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# ALLVAC 718 Plus™ Superalloy for Aircraft Engine Applications

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## 1. Introduction

Innovations on the aerospace and aircraft industry have been throwing light upon building to future's engineering architecture at the today's globalization world where technology is the indispensable part of life. On the basis of aviation sector, the improvements of materials used in aircraft gas turbine engines which constitute 50 % of total aircraft weight must protect its actuality continuously. On the other hand utilization of super alloys in aerospace and defense industries can not be ignored because of excellent corrosion and oxidation resistance, high strength and long creep life at elevated temperatures.

Materials that can be used at the homologous temperature of 0.6 Tm and still remain stable to withstand severe mechanical stresses and strains in oxidizing environments are so-called superalloys, usually based on Ni, Fe or Co (Sims et al, 1987). Nickel-based superalloys are the exceptional group of superalloys with superior materials properties. Their excellent properties range from high temperature mechanical strength, toughness to resistance to degradation in oxidizing and corrosive environment. Therefore they are not only used in aerospace and aircraft industry, but also in ship, locomotive, petro- chemistry and nuclear reactor industries.

Inconel 718 is Ni-based, precipitation- hardening superalloy with Nb as a major hardening element, used for high temperature aerospace applications very widely in recent years (Yaman & Kushan, 1998). However, the metastability of the primary strengthening (γ'', gamma double prime) phase is typically unacceptable for applications above about 650°C. As a result, other more costly and difficult to process alloys, like Waspalloy, are used in such applications. Although Waspalloy is strengthened primarily by γ', it is still more susceptible to weld-related cracking than Inconel 718 (Otti et al, 2005). In these circumstances ALLVAC 718 Plus™ come to stage, which is strengthened with uniform cubic FCC inter metallic γ' phase, innovated by ATI ALLVAC Company very recently. In recent years it has been becoming widespread dramatically for using of disc material in aerospace gas turbine engine parts. The most important reason of this is the high yield and ultimate tensile strength and very good corrosion and oxidation resistance of material together with excellent creep resistance at elevated temperatures. Fig. 1 shows that where wrought alloy 718Plus can be used as a disc material for high pressure (HP) compressor as well as for high pressure (HP) turbine discs (Bond & Kennedy, 2005).

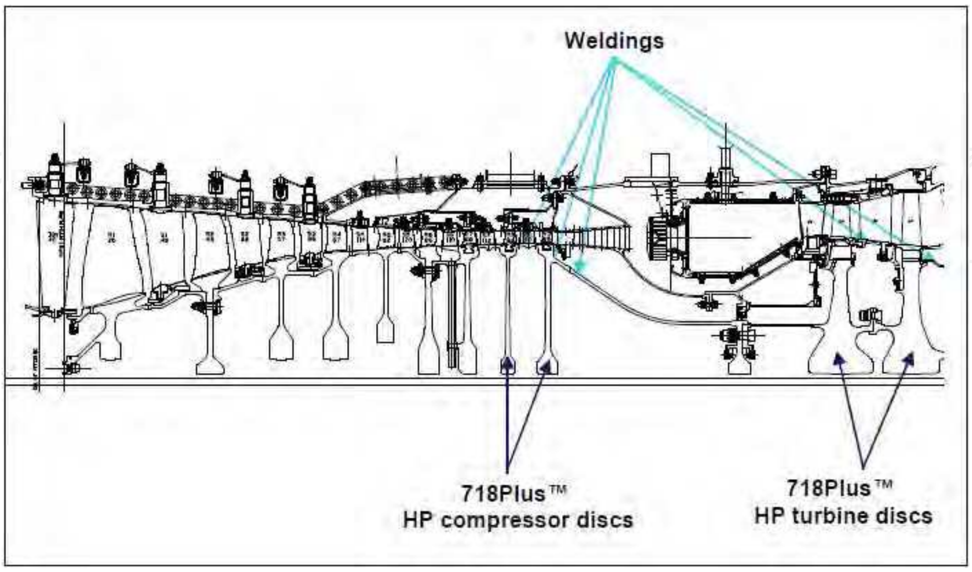



Fig. 1. Potential applications for alloy 718PlusTM in a future high pressure core section (Bond & Kennedy, 2005).

The newly innovated ALLVAC 718 Plus superalloy which is the last version of Inconel 718 has been proceeding in the way to become a material that aerospace and defense industries never replace of any other material with combining its good mechanical properties, easy machinability and low cost.

## 2. Gas turbine engines

Gas turbine engines, also known as jet engines, power most modern civilian and military aircraft. Fig. 2 shows some sections of this kind of an engine. The inlet (intake) directs outside air into the engine. The compressor (shown in a (a) part of Fig. 2) is situated at the exit of the inlet. In order to produce thrust, it is essential to compress the air before fuel is added. In an axial-flow compressor, the air flows in the direction of the shaft axis through alternate rows of stationary and rotating blades, called stators and rotors, respectively. Modern axial-flow compressors can increase the pressure 24 times in 15 stages, with each set of stators and rotors making up a stage. The compressors in most modern engines are divided into low-pressure and high-pressure sections which run off two different shafts. In the combustor, or burner (shown in a (b) part of Fig. 2), the compressed air is mixed with fuel and burned. Fuel is introduced through an array of spray nozzles that atomize it. An electric igniter is used to begin combustion. The combustor adds heat energy to the air stream and increases its temperature (up to about 1930°C), a process which is accompanied by a slight decrease in pressure (~ 1-2%). For best performances, the combustion temperature should be the maximum obtainable from the complete combustion of the oxygen and the fuel. However, turbine inlet temperatures currently cannot exceed about 1100°C because of material limits. Hence, only part of the compressed air is burned in the combustor; the remainder is used to cool the turbine.

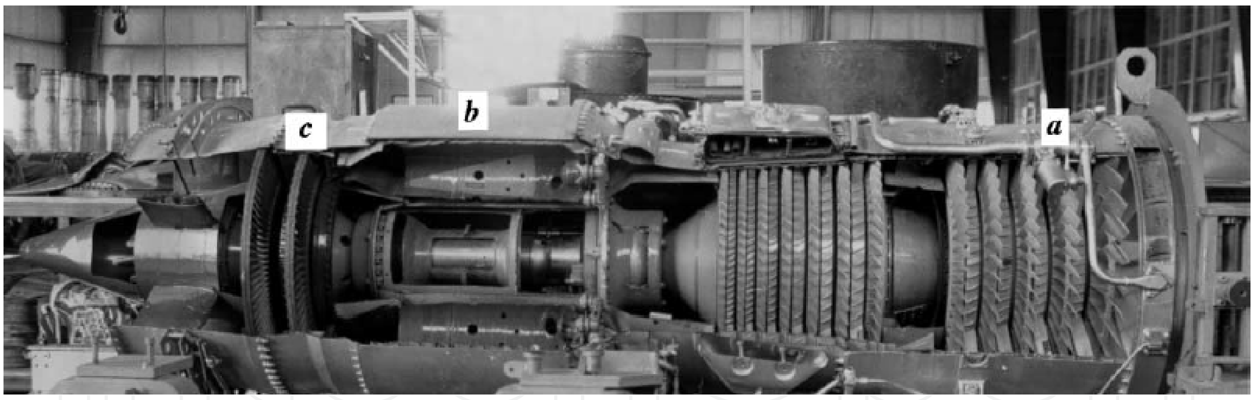


Fig. 2. Some basic sections of a gas turbine engine (Eliaz et al, 2002).

Leaving the combustor, the hot exhaust is passed through the turbine (shown in a (c) part of Fig. 2), in which the gases are partially expanded through alternate stator and rotor rows. Depending on the engine type, the turbine may consist of one or several stages. Like the compressor, the turbine is divided into low-pressure and high-pressure sections (shown in Fig. 3), the latter being closer to the combustor.

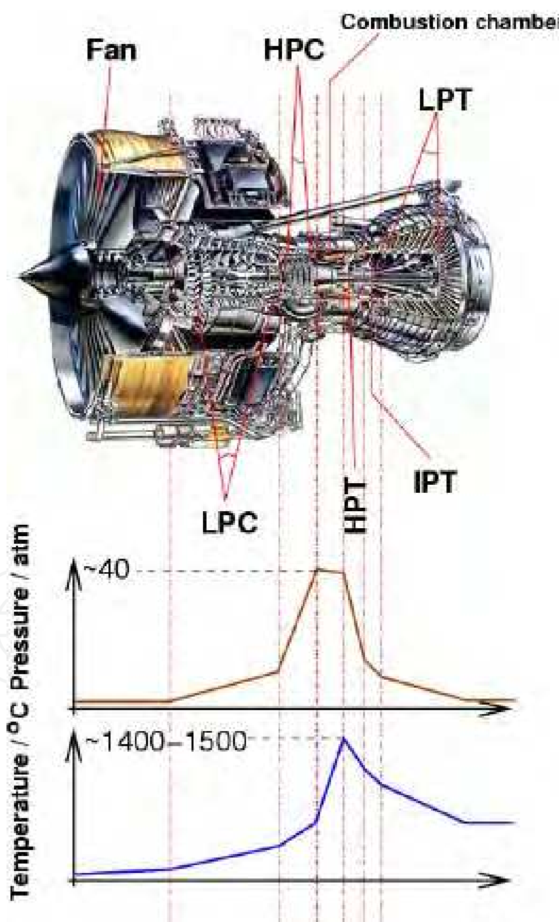


Fig. 3. The temperature and pressure profile in gas turbine (Carlos & Estrada, 2007).

