Physico-chemical structural and mechanical characterization of nickel base superalloys

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Keywords

Nickel-based superalloys, heat treatments, microstructure

1. Introduction

Initially iron-nickel based superalloys (16-25-6 alloy with 16%Cr, 25% Ni and 6%Mo and the first nickel based alloys Nimonic and Inconel) were formed by solid solution hardening. Later, nickel and nickel-iron based superalloys contained small amounts of aluminum and titanium (2-3%) to maintain the high hardness at high temperatures by precipitation of the hardened aluminum-titanium phase (γ'). Currently, nickel-based superalloys contains larger amounts of aluminum (up to 6%), are used at greater temperatures without loosening the mechanical characteristics [1].

2. Physico-chemical characterization

Physical properties as electrical conductivity, specific heat, thermal conductivity and thermal expansion coefficient have low values compared to other complex alloys. These properties are influenced by the presence of basic metals and refractory metals. Density is an important property of complex alloys in the construction of aircraft engines. Modern superalloys have densities of nickel alloys lower than in the past used to build complex components.

Nickel based superalloys are made of austenitic matrix (cubic faced centered), and a variety of secondary phases. The secondary phases are carbides type: MC, $M_{23}C_6$, M_6C, faze γ' [$Ni_3(Al, Ti)$], and γ'' (Ni_3Nb) phases.

3. Structural and chemical characterization

Alloying elements for nickel base superalloys are aluminum and/or titanium, whose concentration does not exceed 10%.

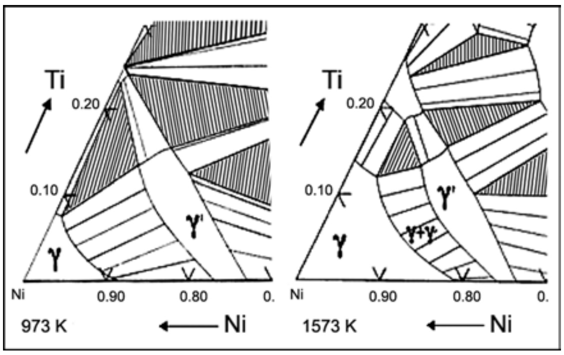


Figure 1. Ni-Al-Ti ternary equilibrium diagram [2].

They form two equilibrium phase: γ and γ'. Phase γ' provides resistance to high temperatures and creep resistance.

The content of γ' phase depends on the chemical composition and temperature, as is shown in Figure 1. The ternary equilibrium diagram (Ni-Al-Ti) shows γ and γ' domains and for a certain chemical composition phase γ' percentage decreases with increasing temperature [2].

Figure 2 shows Al-Ni equilibrium diagram and Figure 3 the crystallographic structure of $AlNi_3$ intermetallic compound.

