be considered as the limit between C&W route and powder metallurgy route. Because of this and because of its intrinsic raw material content, U720Li is significantly more expensive than alloy

718. TMW alloys were recently developed and present better properties than those of U720Li [6-8]. However, the high cobalt content (table 1) strongly affects the alloys cost which are significantly more expensive than other C&W superalloys. 718Plus presents a moderate cost compared to current C&W superalloys [9-10] due to reasonable cobalt content and presence of iron (table 1), but its mechanical properties are significantly lower than those of U720Li and TMW4. Thus, it can be considered that 718Plus and TMW4 don't improve the compromise between cost and mechanical properties currently offered by U720Li.

In this context, Aubert & Duval has focused its research on developing a new cast & wrought disk superalloy that would have the following requirements:

- mechanical properties close to U720Li and significantly higher than 718Plus
- cost equal to 718Plus and lower than U720Li and significantly lower than TMW alloys
- workability better than U720Li and TMW alloys
- a high microstructural stability in the 700-750°C temperature range
- a density lower than that of 718Plus (< 8.3 g.cm-3)

This paper describes the properties and features of two experimental C&W superalloys developed in this research project: Ni30 & Ni33 alloys.

Alloys features

The new superalloys Ni30 & Ni33 developed by Aubert & Duval have an original chemistry with a similar chemical system to that of 718Plus : Ni-Fe-Co-Cr-Mo-W-Al-Ti-Nb with controlled additions of B, C and Zr. Phase diagram modeling was extensively used to design these new superalloys [11]. The ratio Fe/Co was adjusted to obtain the best compromise between cost and creep properties. Cobalt, which is an expensive element, must be as low as possible to decrease the alloy cost. However, results in 718Plus and Astroloy [10, 12] show that cobalt strongly affects creep properties and can not be suppressed to insure high creep properties. Where as iron strongly decreases alloy cost, this element favors the precipitation of σ phase. The iron content was consequently adjusted to obtain Md parameter value at 700°C (γ chemistry estimated with Thermo Calc software) lower than 0.900. This stability requirement doesn't enable iron content as high as that of 718 alloy. As shown in figure 1, the intrinsic raw material cost of Ni30 and Ni33 alloys (rationalized to 718's) is lower than those of other current C&W superalloys over a period of 3 years. This figure confirms that TMW4 is an expensive alloy (due to its high Co content) compared to 718 and other C&W superalloys. The sensitivity of 718Plus cost to Nb price variations explains that 718Plus cost variations are not similar to other C&W superalloys.
Chemistries of Ni30 and Ni33 alloys contain more elements and are well adapted to scrap recycling: it is possible for example to recycle a part of 718 and other superalloys to fabricate these new superalloys contrary to U720Li, TMW4 and other C&W superalloys. This property consolidates their moderate cost.

	Ni	Fe	Cr	Co	Mo	W	Al	Ti	Nb	B*	Zr*	C*	P*
U500	Bal	-	18	18.5	4	-	3	3	-	60	450	400	-
Waspaloy	Bal	-	19	13.5	4.2	-	1.4	3	-	60	-	700	60
U720Li	Bal	-	16	14.5	3	1.25	2.5	5	-	200	300	250	-
TMW4	Bal	-	15	26.2	2.8	1.15	1.9	6	-	170	200	200	-
718	Bal	18	18	-	3	-	0.5	1	5.4	40	-	250	100
718Plus	Bal	10	18	9	2.8	1	1.5	0.7	5.5	40	-	250	100

Table 1 : Chemical composition (wt%) of various C&W superalloys for turbine discs. (* ppm)

The Al, Ti, and Nb content were adjusted with Thermo-Calc software to obtain a higher γ' fraction at 700°C than that of 718Plus (figure 2). The ratio (Ti+Nb)/Al was carefully controlled to avoid the precipitation of deleterious Ni_3Ti-η phase [13, 11]. Mo and W were adjusted to insure a higher solid solution strengthening than that of 718Plus. Mo + W content in γ matrix at 700°C was calculated with Thermo-Calc software to evaluate the solid solution strengthening provided by these elements: Mo + W content in γ matrix was estimated to be respectively equal to 2.6at% and 4at% in 718Plus and Ni30 & Ni33 superalloys.

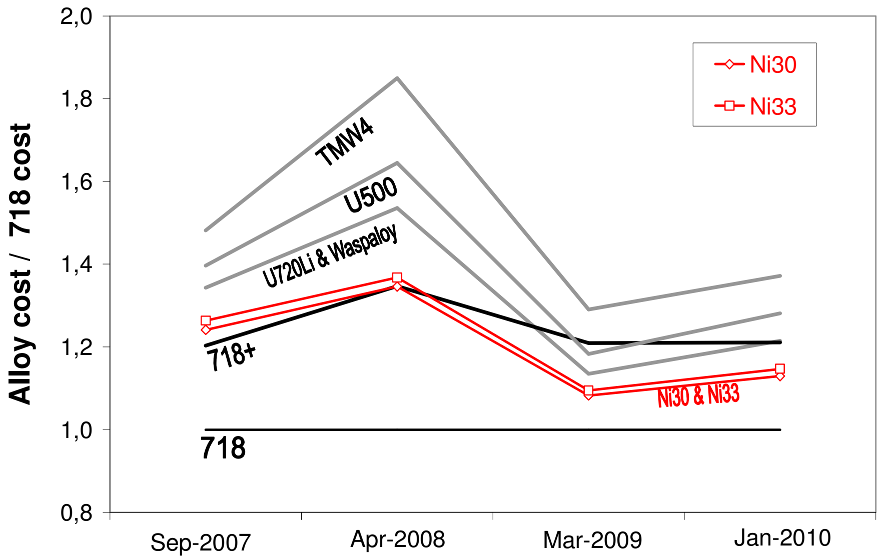


Figure 1 : C&W superalloys cost (cost of alloying elements rationalized to 718's)

Compared to Ni30 alloy, Ni33 alloy has higher levels of Al, Ti and Nb with a similar (Ti+Nb)/Al ratio. This explains that Ni33 has a higher γ' fraction (42%) and a higher γ' solvus (1130°C) than Ni30 according to Thermo-Calc calculations (figure 2).