The turbine provides the power to turn the compressor, to which it is connected via a central shaft, as well as the power for the fuel pump, generator, and other accessories. From thermodynamics, the turbine work per mass airflow is equal to the change in the specific enthalpy of the flow from the entrance to the exit of the turbine. This change is related to the temperatures at these points. The temperature at the entrance to the turbine can be as high as 1650°C, considerably above the melting point of the material from which the blades are made.

The gases, leaving the turbine at an intermediate pressure, are finally accelerated through a nozzle to reach the desired high jet-exit velocity. Because the exit velocity is greater than the free stream velocity, thrust is produced. The amount of thrust generated depends on the rate of mass flow through the engine and the leaving jet velocity, according to Newton's Second Law. Thus, the gas is accelerated to the rear, and the engine (as well as the aircraft) is accelerated in the opposite direction according to Newton's Third Law (Eliaz et al, 2002).

Modern gas turbines have the most advanced and sophisticated technology in all aspects; construction materials are not the exception due their extreme operating conditions. The most difficult and challenging point is the one located at the turbine inlet, because, several difficulties associated to it; like extreme temperature, high pressure, high rotational speed, vibration, small circulation area, and so on. These rush characteristics produce effects on the gas turbine components that are shown on the Table 1 (Carlos & Estrada, 2007).

| | **Oxidation** | **Hot corrosion** | **Interdiffusion** | **Thermal Fatigue** |
|---|---|---|---|---|
| **Aircraft** | Severe | Moderate | Severe | Severe |
| **Land-based Power Generator** | Moderate | Severe | Moderate | Light |
| **Marine Engines** | Moderate | Severe | Light | Moderate |

Table 1. Severity of the different surface related problems for gas turbine applications (Carlos & Estrada, 2007).

In order to overcome those barriers, gas turbine components are made using advanced materials and modern alloys (superalloys) that contains up to ten significant alloying elements.

## 3. Superalloys

These alloys have been developed for high-temperature service and include iron-, cobalt- and nickel based materials, although nowadays they are principally nickel based. These materials are widely used in aircraft and power-generation turbines, rocket engines, and other challenging environments, including nuclear power and chemical processing plants. The aero gas turbine was the impetus for the development of superalloys in the early 1940s, when conventional materials available at that time were insufficient for the demanding environment of the turbine. Therefore it can be said that "The development of superalloys made the modern gas turbine possible".

A major application of superalloys is in turbine materials, jet engines, both disc and blades. Initial disc alloys were *Inco 718* and *Inco 901* produced by conventional casting ingot, forged billet and forged disc route. These alloys were developed from austenitic steels, which are still used in industrial turbines, but were later replaced by *Waspaloy* and *Astroloy* as stress and temperature requirements increased. These alloys were turbine blade alloys with a suitably modified heat-treatment for discs. However, blade material is designed for creep, whereas disc material requires tensile strength coupled with low cycle fatigue life to cope with the stress changes in the flight cycle. To meet these requirements *Waspaloy* was thermomechanically processed (TMP) to give a fine-grain size and a 40% increase in tensile strength over the corresponding blade material, but at the expense of creep life. Similar improvements for discs have been produced in *Inco 901* by TMP. More highly-alloyed nickel-based discs suffer from excessive ingot segregation which makes grain size control difficult. Further development led to alloys produced by powder processing by gas atomization of a molten stream of metal in an inert argon atmosphere and consolidating the resultant powder by HIPing to near-net shape. Such products are limited in stress application because of inclusions in the powder and, hence, to realize the maximum advantage of this process it is necessary to produce 'superclean' material by electron beam or plasma melting.

Improvements in turbine materials were initially developed by increasing the volume fraction of γ´ in changing *Nimonic 80A* up to *Nimonic 115*. Unfortunately increasing the (Ti +Al) content lowers the melting point, thereby narrowing the forging range makes processing more difficult. Improved high-temperature oxidation and hot corrosion performance has led to the introduction of aluminide and overlay coatings and subsequently the development of *IN 738* and *IN 939* with much improved hot-corrosion resistance.

Further improvements in superalloys have depended on alternative manufacturing routes, particularly using modern casting technology like Vacuum casting (Smallman & Bishop, 1999).

In these alloys $\gamma'$ ($Ni_3Al$) and $\gamma''$ ($Ni_3Nb$) are the principal strengtheners by chemical and coherency strain hardening. The ordered $\gamma'$-$Ni_3Al$ phase is an equilibrium second phase in both the binary Ni–Al and Ni–Cr–Al systems and a metastable phase in the Ni–Ti and Ni–Cr–Ti systems, with close matching of the $\gamma'$ and the FCC matrix. The two phases have very similar lattice parameters and the coherency confers a very low coarsening rate on the precipitate so that the alloy overages extremely slowly even at $0.7T\text{m}$. In alloys containing Nb, a metastable $Ni_3Nb$ phase occurs but, although ordered and coherent, it is less stable than γ' at high temperatures (Smallman & Ngan, 2007).

In high-temperature service, the properties of the grain boundaries are as important as the strengthening by γ' within the grains. Grain boundary strengthening is produced mainly by precipitation of chromium and refractory metal carbides; small additions of Zr and B improve the morphology and stability of these carbides. Optimum properties are developed by multistage heat treatment; the intermediate stages produce the desired grain boundary microstructure of carbide particles enveloped in a film of $\gamma'$ and the other stages produce two size ranges of $\gamma'$ for the best combination of strength at both intermediate and high temperatures (Smallman & Ngan, 2007). Table 2 indicates the effect of the different alloying elements and Table 3 indicates the common ranges of main alloying additions and their effects on superalloy properties.

| *Influence* | *Cr* | *Al* | *Ti* | *Co* | *Mo* | *W* | *B* | *Zr* | *C* | *Nb* | *Hf* | *Ta* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Matrix strengthening | √ | | | √ | √ | √ | | | | | | |
| $\gamma'$ formers | | √ | √ | | | | | | | √ | | √ |
| Carbide formers | √ | | √ | | √ | √ | | | | √ | √ | √ |
| Grain boundary strengthening | | | | | | | √ | √ | √ | | √ | |
| Oxide scale formers | √ | √ | | | | | | | | | | |

Table 2. The effect of the different alloying elements (Smallman & Ngan, 2007).

| Element | Range, wt.% | Effect |
|---|---|---|
| Cr | 5-25 | Oxidation and hot corrosion resistance; carbides; solution hardening |
| Mo, W | 0-12 | Carbides; solution hardening |
| Al | 0-6 | Precipitation hardening; oxidation resistance; $\gamma'$ former |
| Ti | 0-6 | Precipitation hardening; carbides; $\gamma'$ former |
| Co | 0-20 | Affects amount of precipitate |
| Ni | Balance | Stabilizes $\gamma$ phase; forms hardening precipitates |
| Nb | 0-5 | Carbides; solution hardening; precipitation hardening |
| Ta | 0-12 | Carbides; solution hardening; oxidation resistance; $\gamma'$ former |

Table 3. Common Ranges of Main Alloying Additions and Their Effects on Superalloys.

The wide range of applications for superalloys has expanded many other areas since they were developed and now includes aircraft and land-based gas turbines, rocket engines, chemical, and petroleum plants. The performance of an industrial gas turbine engines depends strongly on service conditions and the environment in which it operates.

### 3.1 Iron-nickel-based superalloys

Iron-nickel base superalloys evolved from austenitic stainless steels and are based on the principle of combining both solid-solution hardening and precipitate forming elements. As a class, the iron nickel superalloys have useful strengths to approximately 650°C (1200°C). The austenitic matrix based on nickel and iron, with at least 25 wt % Ni needed to stabilize the FCC phase. Other alloying elements, such as Chromium partition primarily to austenite to provide solid-solution hardening. Most alloys contain 25 to 45 wt % Nickel. Chromium in the range of 15 to 28 wt% is added for oxidation resistance at elevated temperature, while 1 to 6 wt% Mo provides solid solution strengthening. The main elements that facilitate precipitation hardening are titanium, aluminum and niobium.