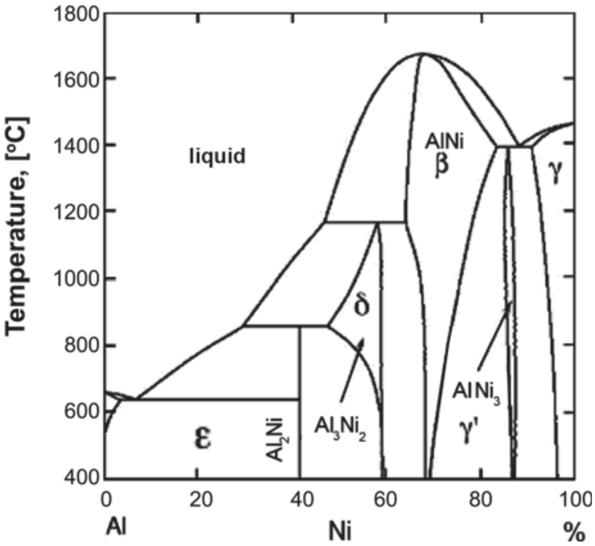


Figure 2. Al-Ni diagram

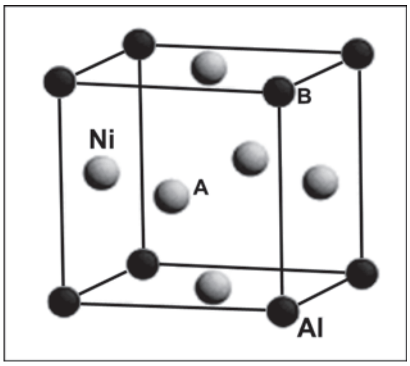


Figure 3. Crystallographic structure of $AlNi_3$ intermetallic compound

From Figure 3 it is observing that the structure compound is cubic faced centered (CFC), Ni atoms are placed at the intersection of the diagonals.

4. Mechanical characterization

The main alloying elements and mechanical characteristics at 20°C are shown in Table 1.

The main nickel based commercial alloys which maintain the mechanical characteristic at temperature of 870°C are shown in Table 2 and in Table 3 are presented the main applications of nickel based alloys.

In Table 4 are presented the chemical composition and applications of some nickel-chromium alloys.

5. General characterization of nickel-based superalloy mark 718 Inconel

Nickel-based superalloy type Inconel 718, with austenitic structure is used at high temperature applications as discs, blades, jet engines. Table 5 shows the chemical composition of nickel based superalloys in wrought and cast state. The chemical composition of nickel-based superalloy Inconel 718 is presented in Table 6, and heat treatments applied are presented in Table 7. Generally small granulation is obtained by rolling and higher granulation is obtained by forging [3].

Figure 4 shows the microstructure of fine and grob grain of nickel base superalloy Inconel 718.

Table 1. Mechanical characteristics of nickel based superalloys

Alloy	Principal alloying element	Tensile strength [N/mm^2]	Yield strength [N/mm^2]	Elongation A_5 [%]	HV10 Hardness	
					Minimum values	Maximum values
Nichel 200 (annealed)	-	380…550	100…275	60-40	120	170
Duranichel 301 (aging hardened)	4.4% Al + 0.6%Ti	min 1300	min 900	min 28	389	515
Monel R 405 (hot rolled)	30% Cu	min 525	min 230	min 35	157	192
Inconel 600 (annealed)	15%Cr+ 8%Fe	min 640	min 210	min 48	191	242
Hastelloy, C-4	16%Cr+ 15% Mo	min 785	min 400	min 54	295	336

Table 2. Main nickel based commercial alloys

Commercial alloy	State	Tensile strength, Rm_{min} [N/mm^2]	Yield strength, $Rp_{0,2\,min}$ [N/mm^2]	Elongation, A_5 min [%]
Astroloz	Wrought	770	690	25
Hastelloy X	Wrought	255	180	50
IN-100	Cast	885	695	6
IN-102	Wrought	215	200	110
Inconel 625	Wrought	285	275	125
Inconel 718	Wrought	340	330	88
MAR-M 200	Cast	840	760	4
MAR-M 432	Cast	730	605	8
Rene 41	Wrought	620	550	19
Udimet 700	Wrought	690	635	27
Waspaloy	Wrought	525	515	35

Table 3. Main applications of pure nickel based superalloys

Nickel alloy commercial	Application
200	Food processing equipment, chemical, electrical and electronic components, aerospace components, electrodes, etc.
205	Conductive wires, anodes, cathodes, etc.
220	Base materials for electronic parts, etc.
230	Special applications for electronic parts
270	Heat exchangers, heat shields, electrodes, etc.