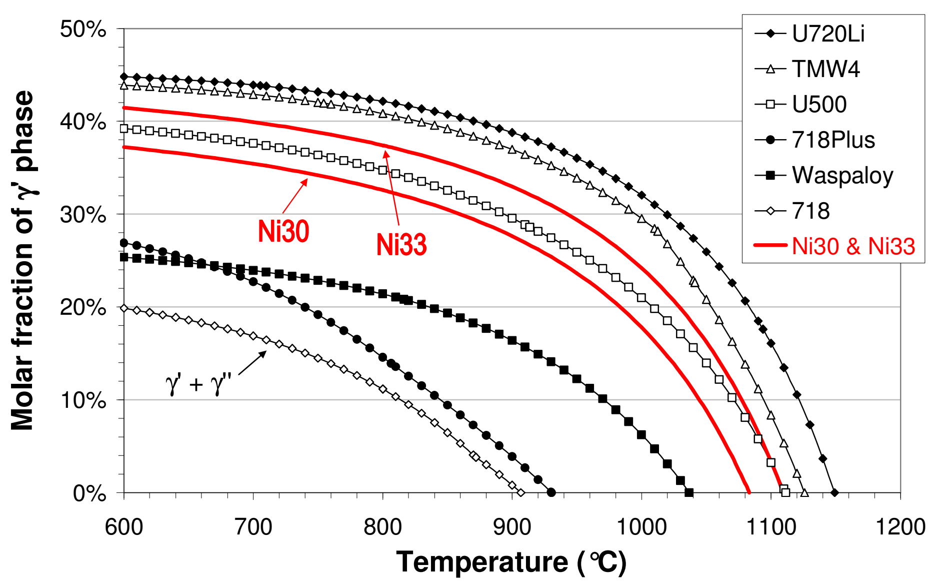


Figure 2 : Molar fraction of γ' with T (°C) calculated by Thermo-Calc software with an internal

database developed by N. Dupin

Alloys processing and microstructure

A first study was carried out to compare the mechanical properties of new alloys with those of 718Plus. Small Ingots of 718Plus, Ni30 and Ni33 were produced through primary vacuum induction (VIM) and hot extruded at 1120°C to 25mm bars (figure 3). 718Plus samples were heat treated with the standard heat treatment 955°C/1h/Air + 790°C/8h/Air + 700°C/8h/Air. Ni30 and Ni33 were subsolvus solution heat treated (1050°C and 1080°C respectively) and aged at 760°C/8h/Air + 650°C/24h/Air.

Ingots in Ni30 and Ni33 were then produced by primary vacuum induction (VIM) and vacuum arc re-melting (VAR). Each of the VAR ingots was 200mm diameter and weighted about 170kg. No defect such as cracks, segregations and pores was observed. The ingots were successfully processed to 80mm diameter billets. Pancakes were successfully upset below the γ' solvus in the temperature range 1050-1100°C. Samples were taken in the pancakes and heat-treated with the following sequence: subsolvus solution heat treatment (1080-1100°C) and air cooling on blanks with a section of 16x16 mm², which can approximate the cooling rate of oil quenched disks. Pancakes of U720Li and 718Plus, which can be considered as references in C&W alloys, were forged to obtain fine grain size. Samples were respectively subsolvus solution heat treated at 1100°C and 955°C, then cooled with the same cooling rate (air cooling on blanks) and aged with their respective standard aging treatments. Results were also compared with typical data obtained on 718 and Waspaloy.

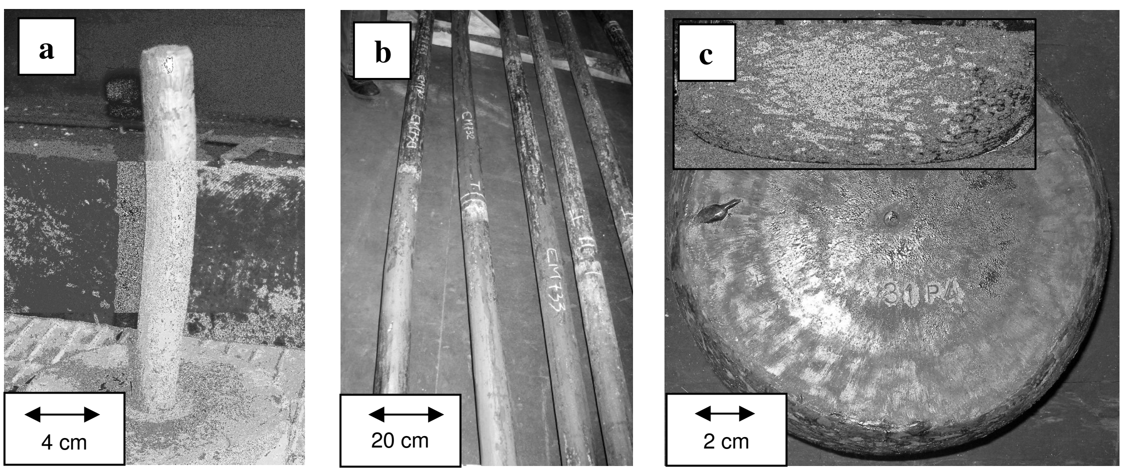


Figure 3: Alloys processing a) Extruded billets from small ingots b) forged billets (80mm diameter) from 170kg ingots c) forged pancakes from 80mm billets

Microstructure examinations on extruded billets from small ingots (figure 4) reveal a homogeneous microstructure with a grain size close to ASTM 5. As expected, intergranular δ phase was observed in 718Plus after full heat treatment. Primary γ' precipitates localized at grain boundaries were not observed in Ni30 and Ni33 alloys due to the temperature of extrusion which was above the γ' solvus. Therefore, a bi-modal γ' distribution was observed inside the grains in Ni30 and Ni33 alloys: the larger (200-300 nm) have coarsened during subsolvus solution heat treatment and the finer (20-30 nm) have precipitated during quenching.