The strengthening precipitates are primarily γ' ($Ni_3Al$), η ($Ni_3Ti$), and γ″ ($Ni_3Nb$). Elements that partition to grain boundaries, such as Boron and Zirconium, suppress grain boundary creep, resulting in significant increases in rupture life. Boron in quantities of 0.003 to 0.03 wt% and, less frequently, small additions of zirconium are added to improve stress-rupture properties and hot workability. Zirconium also forms the MC carbide ZrC. Another MC carbide (NbC) is found in alloys that contain niobium such as Inconel 706 and Inconel 718. Vanadium is also added in small quantities to iron-nickel superalloys to improve both notch ductility at service temperatures and hot workability. Based on their composition and strengthening mechanisms, there are several groupings of iron-nickel superalloys (Campbell, 2008).

The most common precipitate is γ', typified by A-286, V-57 or Incoloy 901. Some alloys, typified by Inconel (IN)- 718, which precipitate γ″, were formerly classed as iron-nickel-base superalloys but now are considered to be nickel-base.

The most common type of iron-nickel-base superalloys is INCONEL 718 which is a precipitation- hardening alloy used for high-temperature applications. In particular, the reputation of wrought Inconel 718 for being relatively easy to weld is generally attributed to the sluggish precipitation kinetics of the tetragonal γ″ strengthening phase. Inconel 718 is a relatively recent alloy as its industrial use started in 1965. It is a precipitation hardenable alloy, containing significant amounts of Fe, Nb and Mo. Minor contents of Al and Ti are also present. Inconel 718 combines good corrosion and high mechanical properties with and excellent weldability. It is employed in gas turbines, rocket engines, turbine blades, and in extrusion dies and containers.

Ni and Cr contribute to the corrosion resistance of this material. They crystallize as a γ phase (face centred cubic). Nb is added to form hardening precipitates γ″ (a metastable inter metallic compound $Ni_3Nb$, centred tetragonal crystal). Ti and Al are added to precipitate in the form of intermetallic γ' ($Ni_3(Ti,Al)$, simple cubic crystal). They have a lower hardening effect than particles. C is also added to precipitate in the form of MC carbides (M = Ti or Nb). In this case the C content must be low enough to allow Nb and Ti precipitation in the form of γ' and γ″ particles. Mo is also frequent in Inconel 718 in order to increase the mechanical resistance by solid solution hardening. Finally, a β phase (intermetallic $Ni_3Nb$), (sometimes called δ phase) can also appear. It is an equilibrium particle with orthorhombic structure. All theses particles can precipitate along the grain boundaries of the γ matrix increasing the intergranular flow resistance of the present alloy. A typical precipitation time temperature (PTT) diagram for this alloy is shown in Fig. 4 (Thomas et al, 2006).

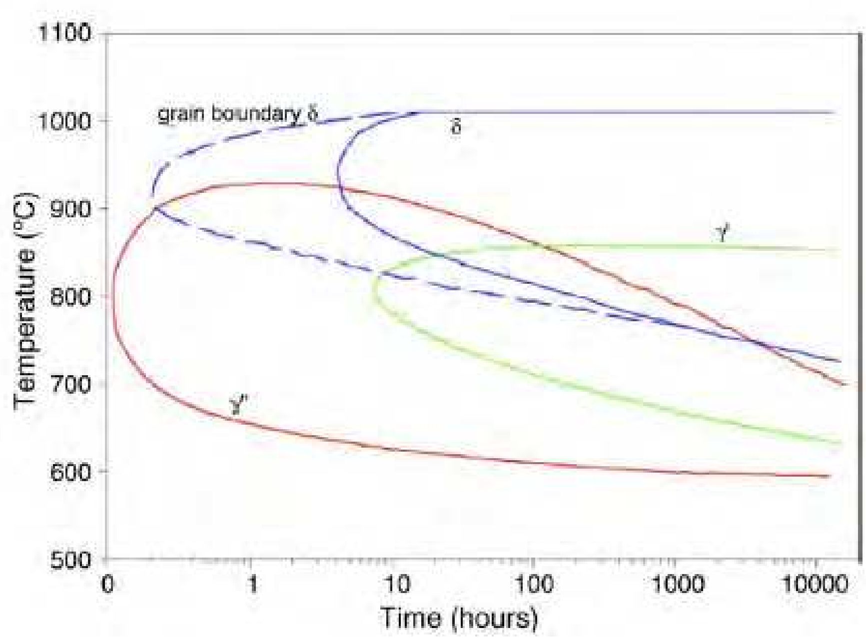



Fig. 4. PTT diagram of different phases in Inconel 718 (Thomas et al, 2006).

### 3.2 Nickel-based Superalloys

Nickel-based superalloys are an unusual class of metallic materials with an exceptional combination of high temperature strength, toughness, and resistance to degradation in corrosive or oxidizing environments. The nickel-based alloys show a wider range of application than any other class of alloys.

The austenitic stainless steels were developed and utilized early in the 1900s, whereas the development of the nickel-based alloys did not begin until about 1930. In aerospace applications nickel-based superalloys are used widely as components of jet engine turbines. Therefore important position of super-alloys in this area is manifested by the fact that they represent at present more than 50 % of mass of advanced aircraft engines. Extensive use of super-alloys in turbines, supported by the fact that thermo-dynamic efficiency of turbines increases with increasing temperatures at the turbine inlet, became partial reason of the effort aimed at increasing of the maximum service temperature of high-alloyed alloys (Jonsta et al, 2007). Therefore in gas turbine applications alloys with good stability and very low crack-growth rates that are readily inspectable by nondestructive means are desired. Fuel efficiency and emissions are also key commercial and environmental drivers impacting turbine-engine materials. To meet these demands, modern nickel-based alloys offer an efficient compromise between performance and economics. The chemistries of several common and advanced nickel-based superalloys are listed in Table 4 and the parts of gas turbine engine in which Nickel-based superalloys (marked red) commonly used are shown in Fig. 5.

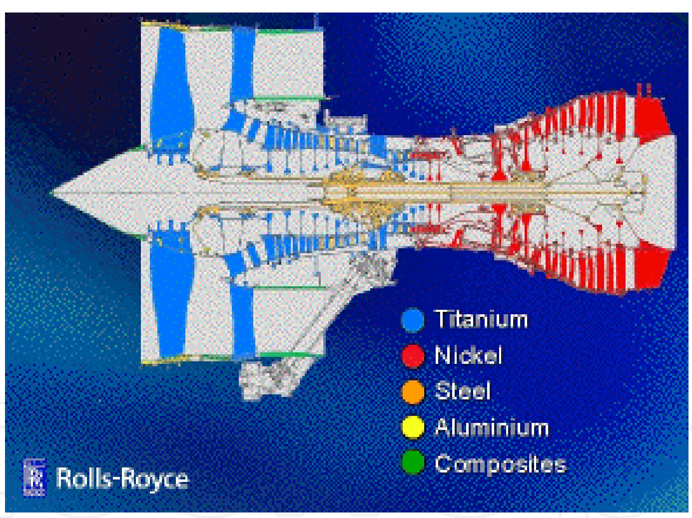



Fig. 5. Commonly used materials in gas turbine engine components.

In the environmental series nickel is nobler than iron but more active than copper. Reducing environments, such as dilute sulfuric acid, find nickel more corrosion resistant than iron but not as resistant as copper or nickel-copper alloys. The nickel molybdenum alloys are more corrosion resistant to reducing environment than nickel or nickel- copper alloys (Philip & Schweitzer, 2003). Nickel-based superalloys are extremely prone to weld cracking.

