The correlation between heat treatment, structure and mechanical characteristics in Inconel 718

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Abstract
The mechanical characteristics of Inconel 718 alloy resulting from the heat treatments currently used in industry are compared with those produced with a newly introduced treatment. The advantages obtainable with the latter concern the minimum creep rate and the characteristics of the welded joints. The results obtained are correlated with the particular physical metallurgy of the material under examination.

Riassunto
Correlazione trattamento termico, struttura e caratteristiche meccaniche della lega inconel 718
Le caratteristiche meccaniche della lega Inconel 718, risultanti dal trattamento termico della pratica industriale corrente, sono confrontate con quelle relative ad un trattamento innovativo. I vantaggi ottenibili con quest'ultimo riguardano la velocità di deformazione per scorrimento e le caratteristiche statiche di giunti saldati. I risultati ottenuti sono correlati con la particolare metallurgia fisica del materiale in esame.

Introduction

Inconel 718 is the registered trade name of a nickel-based superalloy patented by Huntington Alloys in 1962 (1). Its chemical composition is given in Table 1.
The high mechanical strength over the temperature range minus 250 to +700° C and the excellent weldability (compared with other alloys of the same type) have encouraged its use in various sectors of industry (2). Its biggest field of application is in aircraft gas turbines — in particular the greatest users are General Electric and Pratt & Whitney.
From the enormous number of references to Inconel 718 in the literature, we can obtain a great many facts about its technological and mechanical properties.
Nevertheless, bearing in mind that during the same period of the spread of inconel 718 significant progress was made in acquiring basic knowledge of the behaviour of materials, the proper use of the available information demands a critical revision of the same, with integration by means of appropriate investigations.
The heat treatment currently used in industrial practice (TTA) is as follows:
Solution heat treatment by soaking for a period of at least 30 minutes at a temperature of 924 - 1010° C, precipitation ageing by heat soaking for 8 hours at a temperature of 718 ± 14° C, furnace cooling down to 621 ± 14° C and holding at this temperature until the total heat treatment time reaches 18 hours, with final air cooling.

TABLE 1 - Nominal composition of Inconel 718

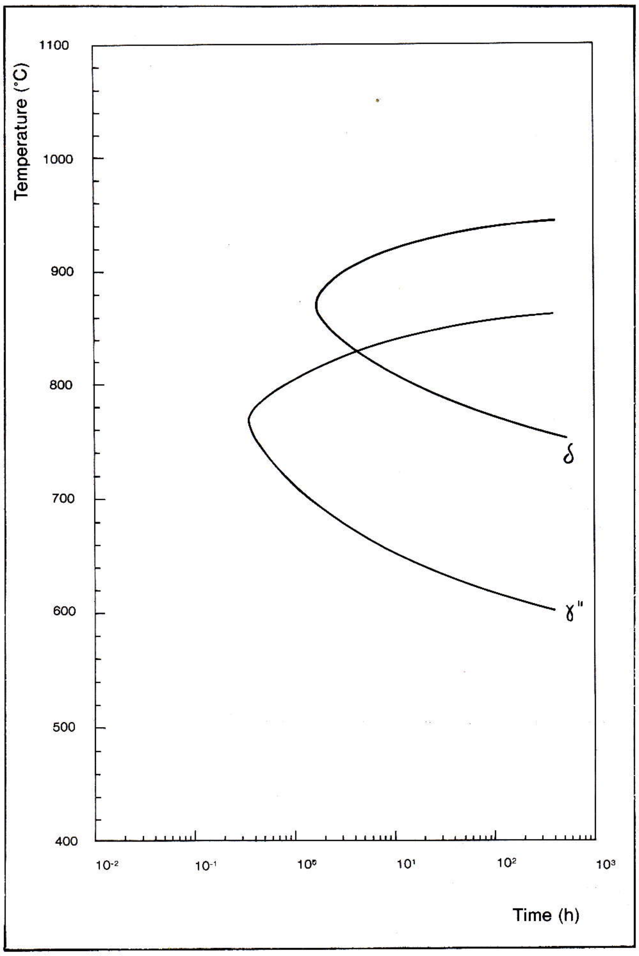
Element	% weight
Carbon	0.08 max.
Manganese	0.35 max.
Silicon	0.35 max.
Phosphorus	0.015 max.
Sulphur	0.015 max.
Chromium	17.0 – 21.0
Cobalt	1.0 max.
Molybdenum	2.80 – 3.30
Niobium + Tantalum	4.75 – 5.50
Titanium	0.65 – 1.15
Aluminium	0.20 – 0.80
Iron	Rest
Copper	0.30 max.
Nickel + Cobalt	50.0 – 55.0
Boron	0.006 max.