Microstructure of forged pancakes (figure 5) are proper to γ/γ' superalloys which are forged below γ' solvus. Grain size is respectively close to ASTM 8 and 10 for Ni30 and Ni33 alloys. Grain size in U720Li and 718 pancakes are close to ASTM 10: Ni33 can be therefore rigorously compared to these alloys due to their similar grain size and cooling rate after solution heat treatment.

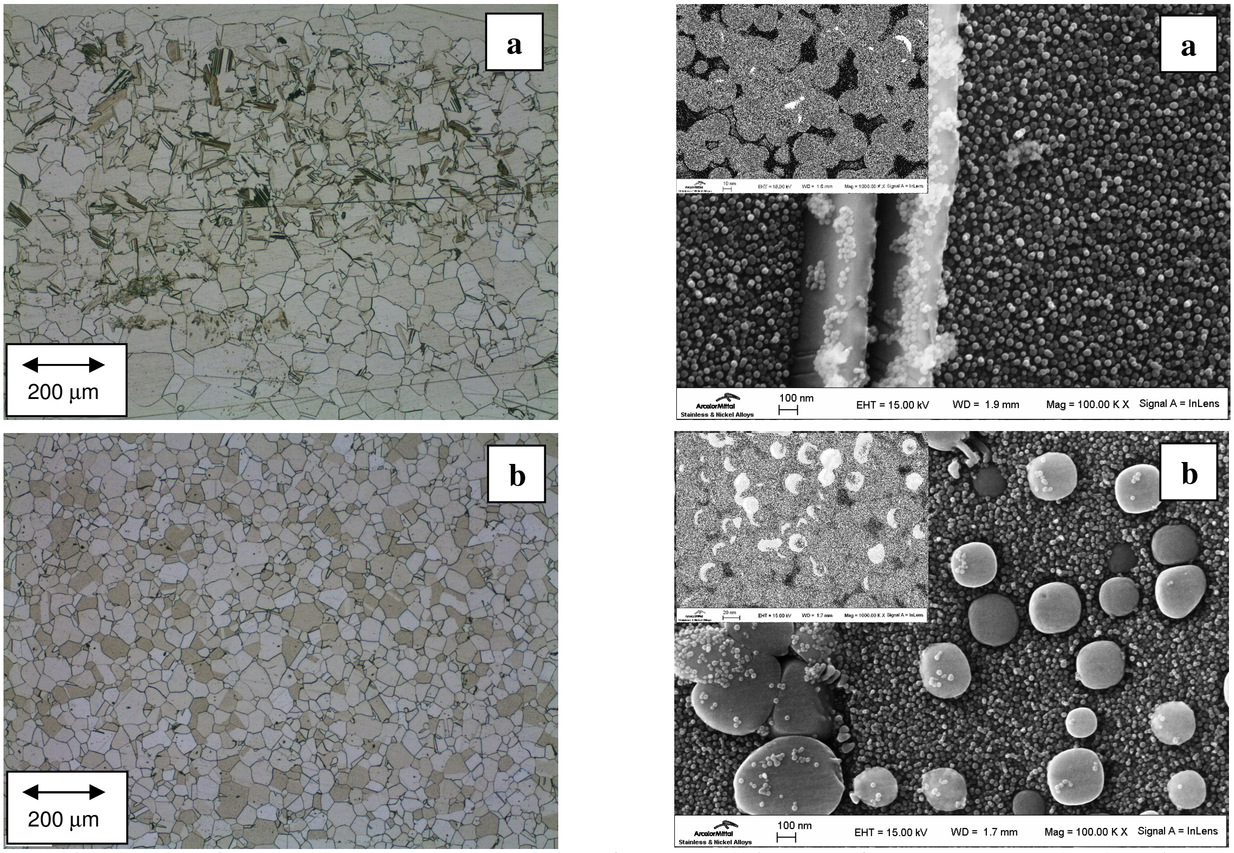


Figure 4 : Microstructure on extruded bars from small ingots after HT a) 718Plus b) Ni30