Table 4. Chemical composition and applications of some nickel-chromium alloys

Ni-Cr alloy	Ni*	Cr	Fe	Mn	Si	Other elements	Applications
	[%]						
Inconel 600	75.0	15.5	8.0	0.5	0.2	-	Heat exchangers, welding electrodes
Inconel 601	60.5	23.0	14.1	0.5	0.2	1.4 Al	Components of electric furnaces, special electrodes
Inconel 625	61.0	21.5	2.5	0.2	0.2	9.0 Mo, 3.6 Co	Nozzles, combustion systems, welding electrodes

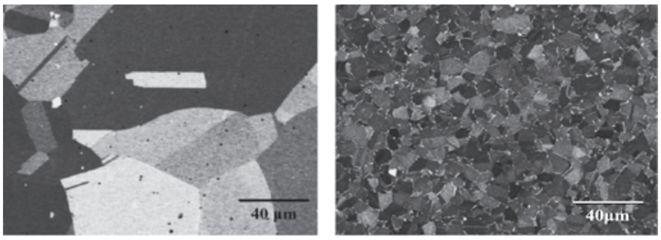
* At maximum percentage values

Table 5. Chemical composition of nickel based in wrought and cast state

Alloy	Ni*	Cr	Co	Mo	Al	Ti	Co	C	B	Zr	Other elementss
	[%]										
Wrought superalloys											
Inconel X-750	73	15	-	-	0.8	2.5	0.9	0.04	-	-	6.8%Fe
Udimet 500	53.6	18	18.5	4.0	2.9	2.9	-	0.08	0.006	0.05	-
Udimet 700	53.4	15	18.5	5,2	4.3	3.5	-	0.08	0.03	0.05	-
Waspaloy	58.3	19.5	13.5	4.3	1.3	3.0	-	0.08	0.006	0.05	-
Astroloy	55.1	15.0	17.0	5.2	4.0	3.5	-	0.06	0.08	-	-
Nimonic 80 A	74.7	19.5	1.1	-	1.5	2.5	-	0.06	-	-	-
Nimonic 90	57.4	19.5	18.0	-	1.4	2.4	-	0.07	-	-	-
Nimonic 115	57.3	15.0	15.0	3.5	5.0	4.0	-	0.15	-	-	-
Cast superalloys											
MAR-M200	64	8.0	10.0	6.0	6.0	1.0	-	0.10	0.015	0.1	4.0 Ta
Inconel 738	61	16.0	8.5	1.7	3.4	3.4	0.9	0.12	0.01	0.10	1.7%Ta; 2.6%W

* At maximum percentage values

Table 8 summarizes the values of some mechanical characteristics determined at two testing temperatures (600°C and 550°C) for Inconel 718 superalloy [4].



a) b)

Figure 4. Superalloy Inconel 718 microstructure: a) austenitic structure with grob grains, b) austenitic structure with fine grains [5]

Table 6. Chemical composition of Inconel 718 nickel-based superalloy

Element [%]	Material	
	Inconel 718 alloy Grob granulation	Inconel 718 alloy Fine granulation
C	0.032	0.023
Si	0.09	0.03
Mn	0.12	0.03
P	0.006	0.002
S	0.0001	0.0017
Ni	53.6	52.3
Cr	18.64	18.00
Mo	2.95	3.18
Co	0.15	0.02
Cu	0.04	0.005
Ti	1.02	0.98
Al	0.479	0.49
Fe	18.05	19.5
Nb	5.11	5.35
Ta	0.017	-
Ni	rest	rest

Table 7. Heat treatments applied Inconel 718 nickel based superalloy

Material	Deformation process	Delivery form	Heat treatments applied	Grain dimensions [µm]
Superalloy 718 gob granulation	Wrought	sheet	Tempering: 1045 °C, air cooling Aging: 720°C for 8 hours, furnace cooling 620°C, cooling in air	100 ÷ 200
Superalloy 718 fine granulation	Rolled	Bar	Tempering: 960 ° C 1 hour, air cooling Aging: 720°C 8 hours, cooling in furnace 620 ° C cooling air 8:00	10 ÷ 20

Table 8. Values of some mechanical characteristics determined at two testing temperatures (600°C and 550°C) for Inconel 718 superalloy [4]

Inconel 718 superalloy	Testing temperature [°C]	Tensile strength [N/mm^2]	Elongation A_5 [%]	HV10 Hardness
Grob granulation	600	1000…1089	min 21	320…425
Fine granulation	550	1180...1212	min 21	350…440

Figure 5 shows the fatigue variation of superalloy Inconel 718 with a fine and grob austenitic structure.