High-temperature strength of Ni-base superalloys depends mainly, on the volume fraction and morphology of γ´ precipitates. Several basic factors contribute to the magnitude of hardening of the alloy (Sajjadi & Zebarjad, 2006).

| Alloy | Cr | Ni | Co | Mo | W | Nb | Ti | Al | Fe | C | B | Other |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A286 | 15 | 26 | — | 1.25 | — | — | 2 | 0.2 | 55.2 | 0.04 | 0.005 | 0.3 V |
| AF115 | 10.7 | 56 | 15 | 2.8 | 5.9 | 1.7 | 3.9 | 3.8 | — | 0.05 | 0.02 | 0.75 Hf; 0.05 Zr |
| AF2-1DA | 12 | 59 | 10 | 3 | 6 | — | 3 | 4.6 | <0.5 | 0.35 | 0.015 | 1.5 Ta, 0.1 Zr |
| AF2-1DA6 | 12 | 59.5 | 10 | 2.75 | 6.5 | — | 2.8 | 4.6 | <0.5 | 0.04 | 0.015 | 1.5 Ta, 0.1 Zr |
| Alloy 706 | 16 | 41.5 | — | — | — | — | 1.75 | 0.2 | 37.5 | 0.03 | — | 2.9 (Nb+Ta), 0.15 Cu |
| Alloy 718 | 19 | 52.5 | — | 3 | — | 5.1 | 0.9 | 0.5 | 18.5 | 0.08 | — | 0.15 Cu |
| APK12 | 18 | 55 | 15 | 3 | 1.25 | — | 5 | 2.5 | — | 0.03 | 0.035 | 0.035 Zr |
| Astroloy | 15 | 56.5 | 15 | 5.25 | — | — | 3.5 | 4.4 | <0.3 | 0.06 | 0.03 | 0.06 Zr |
| Discaloy | 14 | 26 | — | 3 | — | — | 1.7 | 0.25 | 55 | 0.06 | — | |
| IN100 | 10 | 60 | 15 | 3 | — | — | 4.7 | 5.5 | <0.6 | 0.15 | 0.015 | 0.06 Zr, 1.0 V |
| KM-4 | 12 | 56 | 18 | 4 | — | 2 | 4 | 4 | — | 0.03 | 0.03 | 0.03 Zr |
| MERL-76 | 12.4 | 54.4 | 18.6 | 3.3 | — | 1.4 | 4.3 | 5.1 | — | 0.02 | 0.03 | 0.35 Hf; 0.06 Zr |
| N18 | 11.5 | 57 | 15.7 | 6.5 | — | — | 4.35 | 4.35 | — | 0.015 | 0.015 | 0.45 Hf; 0.03 Zr |
| PA101 | 12.5 | 59 | 9 | 2 | 4 | — | 4 | 3.5 | — | 0.15 | 0.015 | 4.0 Ta; 1.0 Hf; 0.1 Zr |
| René 41 | 19 | 55 | 11 | 10 | — | — | 3.1 | 1.5 | <0.3 | 0.09 | 0.01 | |
| René 88 | 16 | 56.4 | 13.0 | 4 | 4 | 0.7 | 3.7 | 2.1 | — | 0.03 | 0.015 | 0.03 Zr |
| René 95 | 14 | 61 | 8 | 3.5 | 3.5 | 3.5 | 2.5 | 3.5 | <0.3 | 0.16 | 0.01 | 0.05 Zr |
| Udimet 500 | 19 | 52 | 19 | 4 | — | — | 3 | 3 | <4.0 | 0.08 | 0.005 | |
| Udimet 520 | 19 | 57 | 12 | 6 | 1 | — | 3 | 2 | — | 0.08 | 0.005 | |
| Udimet 700 | 15 | 55 | 17 | 5 | — | — | 3.5 | 4 | <1.0 | 0.07 | 0.02 | 0.02 Zr |
| Udimet 710 | 18 | 55 | 14.8 | 3 | 1.5 | — | 5 | 2.5 | — | 0.07 | 0.01 | |
| Udimet 720 | 18 | 55 | 14.8 | 3 | 1.25 | — | 5 | 2.5 | — | 0.035 | 0.033 | 0.03 Zr |
| Udimet 720LI | 16 | 57 | 15.0 | 3 | 1.25 | — | 5 | 2.5 | — | 0.025 | 0.018 | 0.03 Zr |
| V57 | 14.8 | 27 | — | 1.25 | — | — | 3 | 0.25 | 48.6 | 0.08 | 0.01 | 0.5 V |
| Waspaloy | 19.5 | 57 | 13.5 | 4.3 | — | — | 3 | 1.4 | <2.0 | 0.07 | 0.006 | 0.09 Zr |

Table 4. The chemical compositions of several superalloys (wt.%) (Furrer & Fecht, 1999).

### 3.3 Cobalt-based Superalloys

The cobalt-based superalloys (Table 5) are not as strong as nickel-based superalloys, but they retain their strength up to higher temperatures. They derive their strength largely from a distribution of refractory metal carbides (combinations of carbon and metals such as Mo and W), which tend to collect at grain boundaries (Fig. 6). This network of carbides strengthens grain boundaries and alloy becomes stable nearly up to the melting point. In addition to refractory metals and metal carbides, cobalt superalloys generally contain high levels of Cr to make them more resistant to corrosion that normally takes place in the presence of hot exhaust gases. The Cr atoms react with oxygen atoms to form a protective layer of $Cr_2O_3$ which protects the alloy from corrosive gases. Being not as hard as nickel-based superalloys, cobalt superalloys are not so sensitive to cracking under thermal shocks as other superalloys. Co-based superalloys are therefore more suitable for parts that need to be worked or welded, such as those in the intricate structures of the combustion chamber (Jovanović et al).

| Alloy | C | Mn | Si | Cr | Ni | Mo | W | Fe | Co |
|---|---|---|---|---|---|---|---|---|---|
| X-45 | 0.25 | .5 | 0.9 | 25 | 10 | - | 7.5 | <2 | Bal. |
| X-40 | 0.5 | .5 | 0.9 | 25 | 10 | - | 7.5 | <2 | Bal. |
| FSX-414 | 0.35 | .5 | 0.9 | 29.5 | 10 | - | 7.5 | <2 | Bal. |
| WI-52 | 0.45 | .4 | 0.4 | 21 | - | - | 11 | 2 | Bal. |
| Haynes -25 | 0.1 | 1.2 | 0.8 | 20 | 10 | - | 15 | <3 | Bal. |
| F-75 | 0.25 | .5 | 0.8 | 28 | <1 | 6 | <.2 | <0.75 | Bal. |
| Haynes Ultimet | 0.06 | .8 | 0.3 | 25 | 9 | 5 | 2 | 3 | Bal. |
| Co 6 | 1.1 | | 0.8 | 29 | <3 | <1.5 | 5.5 | <3 | Bal. |

Table 5. The chemical composition of some Cobalt-based superalloys (Jovanović et al).

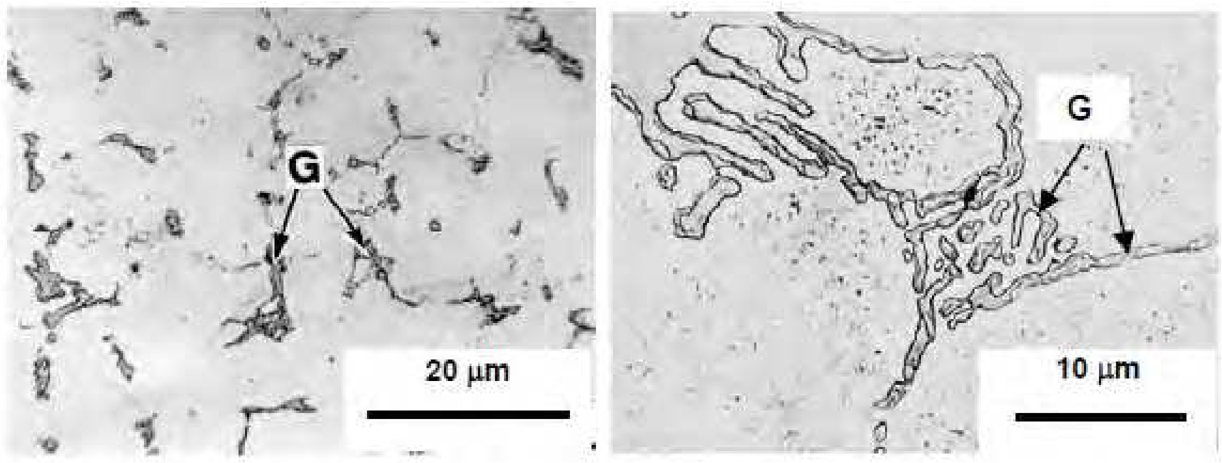



Fig. 6. Optical micrograph of Haynes-25. G mainly $M_6C$ carbides (Jovanović et al).

## 4. ALLVAC 718 plus™

Inconel 718 is a nickel base superalloy that is used extensively in aerospace applications because of its unique high temperature mechanical properties. Since it was invented by Eiselstein, it has been used as a material of construction for aero-engine and land based turbine components. The reasons for alloy 718's popularity include excellent strength, good hot and cold workability, the best weldability of any of the superalloys and last, but not least, moderate cost. However, the application of the alloy has been limited to a temperature below 650 ◦C, as its properties deteriorate rapidly on exposure above this temperature due to the instability of the main strengthening phase of the alloy, γ″ (Idowu & Ojo, 2007). With prolonged exposure at this temperature or higher, γ″ rapidly overages and transforms to the equilibrium δ phase with an accompanying loss of strength and especially creep life (Kennedy, 2005).