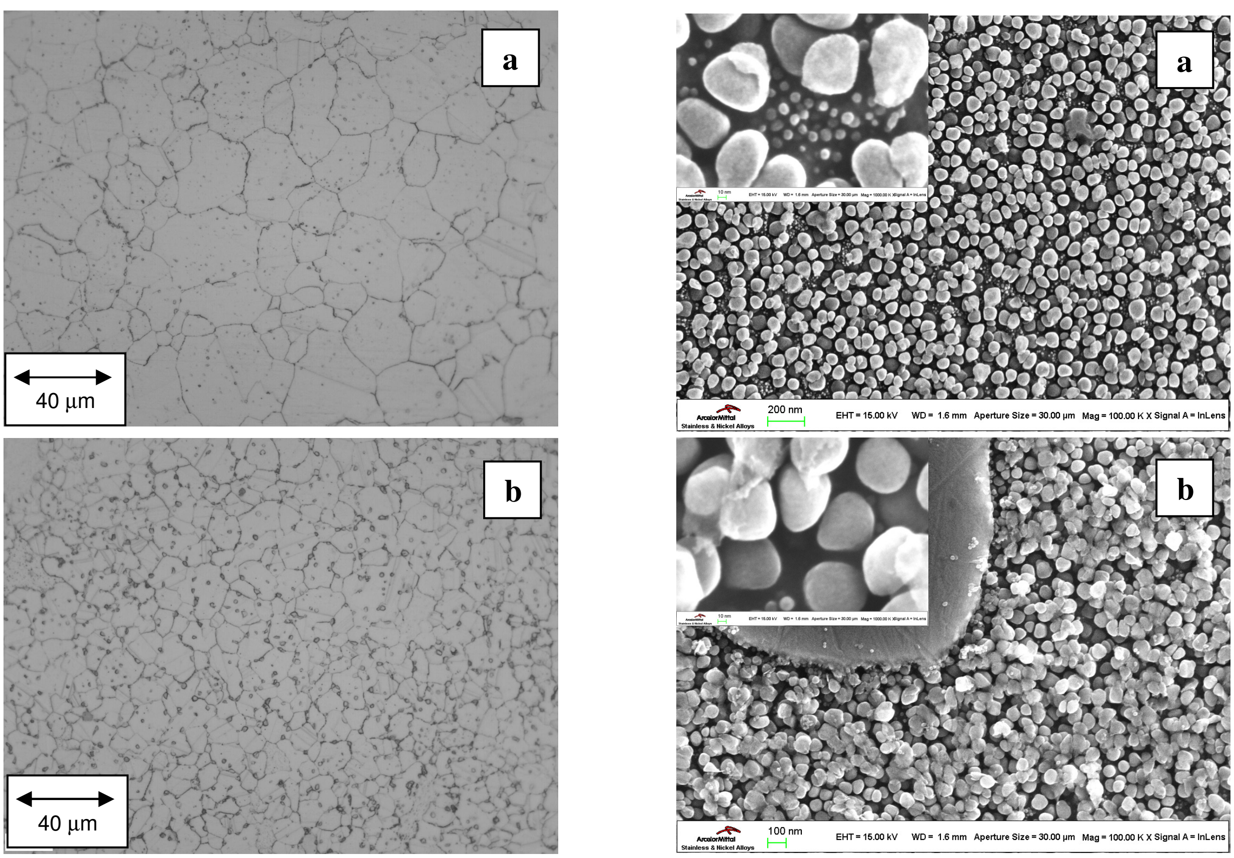
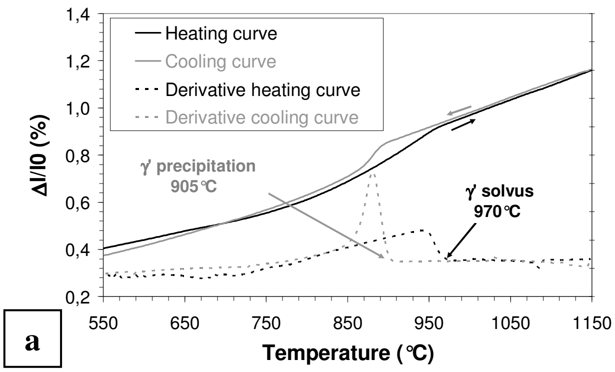


Figure 5: microstructure on forged pancakes from 170kg ingots after HT a) Ni30 b) Ni33

Mechanical and metallurgical properties

<u>γ' precipitation and γ' solvus</u>

Dilatometry tests were performed with a NETZSCH instrument on samples taken from billet extruded from small ingots. Tests were performed up to 1150°C with a constant rate (during heating and cooling) equal to 5°C/min (figure 6).



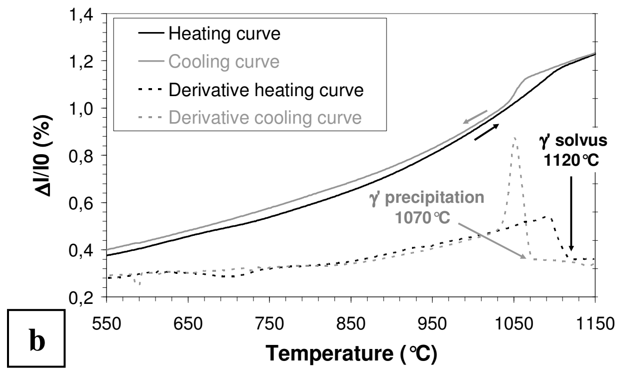


Figure 6 : Dilatometry tests performed on a) 718Plus and b) Ni30 alloy

These tests usually may lead to an over-estimation of γ' solvus due to the dynamic dissolution of the γ' phase. γ' solvus at the equilibrium, which can be more rigorously evaluated with heat treatment, is between the γ' solvus estimated by Thermo-Calc software and dilatometry test : γ' solvus is close to 950°C in 718Plus and close to 1100°C in Ni30.
With a cooling rate equal to 5°C/min from an initial temperature of 1150°C, γ' precipitation occurs during cooling at a temperature close to γ' solvus – 55°C ± 10°C in both alloys.

<u>Hot workability</u>

Hot workability was evaluated with tensile tests carried out with a strain rate equal to 10^{-1} s^{-1} up to 1180°C with samples taken in homogenized ingots (figure 7). No heat treatment (except homogenization) was performed before the tests to improve workability.

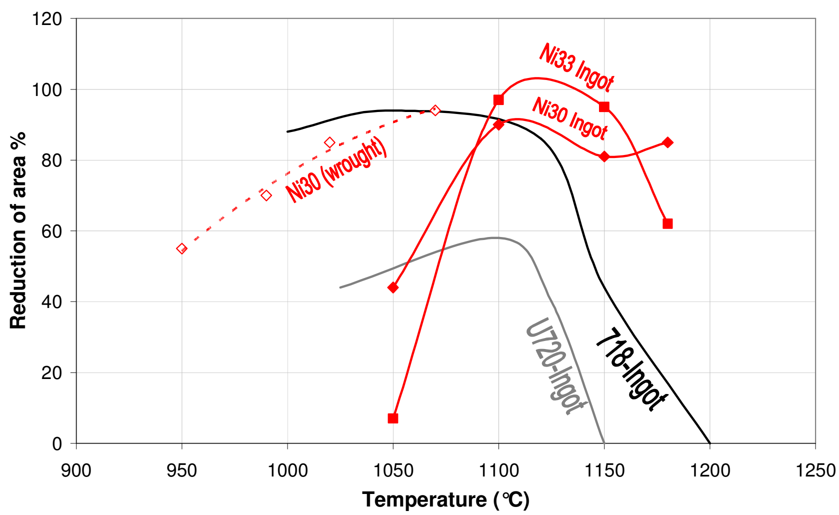


Figure 7 : Hot tensile workability with a rapid strain rate of various C&W alloys

The new alloys show clearly a better workability after homogenization than U720Li. The reduction of area is high enough in the 1100–1170 °C temperature range to enable a forging above γ' solvus. Results obtained on the forged billet show that finer grain size improves significantly the workability: these alloys can be easily forged below γ' solvus to obtain microstructures with fine grain size. This workability behavior clearly differs from that of U720Li alloy which can not be forged (without any cracks) above γ' solvus. The TMW alloys workability seems to be very similar to U720Li's: TMW alloys have a poor ductility above the γ' solvus and have to be processed below the γ' solvus [8].