At the Idaho National Engineering Laboratory a new heat treatment has been developed which enables toughness values to be obtained markedly superior to those achieved with the conventional heat treatment (3). This improvement becomes especially important when the material is to be used in the fabrication of welded structures. The method of carrying out this innovative treatment is as follows:
Solution heat treatment at a temperature of 1093° C for 1 hour, furnace cooling down to 718° C for 4 hours, subsequent cooling in furnace down to a temperature of 621° C, holding for 16 hours at the last temperature, air cooling down to ambient temperature.
In laying down the experimental activity at the Fiat Research Centre, it was taken into consideration the heat treatment developed at the Idaho National Engineering Laboratory, since the present data are incomplete for adopting the new heat treatment in industrial practice. On the other hand, the survey of technological and mechanical characteristics for different heat treatments enables us to create a basis of useful data for investigating the correlation between microstructure and properties.

Structure

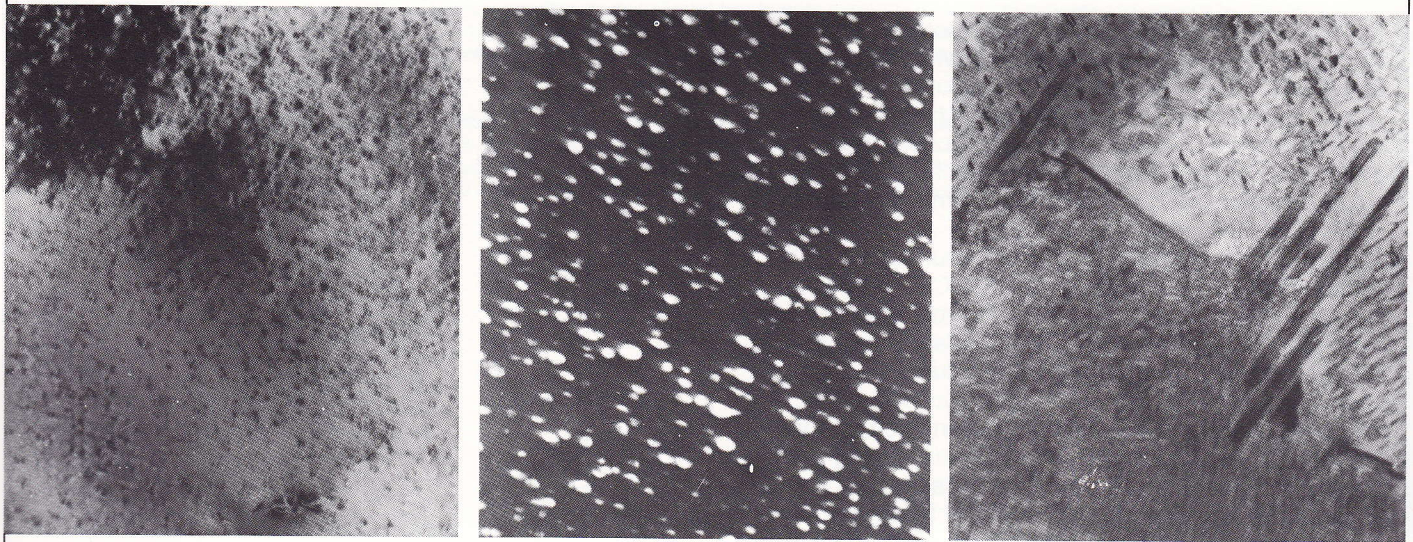
The structure of Inconel 718, resulting from the prescribed heat treatments, is rather complex: the matrix is of f.c.c. type, the secondary phases which determine the particular behaviour of the alloy are characterised by the presence of niobium (4,5).
The γ' phase, Ni_3 (Al,Ti, Nb), precipitates in the form of ordered and coherent spherical particles; however, in contrast to most other superalloys, the γ' contributes only 10 - 20% to the overall strengthening of the matrix. The alloy's high strength is due mainly to the presence of the γ'' phase. This has a b.c.t. structure, ordered and coherent, precipitated in the form of plates, whose fraction of volume is about 16%.
Both γ' and γ'' phases are metastable; they can change into δ phase (Ni_3Nb), having an orthorhombic lattice not coherent. The formation of the δ phase involves a deterioration in the mechanical properties of the alloy.
In the present work, determination of the precipitation curves of the secondary constituent phases of Inconel 718 alloy was done by several techniques: hardness testing, optical metallography and electron microscopy. Crop-ends of rod, solution treated at 1090° C, where subjected to isothermal ageing at temperatures between 500 and 1050° C, and times from 15 minutes to 250 hours. On the basis of the results of hardness analyses, the precipitation curve for the γ'' phase was drawn with reference to the conditions determining hardness values $\geqslant$ 250HV; the curve in Fig. 1 was