Other wrought, commercial superalloys exist which have significantly greater temperature capability such as Waspaloy and René 41. These alloys are typically γ′ hardened and are significantly more difficult to fabricate and weld. Because of this and because of their intrinsic raw material content, these alloys are significantly more expensive than alloy 718. There have been numerous attempts to develop an affordable, workable 718-type alloy with increased temperature capability. After a number of years of systematic work, including both computer modeling and experimental melting trials, ATI Allvac has developed a new alloy, Allvac® 718Plus™, which offers a full 55°C temperature advantage over alloy 718. The alloy maintains many of the desirable features of alloy 718, including good workability, weldability and moderate cost (Kennedy, 2005).

ATI Allvac has extensively investigated the 718Plus alloy billet properties, both as an internal program and as part of the Metals Affordability Initiative program entitled "Low-Cost, High Temperature Structural Material" for turbine engine ring-rolling applications. The objective of all these programs is to develop an alloy with the following characteristics:

- 55°C temperature advantage based on the Larson-Miller, time-temperature parameter
- Improved thermal stability; equal to Waspaloy at 704°C
- Good weldability; at least intermediate to 718 and Waspaloy alloys

- Minimal cost increase; intermediate to 718 and Waspaloy alloys
- Good workability; better than Waspaloy alloy

The use of 718Plus alloy in elevated temperature applications is of interest for military systems. In particular, the manufacturing difficulties associated with alloys such as Waspaloy provide a need for a material with similar component capabilities, but with better producibility. Initial characterization shows that the alloy exhibits many similarities to Alloy 718, including good workability, weldability and intermediate temperature strength capability (Bergstrom & Bayhan, 2005).

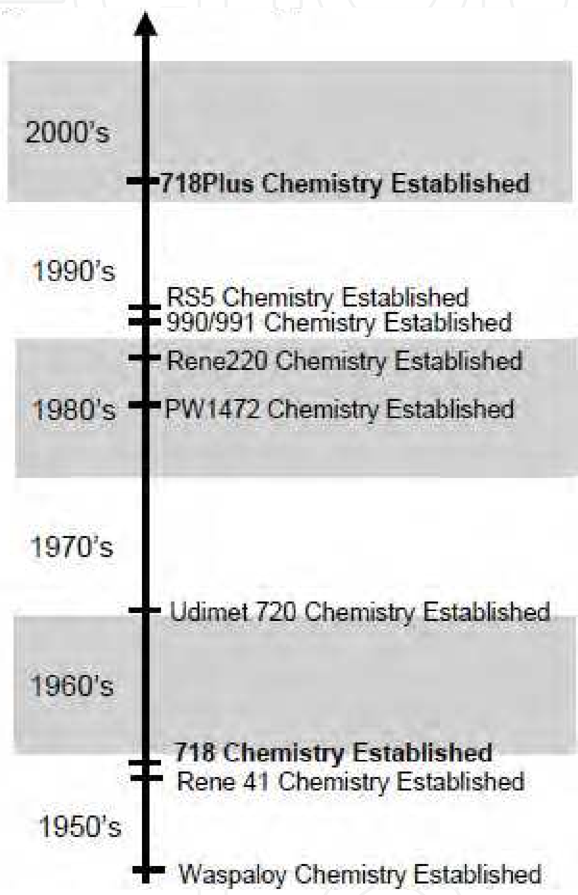



Fig. 7. Developments leading up to alloy 718 and subsequent efforts to improve capability over 718 (Otti et al, 2005).

Since the advent of the first superalloys over 60 years ago, alloy developers have worked to promote strength and high temperature stability while balancing processability. Processing constraints for many alloy systems preclude their general use for cast and wrought forging applications. Instead these compositions are used in the cast form, or are producible only using powder metallurgy. The development and introduction of alloy 718 in the late 1950's offered a significant breakthrough in malleability and weldability relative to other high strength alloys available at that time including Waspaloy and René 41 which are primarily gamma prime strengthened. Since the introduction of alloy 718 a significant number of alloys have been examined, including cast as well as wrought alloys, with the primary intent to maintain or improve properties and provide increased thermal stability while maintaining favorable processability. Some of the alloys developed subsequently are shown along with 718, Waspaloy, and René 41 in the development timeline of Fig. 7. A key requirement beyond strength, toughness, fatigue, creep, crack growth resistance, and processability which has also driven composition development is weldability (Otti et al, 2005).

### 4.1 Chemistry

There are lots of wrought alloys in use for gas turbine engine parts, such as Waspalloy, which have high temperature capability. But they are typically much more difficult to manufacture and fabricate into finished parts and also significantly more expensive than alloy 718 (Bond & Kennedy, 2005). Therefore when ALLVAC 718 plus is compared to Inconel 718 this newly modified super alloy has the higher content of Al+ Ti, the higher ratio of Al/ Ti and the addition of W and Co instead of Fe. As a result it provides increased temperature capacity up to 55°C and impressive thermal stability. Therefore it closes the gap between Inconel 718 and Waspalloy, as combining the good processability and weldability of Inconel 718 with the temperature capability of Waspalloy. (Schreiber et al, 2006). The chemical compositions of the ALLVAC 718 plus with Inconel 718 and Waspalloy are given in Table 6.

| Alloy | Chemistry, wt% | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | C | Cr | Mo | W | Co | Fe | Nb | Ti | Al | P | B |
| 718Plus | 0.025 | 18.0 | 2.70 | 1.0 | 9.0 | 10.0 | 5.40 | 0.70 | 1.45 | 0.007 | 0.004 |
| 718 | 0.025 | 18.1 | 2.90 | – | – | 18.0 | 5.40 | 1.00 | 0.45 | 0.007 | 0.004 |
| Waspaloy | 0.035 | 19.4 | 4.25 | – | 13.25 | – | – | 3.00 | 1.30 | 0.006 | 0.006 |

Table 6. Nominal chemistry comparison of the ALLVAC 718 plus, Inconel 718 and Waspalloy (Cao, 2005).

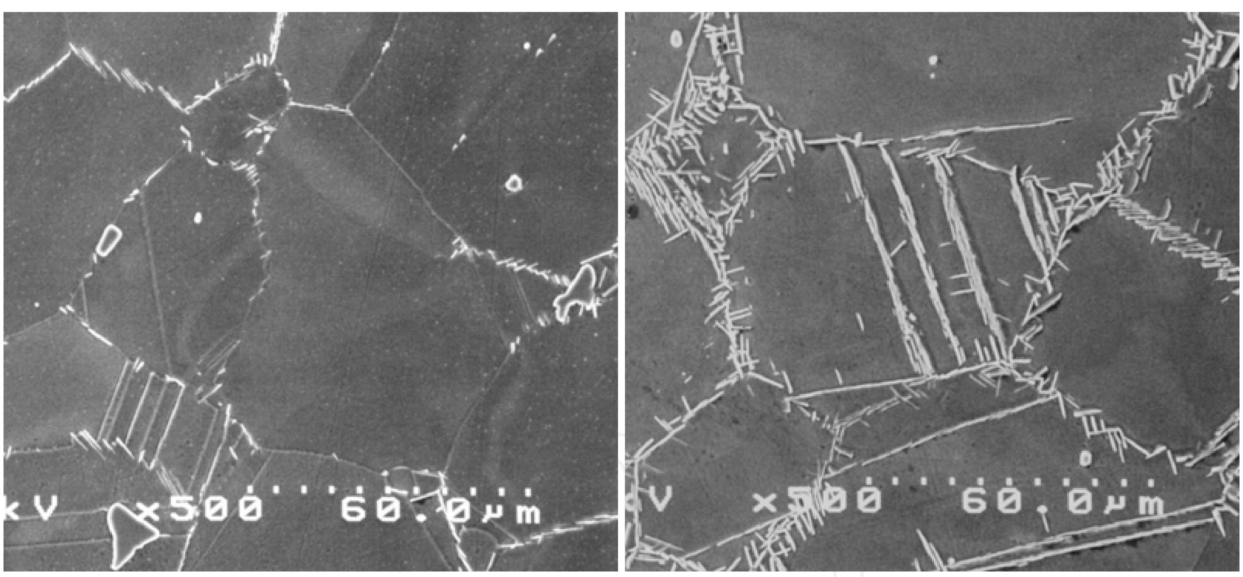
Alloy 718Plus has a much larger content of γ′ and γ ″ than alloy 718 and a smaller amount of δ phase. Solvus temperatures for γ′ and γ″ are also higher in alloy 718Plus. All of these points likely contribute to improved high temperature properties. One of the major differences between alloy 718 and Waspaloy is the speed of the precipitation reaction. The γ″ precipitation in alloy 718 is very sluggish and accounts in part for the good weldability and processing characteristics of the alloy.