Microstructural stability

Matrix chemistry of new alloys was carefully controlled to avoid the precipitation of TCP phases. Thermo-calc software was used to estimate the fraction of TCP phases (sigma and mu phases) at various temperatures. New Phacomp was also used to evaluate if new alloys were prone to the precipitation of sigma-phase [14]. Md parameter (1) was calculated for various alloys with the matrix chemistry at 700°C determined by Thermo-Calc. TCP phases were suspended for this calculation : γ matrix chemistry was evaluated only in presence of γ, γ' and MC carbides.
Results show that microstructural stability of new superalloys is theoretically as good as those of U720Li [15] and TMW4 [8] and probably better than that of 718Plus [16] according to this theoretical approach (figure 8). U500 is known to be unstable [17] and has higher Md 700°C value and higher TCP phases amount than other C&W superalloys.

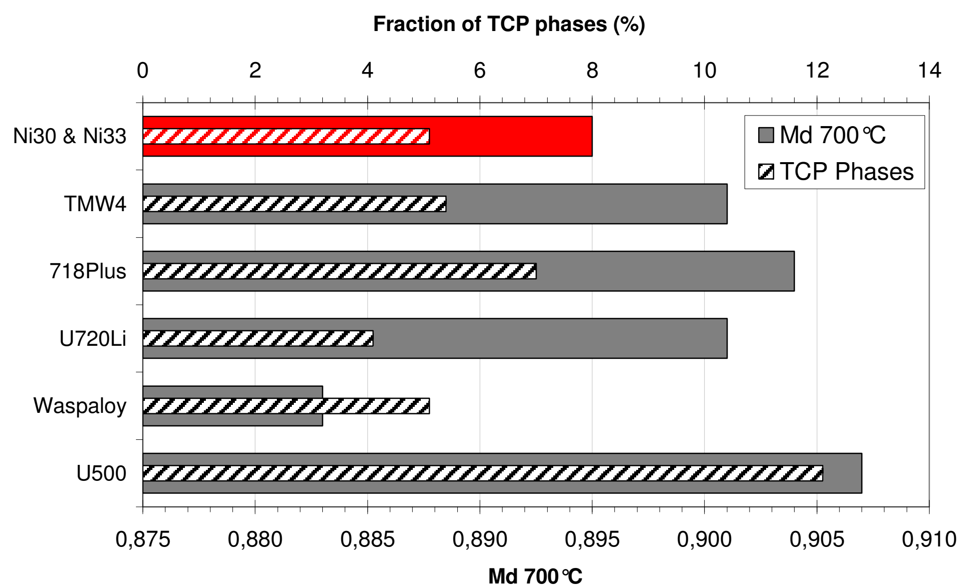


Figure 8 : Evaluation of microstructural stability in alloys design

The microstructural stability of the new alloys was assessed with long term aging in the 750-800°C temperature range. Hardness and SEM examinations were performed at different times on various C&W alloys. SEM examinations are performed to identify the presence of deleterious phases after long-term aging: it is known that TCP phases like σ-phase or mu-phase strongly affect the ductility and the notch sensivity. Hardness are performed to evaluate the γ' phase stability which can affect the alloy strengthening (creep life, tensile properties…etc).

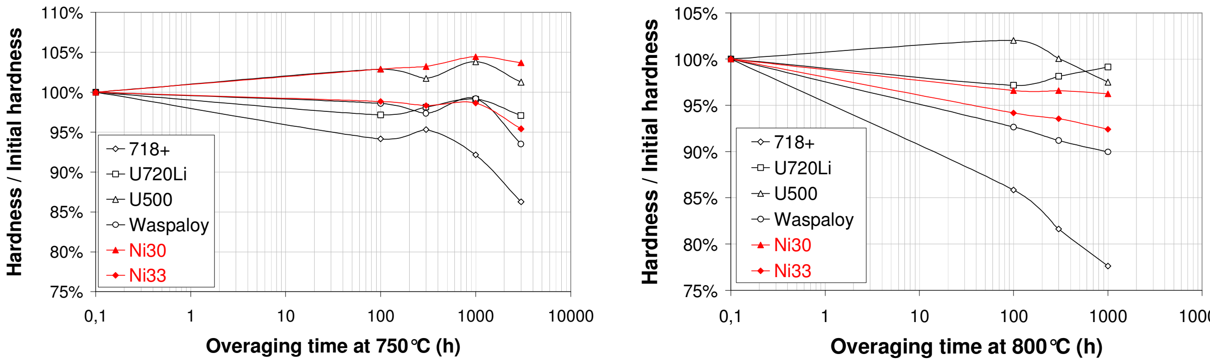


Figure 9 : Hardening response of various C&W alloys for long-term aging at 750°C and 800°C after standard heat treatment (solution HT + aging)

Hardness of Ni30 and Ni33 alloys is quite stable at 750°C and slightly decreases at 800°C. Hardening evolution of these alloys appears to be similar to those of U720Li and Waspaloy. No TCP phases were observed in Ni30 and Ni33 after 1000h at 750°C. As shown on figures 5 and 10, γ' precipitates slightly coarsen after this overaging in both alloys. 718Plus hardness slightly decreases at 750°C and drops at 800°C contrary to other C&W superalloys. As shown on figure 11, γ' precipitates coarsen more quickly in this alloy at temperatures higher than 700°C.