Fig. 1 - Precipitation curves for γ'' and δ phases.



constructed by interpolating hardness data obtained experimentally. The same figure shows the δ -phase formation curve obtained by optical microscope analysis.
Some specimens were subsequently analysed by transmission electron microscopy, with the aim of verifying the precipitation curve and acquiring information on the evolution of the γ'' and δ phases. Some of the metallographs obtained are shown in Fig. 2.
Examination of the precipitation curves allows us to distinguish a fundamental difference between the conventional heat treatment and the innovative one: in the former, solution heat treatment principally concerns the γ'' phase, while in the latter it concerns, both γ'' and δ phases. The δ phase dissolution improves the effectiveness of the γ'' -phase precipitates which are produced in subsequent phases by heat treatment.
The negative aspect of the new heat treatment lies in the growth of grain size. Metallographic analysis carried out for both conditions of heat treatment showed a grain size equal to ASTM 5 for the conventional H.T. and ASTM 2 for the innovative one. Furthermore, electron

Fig. 2 - Structure evolution following exposure at 775° C.



a) γ'' phase nucleation (15′); b) γ' and γ'' phases precipitation (4h); c) δ phase formation (64h).

TABLE 2 - Tensile characteristics revealed on material subjected to conventional heat treatment (A) and on materials subjected to innovative treatment (B)

STATIC CHARACTERISTICS					
H.T.	T. Test (° C)	R (MPa)	$R_{0.2}$ (MPa)	A (%)	Z (%)
A	R.T.	1369	1060	24	50
		1355	1049	23	53
	649	1102	913	20	48
		1116	933	21	45
	704	954	794	11	26
		974	901	12	22
B	R.T.	1321	971	19	39
		1358	1009	20	37
	649	1061	782	22	42
		1087	856	18	40
	704	1020	798	16	40
		968	808	17	50

TABLE 3 - Experimental conditions of creep test at 704° C and results obtained in terms of time, elongation and reduction of area at failure

Stress (MPa)	H.T.	t (h)	A (%)	Z (%)
260	A	4838	31	54
	A	4914	32	54
	B	7595	20	32
280	A	3570	24	52
	A	3762	42	60
	B	5684	13	26
300	A	2561	30	53
	A	2953	29	53
	B	3937	15	22
340	A	1946	27	54
	B	2822	11	22
380	A	778	23	53
	B	1013	11	26
450	A	262	29	50
	B	284	10	18

microscopy revealed a greater amount of MC type carbides, at grain boundaries, in materials subjected to the innovative treatment. For both types of treatment the presence of the Laves phases was not shown up.

MECHANICAL CHARACTERISTICS

Tensile properties

Tensile characteristics were determined, on specimens subjected to both treatments, at room temperature, 649 and 704° C. The tensile strength (R), the 0.2% proof stress (R 0.2), the elongation at failure (A) and the reduction of area (Z), obtained, are given in Table 2.

Creep

Creep tests have been performed using multi-specimen and single-specimen furnaces available at Fiat Research Center. Test conditions were fixed on the basis of data given in the technical literature (16): temperature 704° C with six different stress levels, 260, 280, 300, 340, 380 and 450 MPa. Table 3 recapitulates the data regarding time, elongation and reduction of area at failure.
It is possible to see, as with the increase in time up to failure obtained using the new treatment, a reduction in ductility takes place, whether in terms of section reduction or of elongation.
The availability of elongation data as a function of time enabled us to obtain values for minimum creep rate ($\dot{\varepsilon}$) and to correlate this with the imposed stress (σ).
Fig. 3 shows the results obtained. It is clear from these

Fig. 3 - Stationary creep rates, as a function of stress at a temperature of 704° C.