Analyzing the results of fatigue tests (S-Nf) shown in Figure 5 results:

• In the lower durability zones and high stress, differences of the grain size does not influence much the results for the material examined with the two types of grains

• In the high durability and low stress zone (polycyclic fatigue region) difference in grain have very different outcomes, thus fine granulated material is superior with high fatigue resistance.

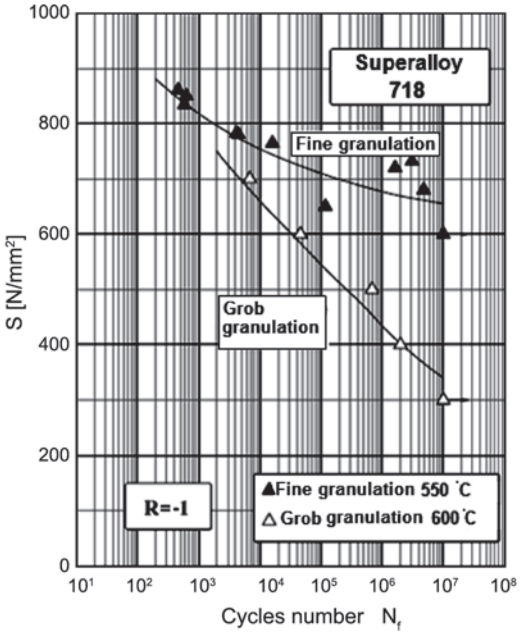


Figure 5. Fatigue variation of Inconel 718 superalloy

Figure 6 is shows the structure of nickel-based superalloy Type Inconel 718.

The structure consists of austenite γ, γ' and γ" phases and complex carbides. In Figure 7 are presented the characteristic structures of superalloy type 718 in wrought and cast state.

In wrought state at the austenitic grain boundaries (γ') are placed $M_{23}C_6$ precipitation and in the base mass are developed MC precipitation and in cast state in the base table (metal) occurs structures γ' normally cooled, at the dendrites limits are $M_{23}C_6$ and MC precipitation. It is noted that the wrought

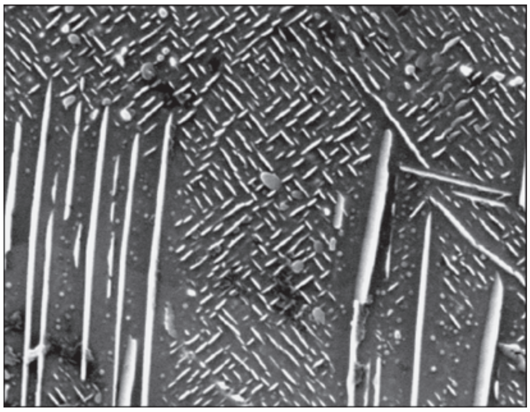


Figure 6. Microstructure of nickel-based superalloy Type Inconel 718 [2000×] [5]

alloys are formed macles in γ' grains whose size is based on the degree of material forging [5]. Figure 8 is shown the microstructure of nickel based alloy Inconel 718, initial state.