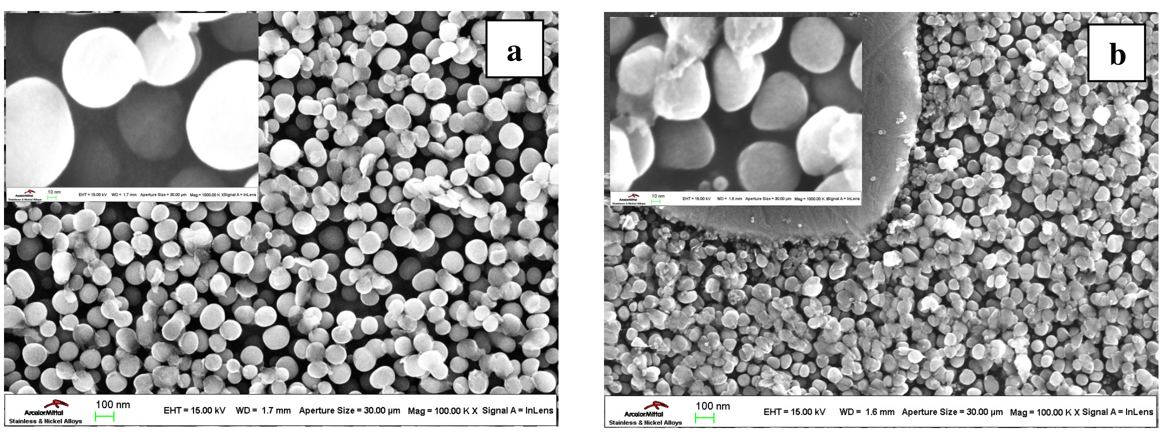


Figure 10 : SEM examinations after 1000h at 750°C (a) Ni30 (b) Ni33

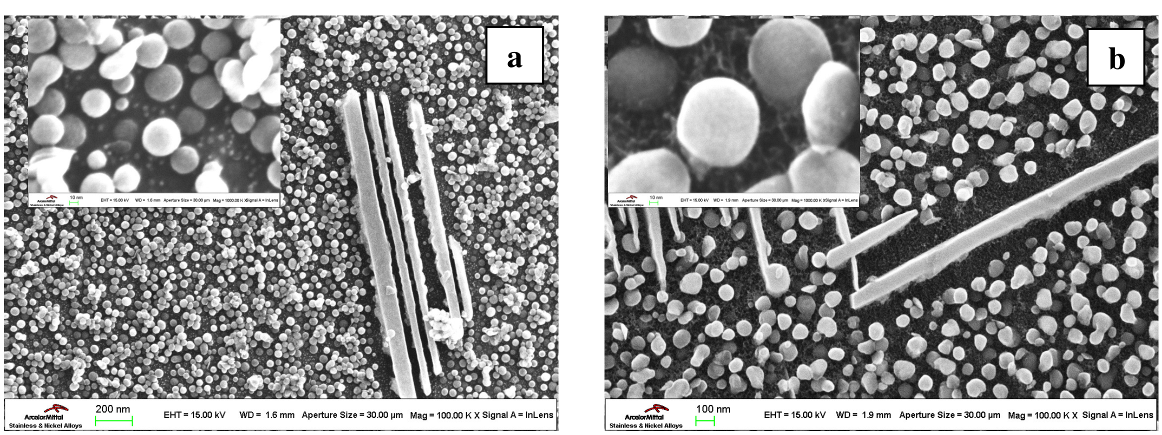
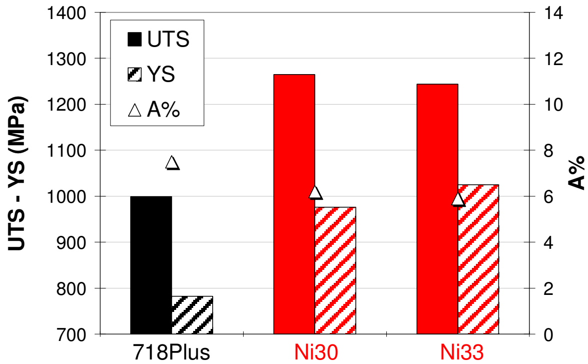


Figure 11 : SEM examinations on 718Plus (a) after standard HT (b) after 1000h at 750°C

Tensile and creep properties : results obtained on small ingots

Tensile tests at 700°C were performed on Ni30, Ni33 and 718Plus. These results show that Ni30 and Ni33 tensile strength are clearly much superior to those of 718Plus (figure 12).



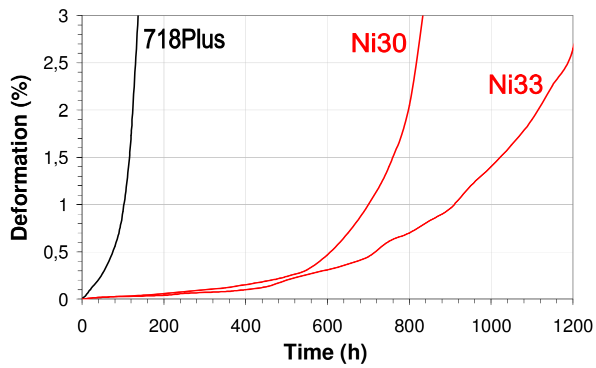


Figure 12 : Mechanical properties of 718Plus and Ni30-Ni33 alloys obtained on small ingots

Tensile creep tests were performed in air at 700°C/600MPa on extruded billets from small ingots. Both Ni30 and Ni33 alloys exhibit a creep strength significantly higher than that of 718Plus, with a 5 to 7 times creep rupture life improvement. These better properties can be explained by the higher γ' fraction and solid solution strengthening of Ni30 and Ni33 alloys.