In 718- type alloys primarily Fe, Co, Mo and W are the matrix elements. The effects of alloying elements on microstructure, mechanical properties, thermal stability and processing characteristics of alloy are important factors. Niobium is one of the major hardening elements and the other two is Al and Ti. The change in Al/ Ti ratio and the increase in Al+ Ti content converts the alloy into a predominantly γ′ strengthening alloy and it gives the alloy an improved thermal stability. Furthermore the modification on the content of Al and Ti develop the optimum mechanical properties of the alloy. Another factor on the improvement of the mechanical properties and thermal stability is the addition of Co up to about 9 wt%. Still further improvement occurs with Fe content of 10 wt%, 2.8 wt% Mo and 1 wt% W (Cao & Kennedy, 2004). Very small additions of P and B further increases stress rupture and creep resistance.

### 4.2 Strengthening mechanisms

As mentioned before, the primary strengthening phase is γ′ with a volume fraction ranging from 19.7-23.2 %, depending on the quantity of δ phase. Gamma prime strengthened alloys like Waspaloy and René 41 have much greater stability at higher temperature than γ″ strengthened alloys like 718 since γ″ grows rapidly and partially decomposes to equilibrium δ phase at temperatures in the 650–760°C range. Studies of the γ′ phase in 718Plus alloy show it to be high in Nb and Al, which is very different from the γ′ present in Waspaloy and René 41 and may account for its unique precipitation behavior and strengthening effects.

Like most superalloys there is a strong relationship between processing, structure and properties for alloy 718Plus. Optimum mechanical properties are achieved with a microstructure which has a small amount of rod shaped δ particles on the grain boundaries like that shown in Fig. 8 (a). Excessively high forging temperatures or high solution heat treating temperatures will result in structures with little or no δ phase precipitates that are prone to notch stress rupture failure. It is reported that no notch problems have been experienced using the 954°C solution temperature, probably because some δ phase can be precipitated at this temperature. However, excessively long heating times and possibly large amounts of stored, strain energy can result in large amounts of δ phase appearing on grain boundaries, twin lines and intragranularly, Fig. 8 (b). Such structures can lead to lower than expected tensile and rupture strength (Kennedy, 2005).




(a) (b)

Fig. 8. SEM Micrographs of Alloy 718Plus™ with (a) Preferred δ Phase Morphology and (b) Excessive δ Phase (Kennedy, 2005).

Alloy 718Plus does contain δ phase which is beneficial for conferring stress rupture notch ductility and controlling microstructure during thermo-mechanical processing. However, the volume fraction of the delta phase is considerably less than is found in alloy 718 and tends to be more stable with a much slower growth rate at elevated temperatures. Some γ″ may also be present in 718Plus alloy but in a much lower quantity, less than 7% (Jeniski & Kennedy, 2006).

When Inconel 718 is compared with the ALLVAC 718 plus it is reported that the size of strengthening phases increases in both alloys after long time thermal exposure (Fig. 9), but more significantly in alloy 718. In alloy 718, the average size of γ″+γ′ grows from about 15 nm at as heat-treated condition to almost 100 nm after 500 hrs long time aging at 760°C as indicated in Fig. 10 and the main strengthening phase γ″ grows to about 200nm in estimation (see Fig. 11). However, in alloy 718Plus, the main strengthening phase γ′ coarsens slowly and the average size of γ′ is still about 70 nm as indicated in Figure 9. These important quantitative phase analyses results convince us that alloy 718Plus has a superior stable microstructure in comparison with alloy 718 (Xie et al, 2005).

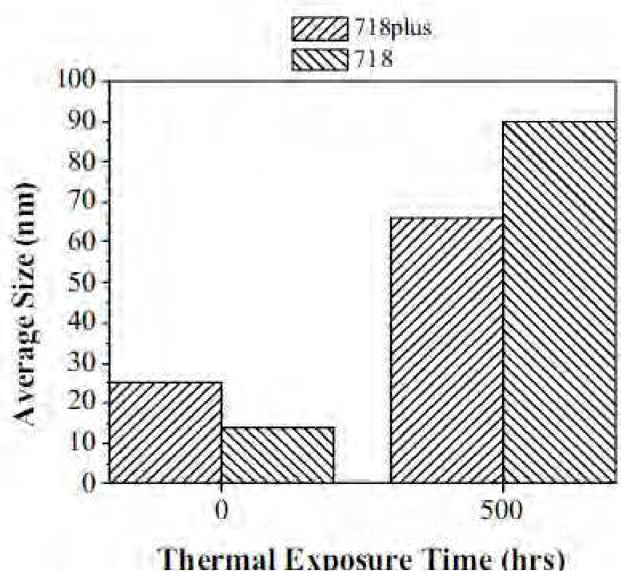



Fig. 9. The size of strengthening phases in Alloy 718 and Alloy 718 plus (Xie et al, 2005).

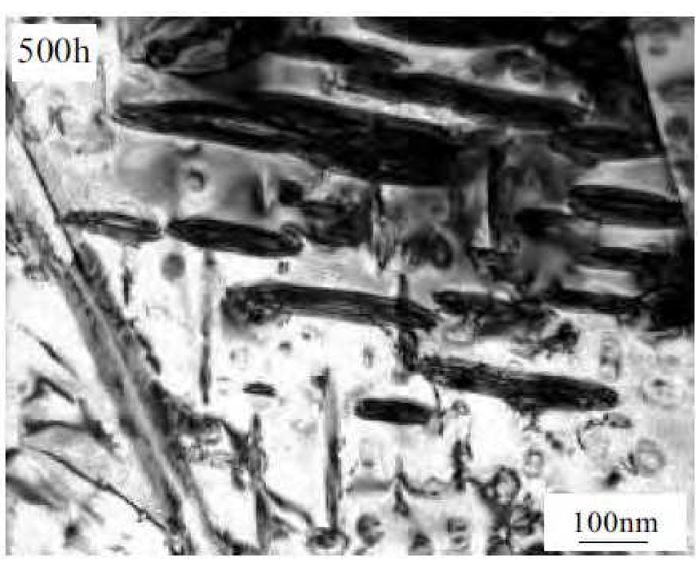



Fig. 10. The coarsening of strengthening phases γ´´ and γ´ in alloy 718 after 760°C (Xie et al, 2005).

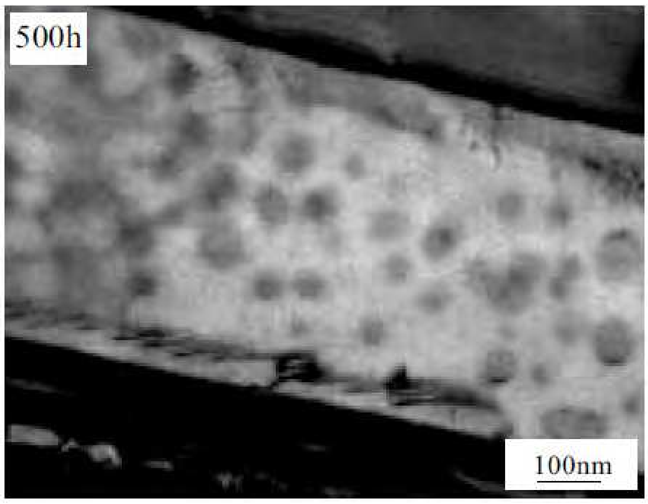



Fig. 11. The coarsening of strengthening phase γ´ in alloy 718 plus after 760°C Aging (Xie et al, 2005).

### 4.3 Microstructure

The microstructure of 718 plus in as received hot-rolled condition consists of FCC austenitic matrix with an average grain size of 50 µm. Fig. 12 shows the optical micrograph of the alloy. It can be seen that precipitates with round-to-blocky morphology are randomly dispersed within the microstructure (Vishwakarma et al, 2007).

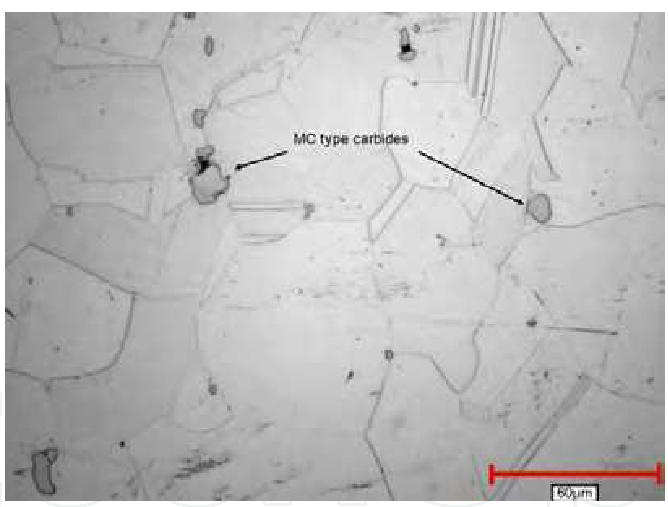



Fig. 12. Optical microstructure of as received 718 plus alloy (Vishwakarma et al, 2007).