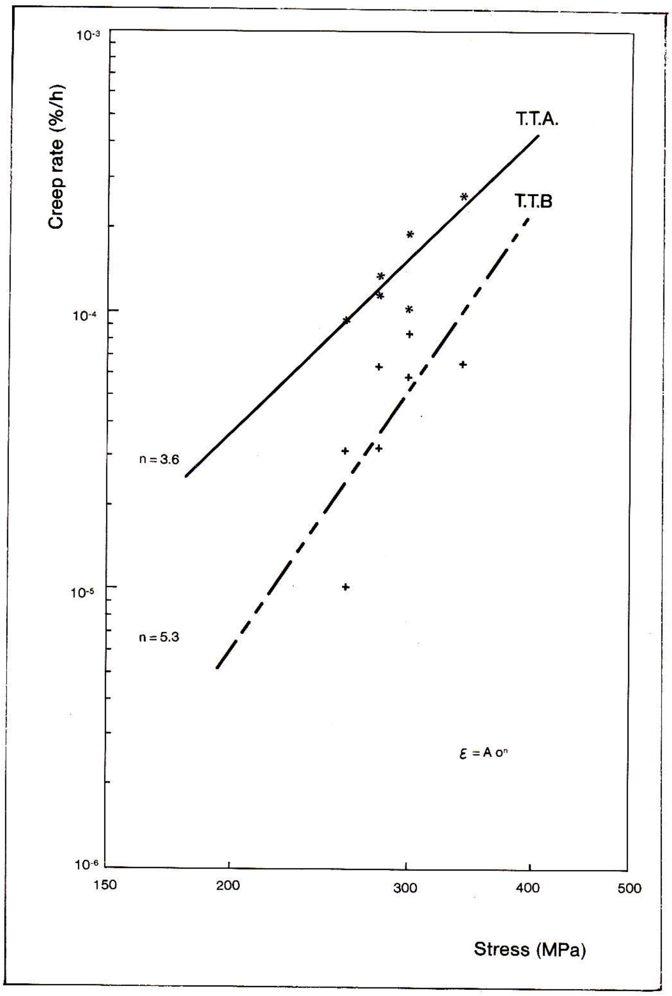


TABLE 4 - Influence of post-welding heat treatment on tensile characteristics at room temperature

STATIC CHARACTERISTICS				
Post-welding heat treatment	R (MPa)	$R_{0.2}$ (MPa)	A (%)	Failure zone
Untreated	807	423	38	S
	822	407	41	S
718° C × 4 h	1246	1033	6	S
621° C × 8 h	1303	1116	8	S
A	1296	1034	8	S
	1300	1054	19	S
B	1275	981	17	S
	1232	1008	20	MB

S = failure corresponding to weld.
MB = failure of parent metal.

TABLE 5 - Influence of post-welding heat treatment on tensile characteristics at room and high temperature

H.T.	T. Test (c)	R (MPa)	$R_{0.2}$ (MPa)	A (%)	Failure zone
A	R.T.	1296	1034	8	P
		1300	1054	19	S
	649	958	805	7	S
		1056	846	7	S
	704	919	740	6	S
B	R.T.	1275	981	17	S
		1232	1008	20	MB
	649	1056	781	19	MB
		1071	813	13	MB
	704	901	741	11	S
		946	762	17	MB

results that the creep rate is noticeably reduced with the new treatment, compared with that obtained when the alloy is subjected to the conventional treatment.

Welding

The influence of post-welding heat treatment on the tensile characteristics of TIG-welded joints was evaluated. The welding was carried out on material in the solution-heat-treated state, with subsequent cleaning-up of the weld bead.
Table 4 presents the tensile characteristics, obtained at room temperature, for different post-weld heat treatments. In addition, hot (649 and 704° C) tensile tests were made on welded joints subjected to solution heat treatment and ageing, for both the heat treatments considered. The results obtained are presented in Table 5.
It is possible to see how adopting the new treatment, joints are obtained with mechanical characteristics practically identical with those of the parent material. Analysis by scanning electron microscope has revealed the formation of Laves phases in the welding process (Fig. 4); the improvement in mechanical properties resulting from the new heat treatment is presumably due to the dissolution of such phase

Fig. 4 - Evidence of Laves phase.
Composition (% weight): Ni 34, Fe 15, Cr 15, Nb 23, Mo 12, Ti 1.

Conclusions

The advantages obtainable with the innovative heat treatment of Inconel 718 concern the creep deformation rate and the tensile characteristics of the welded joints.
Considering the type of dependence of creep rate on a stress ($n \sim 4$), it is possible to suppose that the deformation mechanism is intragranular; therefore the greater creep resistance obtained with the innovative heat treatment could be correlated with the greater effectiveness of the γ'' -phase distribution obtained with this treatment.
The new heat treatment presents advantages such as post-weld heat treatment; it endows the junction zones with static characterisitic identical with those of the parent metal. The improvement obtained must be attributed to the solution of the Laves phases formed during the welding process.
The negative elements encountered in the behaviour of material subjected to the new treatment must be attributed to the greater grain size. This results, in fact, in deterioration of the tensile characteristics at room temperature, and of the ductility under creep conditions.

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