Tensile properties : results obtained on 170kg ingots

Tensile tests and tensile creep tests were performed at various temperatures on forged pancakes in Ni30 and Ni33 alloys. Results were compared with tests performed in same conditions (same cooling rate) on a forged pancake in U720Li with a grain size close to ASTM 10. These tests reveal that tensile properties of new Ni30 and Ni33 superalloys are comparable to those of U720Li and are therefore clearly much superior to those of 718 and Waspaloy (figure 13 and figure 14). Elongation was higher than 10% in all tested conditions.

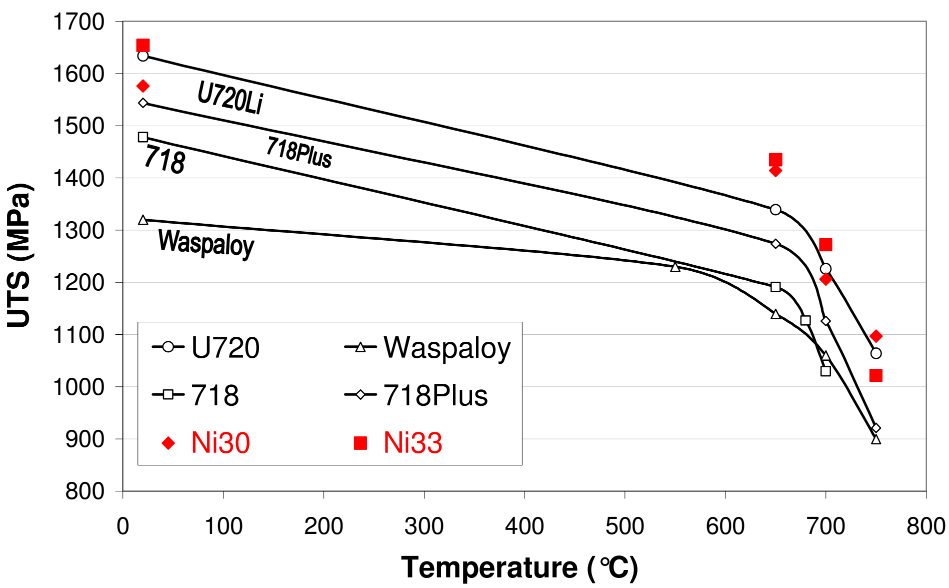


Figure 13 : Ultimate tensile strength as a function of temperature

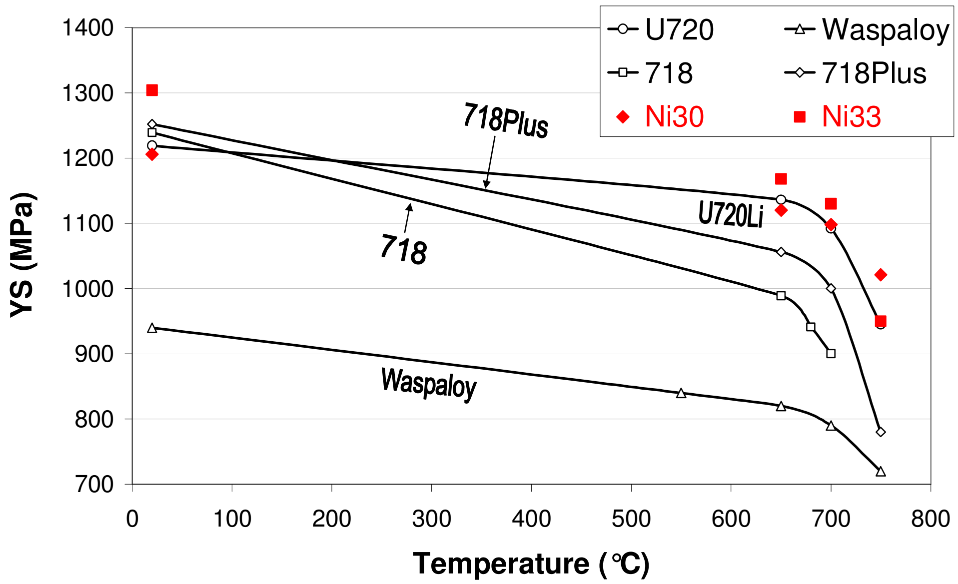


Figure 14 : Yield strength as a function of temperature

<u>Creep properties : results obtained on 170kg ingots</u>

Creep properties of Ni30 and Ni33 alloys seem to be slightly superior to those of U720Li and consequently better than those of other C&W superalloys (figure 15). In the high temperature and low stress test region, Ni30 shows higher properties than Ni33 probably due to its larger grain size.