SEM/EDS analysis of the precipitates shows them to be mainly Nb-rich MC type carbides containing Ti and C. As laves phase can be eliminated by high temperature homogenization and thermo–mechanical processing of wrought Inconel 718 and 718 Plus type of alloys, it is therefore not observed in the microstructure of the as received material. The delta phase, which is commonly observed in Inconel 718, is not observed in the as received microstructure of 718 plus alloy (Vishwakarma et al, 2007).

Heat treated at 950ºC for 1 hour microstructure of 718 plus alloy, grain size of 54 µm, which has normal B and P concentrations, has shown in Fig. 13. It can be seen that needle like δ phase is observed on the grain boundaries and occasionally intra-granularly on the twin boundaries. And also seen in the microstructure, round and blocky shaped MC type carbide particles are randomly distributed. Ti-rich carbo-nitride particles can be also observed (Vishwakarma & Chaturvedi, 2008). Intermetallic phases like FCC $\gamma'$ and BCT $\gamma''$ are expected to form in 718 plus alloys but $\gamma'$ is the main strengthening phase in these superalloys (Cao & Kennedy, 2004).

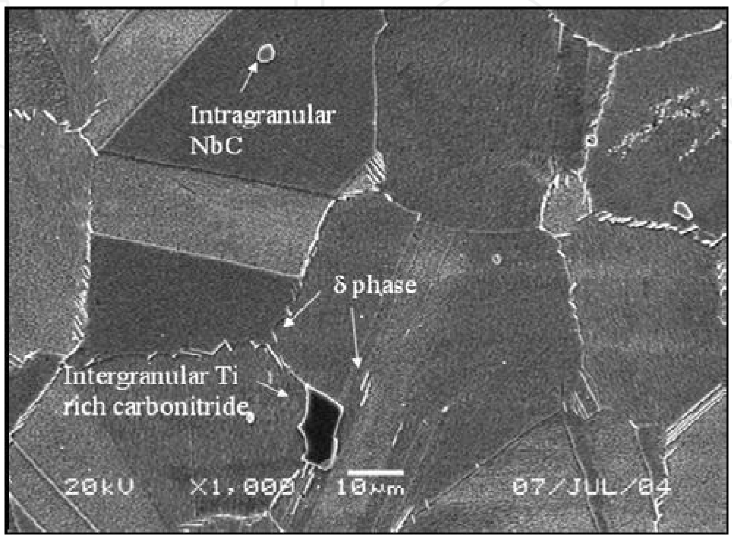



Fig. 13. Microstructure of 718 plus alloy heat treated at 950ºC for 1 h (Vishwakarma & Chaturvedi, 2008).

### 4.4 Mechanical properties

Alloy 718Plus™ has a significant strength advantage over alloy 718 at temperatures above 650°C and over the entire temperature range compared to Waspaloy and A286. Elongation for alloy 718Plus™ over the entire temperature range remained high at 18% minimum. These data are consistent with comparisons of alloy 718, Waspaloy, A286 and alloy 718Plus™ in other product forms, including billet, rolled rings, forgings and sheet (Bond & Kennedy, 2005). In Fig. 14 shows the effect of temperature on room temperature ultimate tensile strength for several alloys. The tensile strength of ALLVAC 718 plus and Waspaloy is shown in Fig. 15.

It is reported by ATI ALLVAC Cooperation that extensive studies demonstrated that this alloy has shown superior tensile and stress rupture properties to alloy 718 and comparable properties to Waspaloy at the temperature up to 704°C. However, relatively speaking, the data on fatigue crack propagation (FCP) resistance of this alloy are still insufficient. Alloys 718Plus, 718 and Waspaloy have similar fatigue crack growth rates under 3 seconds triangle loading at 650°C with 718Plus being slightly better. Waspalloy shows the best resistance to fatigue crack growth under hold time fatigue condition while the resistance of 718Plus is better than that of Alloy 718 (Liu et al, 2005).

Examination of the fatigue fracture surfaces by scanning electronic microscope (SEM) revealed transgranular crack propagation with striations for 718Plus at room temperature. The fracture mode at 650ºC is the mixture of intergranular and transgranular modes (Liu et al, 2004).

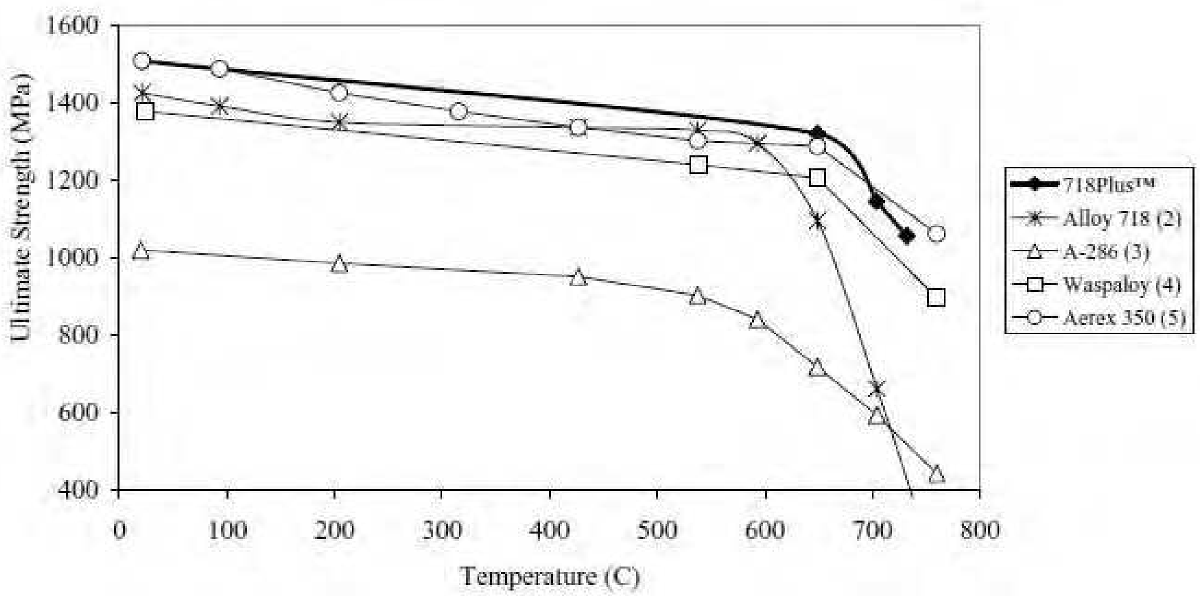



Fig. 14. Effect of test temperature on room temperature tensile ultimate tensile strength for several alloys (Bond & Kennedy, 2005).

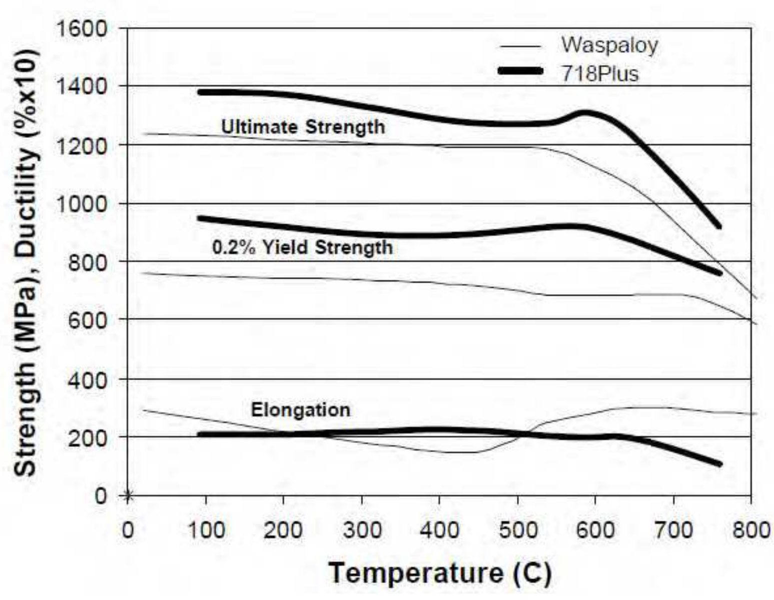



Fig. 15. The tensile strength of Alloy 718 plus and Waspaloy (Otti et al, 2005).

Direct aging can be effectively applied to alloy 718Plus to improve its mechanical properties, including strength and stress rupture life of alloy 718Plus. Considering the fine grain size and high strength resulting from direct aging, the low cycle fatigue resistance of this alloy should also be significantly improved although further experimental verification is necessary. DA processing of this alloy is also different from Waspaloy in that hot working at temperatures above the γ′ solvus can achieve a good, direct age response (Cao & Kennedy, 2005).