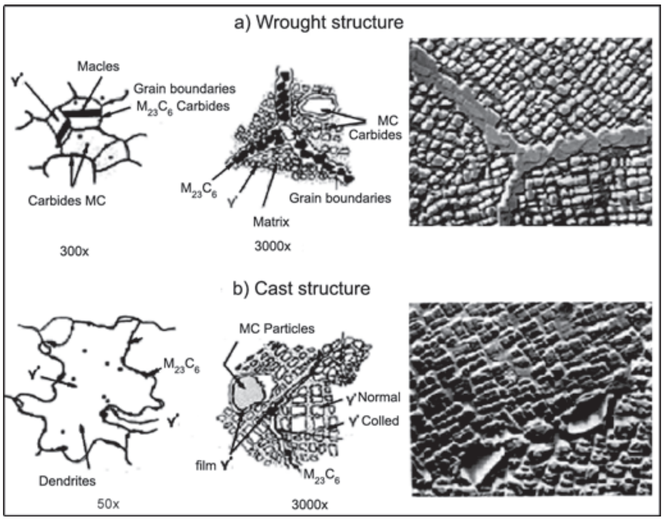
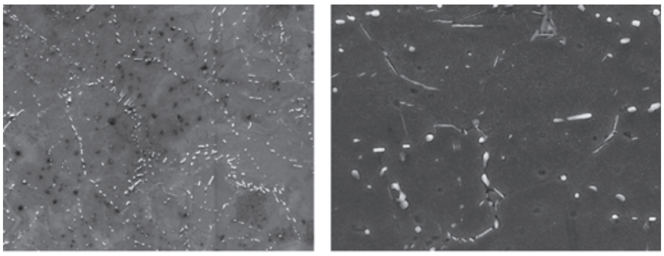


Figure 7. Characteristics structures of nickel based superalloy: (a) wrought state (b) cast state [3].



a) b)

Figure 8. Microstructure Inconel tip 718 superalloy: a) 200×, b) 500 ×.

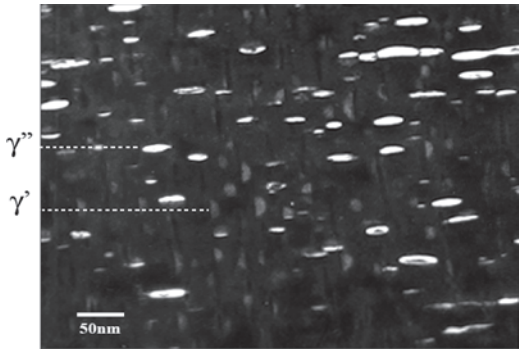


Figure 9. Microstructure nickel-based superalloy, Inconel 718

There is an non-uniform distribution of γ' and γ" particles mainly located on grain boundaries. In Figure 9 is shown the microstructure of nickel-based superalloy, Inconel 718 after aging 24 hours at 750°C. Following the heat treatment mentioned, in the structure have developed two distinct phases γ' and γ" in austenitic structure (γ) with hardness between 560 and 720 HV10.

Table 9 shows the alloying elements of Ni-based superalloys and their influence on the structure of superalloys.

Table 9. Alloying elements influence on the superalloys structure

Element	Influence mode
Nickel	CFC matrix, γ' formation
Cobalt	Hardening solution, influence the γ' phase, influences the formation of complex carbides
Chromium	Improves oxidation resistance
Titan	Formation γ' phases
Aluminum	Formation γ' phases improves oxidation resistance
Carbon	Carbide forming elements

6. Conclusions

5.1. When temperatures tend to 540°C, usual steels and titanium alloys do not have the hardness required to the application, they also may show and corrosion phenomena at these temperatures

5.2. For applications at high temperatures (1200°C) a high hardness is necessary, for which are used nickel-based superalloys

5.3. Nickel base alloys can be used at higher temperatures than refractory alloys.

5.4. At lower temperatures and depending on the hardness required the nickel-based superalloys can be replaced with iron-nickel based alloys, because they are cheaper than nickel-based superalloys

5.5. The majority of forged nickel-based superalloys have chromium content to ensure higher corrosion resistance. If the cast superalloys based on nickel, the chromium content is lower and are added other elements to ensure alloy hardness at high temperatures. In the case of nickel-based superalloys, aluminum content is higher and the chrome content is lower. However, resistance to oxidation of nickel based superalloys is the same or even higher.

5.6. Superalloys have very good resistance to oxidation but not sufficient corrosion resistance. In many applications at high temperatures (760°C) as aircraft turbines, superalloys must be covered. Coverage technology depends on the application of the superalloy, it s can be used as coatings elements such as nickel, chromium, tungsten, molybdenum.

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