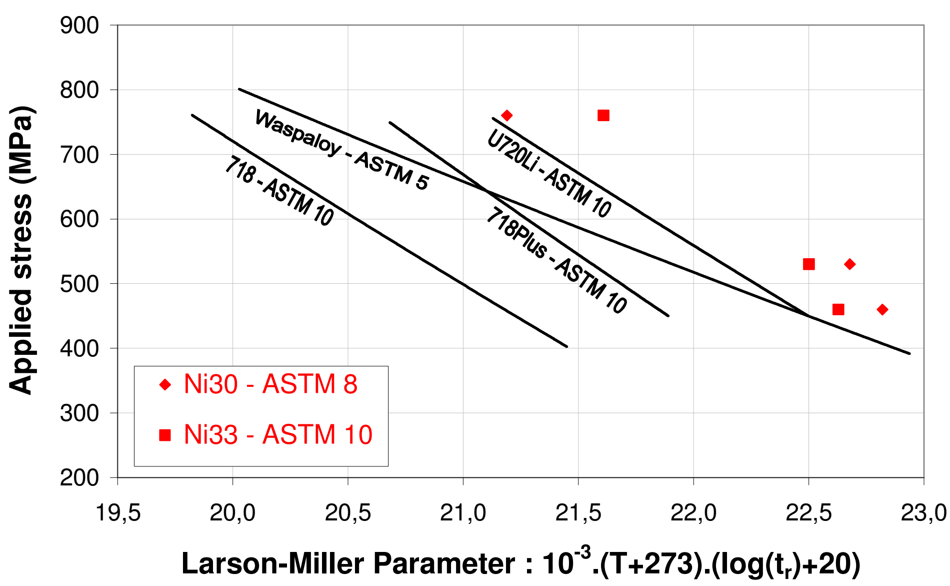


Figure 15 : Comparison of creep properties of C&W superalloys

Fatigue tests : results obtained on 170kg ingots

Stress controlled Fatigue tests were performed in air at 650°C with a sinusoidal wave form signal, a frequency equal to 10Hz, a maximal stress equal to 1050MPa and a stress ratio close to 0. Results show that Ni33 and Ni30 alloy lead to higher fatigue lives than U720Li for a similar grain size close to ASTM 10 (figure 16).

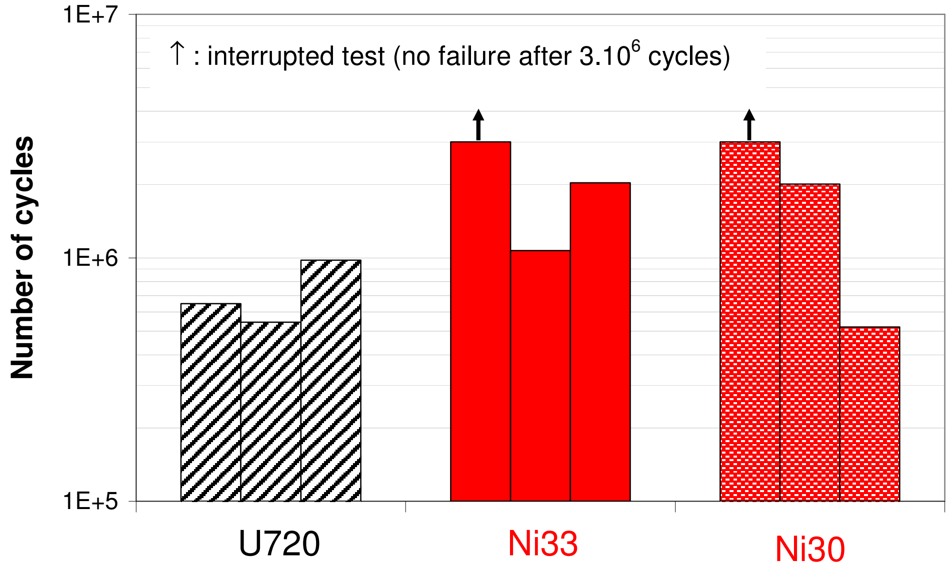


Figure 16 : Fatigue properties at 650°C of Ni30 and Ni33 alloy compared to U720Li

Density

Density was evaluated with Hull method [18] to design Ni30 and Ni33. As expected, density measurements on forged pancakes show that density of Ni30 and Ni33 is lower than that of 718Plus and higher than that of U720Li (figure 17).

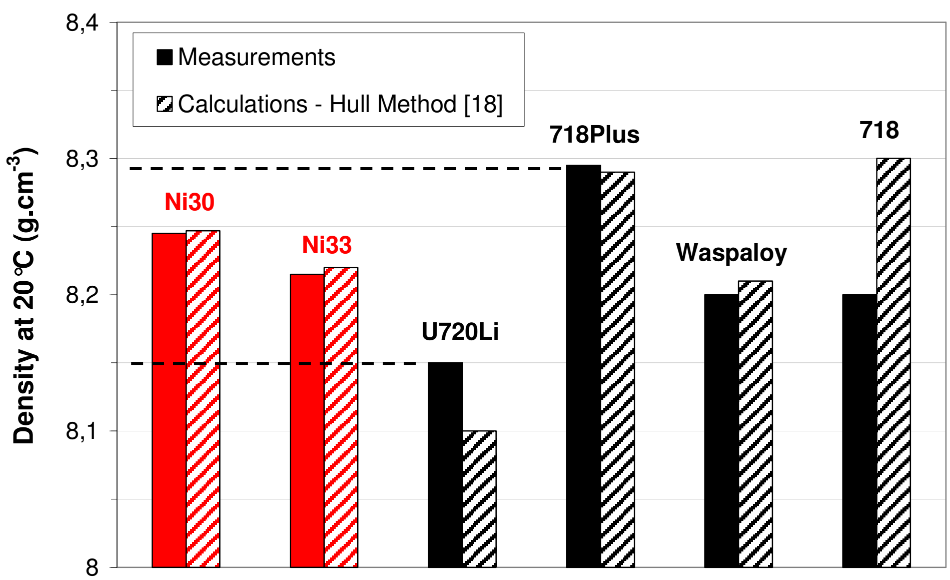


Figure 17 : Density of Ni30 and Ni33 compared to other C&W superalloys

Conclusions

Aubert & Duval has developed new C&W superalloys which present a lower cost compared to other γ/γ' C&W superalloys (U720Li, U500, TMW4) and a moderate cost increase compared to 718 alloy. Workability tests show that the manufacturing of these alloys should be easier than that of U720Li and that supersolvus forging is possible on these new grades contrary to this last grade. High γ' fraction (35-40%) associated with a high solid solution strengthening of the matrix explain the best mechanical properties obtained with these alloys. Tensile, creep, fatigue tests show that the mechanical properties are at least similar to those of U720Li and significantly higher than those of 718Plus. Long term aging performed at 750°C and 800°C confirm that new alloys have a good microstructural stability comparable to U720Li in this temperature range.
Based on these results, it should be possible to extend performance capabilities, in terms of cost and mechanical properties, of most current C&W superalloys for turbine disks. Full scale productions will supply useful experience for processing these new alloys in manufacturing level.

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