### 4.5 Weldability

There are numerous types of superalloys with a difference in weldability among the types. The solid solution alloys are the easiest to weld because they don't undergo drastic metallurgical changes when heated and cooled. Because of their limited strength, however, they are only used in certain areas of a gas turbine, such as the combustor.

The precipitation-strengthened alloys are more demanding during welding and post welding because of the precipitation of the hardening phase that usually contains aluminum, titanium, or niobium. These elements oxidize very easily and, therefore, alloys that contain them need better gas protection during welding. A third type of superalloy is the mechanically alloyed materials that cannot be welded without suffering a drastic drop in strength. These alloys are usually joined by mechanical means or diffusion bonding. In addition to those elements that enable a superalloy to undergo precipitation hardening, such as aluminum, titanium, and niobium, other elements are added to enhance mechanical properties or corrosion resistance. These include boron and zirconium, which are often intentionally added to some alloys to improve high temperature performance but at a cost to weldability. There are numerous other elements that are not intentionally added but can be present in very small quantities that are harmful, such as lead and zinc. These are practically insoluble in superalloys and can cause hot cracking during solidification of the welds. Small quantities of these elements on the surface of a metal can cause localized weld cracking. Sulfur is considered detrimental if present in too large a quantity, but can cause low weld penetration problems if present in very low amounts (Donald & Tillack, 2007).

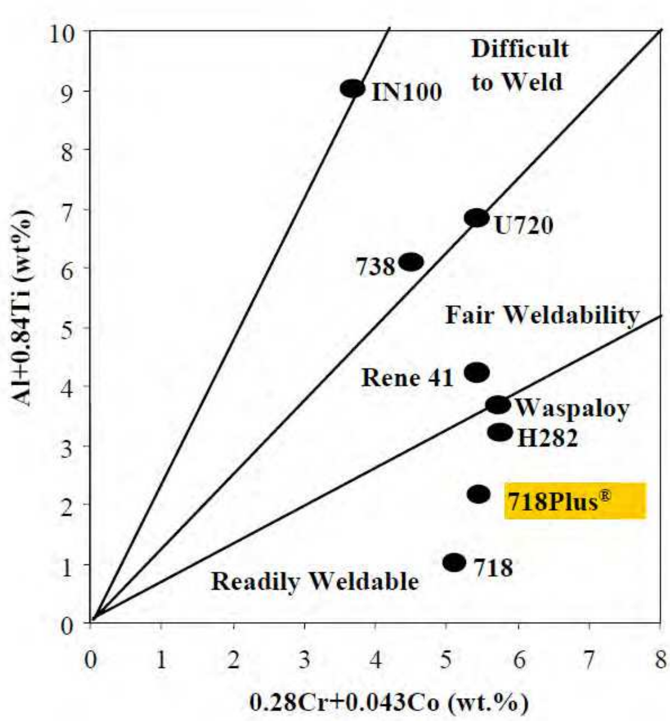



Fig. 16. Effect of chemistry on post-weld heat cracking (Jeniski & Kennedy, 2006).

It is reported that limited weldability testing has been conducted on 718Plus alloy but results have been encouraging. Weldability of alloy 718Plus is believed to be quite good, at least intermediate to alloys 718 and Waspaloy (Kennedy, 2005). Improved weldability over Waspaloy is one of the primary drivers for 718Plus alloy in engine applications. Figure 16 shows the weld cracking tendency for a number of well known commercial alloys and illustrates the good welding characteristics expected with 718Plus alloy based on its chemistry (Jeniski & Kennedy, 2006). Some micrographs of the Electron Beam Welded ALLVAC 718 plus, Inconel 718 and Waspaloy rings are shown in Fig. 17.

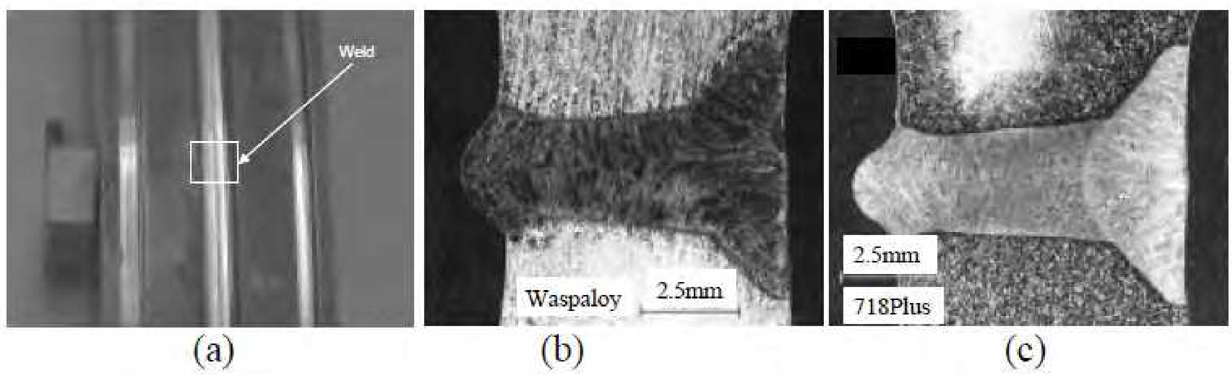



Fig. 17. EB welding of 890 mm diameter rolled rings, (a) typical weld location for 718, Waspaloy, and 718Plus welds and typical welds for (b) Waspaloy, and (c) 718Plus (Otti et al, 2005).

### 4.6 Cost and Applications

The first commitment to a production use of alloy 718Plus has been made for a high temperature tooling application, replacing Waspaloy as a hot shear knife. Other applications include aero and land-base turbine disks, forged compressor blades, fasteners, engine shafts and fabricated sheet/plate components. Product forms include rolled or flash butt welded rings, closed die forgings, bar, rod, wire, sheet, plate and castings.

The alloy also can be used for flash-butt welded ring applications. Sheet form of the alloy is being considered for fabricated engine parts such as turbine exhaust cases and engine seals. Fasteners remain another potential application for 718Plus alloy. The property advantages for 718Plus alloy have also led to its being considered for rotating parts. Cao and Kennedy have shown that 718Plus alloy is capable of direct aging (DA), low temperature working followed by aging with no prior solution heat treatment. DA processing resulted in the production of very fine grain material with yield strength improvement at 704°C of 70-100 MPa. The alloy is also being considered for blading applications in areas where alloy 718 is limited due to elevated operating temperatures.

The alloy has also other applications outside of the jet and power turbine engines. Any application that currently uses alloys 718, Waspaloy, René 41 or other nickel-based superalloys can consider 718Plus alloy as a substitute for reasons of cost savings or increased temperature capability. Other markets where 718Plus alloy has potential are automotive turbo-chargers or industrial markets like chemical process or oil and gas where alloy 718 is used (Jeniski & Kennedy, 2006).

The cost of finished components of alloy 718 Plus is expected to be intermediate to alloys 718 and Waspaloy (Kennedy, 2005).

## 5. Acknowledgment

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## 6. Conclusion

A superalloy is a metallic alloy which is developed to resist most of all high temperatures, usually in cases until 70 % of the absolute melting temperature. All of these alloys have an excellent creep, corrosion and oxidation resistance as well as a good surface stability and fatigue life.

The main alloying elements are nickel, cobalt or nickel – iron, which can be found in the VIII· group of the periodic system of the elements. Fields of application are found particularly in the aerospace industry and in the nuclear industries, e.g. for engines and turbines.

The development of these advanced alloys allows a better exploitation of engines, which work at high temperatures, because the Turbine Inlet Temperature ( TIT ) depends on the temperature capability of the material which forms the turbine blades. Nickel-based superalloys can be strengthened through solid-solution and precipitation hardening.

Nickel-based superalloys can be used for a higher fraction of melting temperature and are therefore more favourable than cobal-based and iron-nickel-based superalloys at operating temperatures close to the melting temperature of the materials.

The newly innovated nickel based ALLVAC 718 Plus superalloy which is the last version of Inconel 718 has been proceeding in the way to become a material that aerospace and defense industries never replace of any other material with combining its good mechanical properties, easy machinability and low cost.

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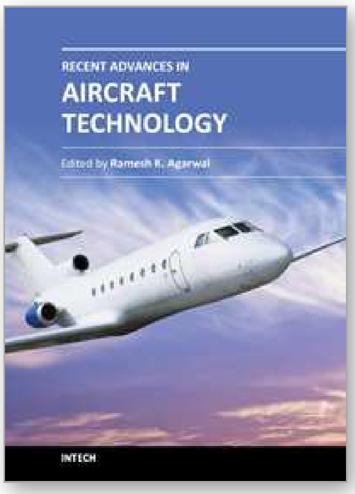




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