DEVELOPMENT OF A LOW THERMAL EXPANSION, CRACK GROWTH RESISTANT SUPERALLOY

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Abstract

Low thermal expansion superalloys have been used for a number of years in a variety of applications, including gas turbine engines. The low thermal expansion characteristics of the most widely used class of materials are derived from the ferromagnetic characteristics of Ni, Fe, and Co-based austenitic matrices containing little or no Cr. Over time, a progression of alloy developments ensued, aimed at improving the oxidation resistance and stress accelerated grain boundary oxygen (SAGBO) attack. While notch rupture tests have been used to screen for the SAGBO phenomenon, a more sensitive measure of this characteristic is the sustained load crack growth test performed in air.

This paper describes some final iterations in the development of a new class of low expansion superalloys utilizing high Al content and $\gamma,\,\gamma',$ and β phases in the microstructure. Such alloys provide good general oxidation resistance, and rupture strength and ductility, and varying degrees of crack growth resistance. A number of designed factorial experiments were carried out to optimize 538°C crack growth resistance, yet maintain a balance of other important engineering properties. These experiments included examinations of Ni, Fe, Co, Cr, Nb, and Ti content combined with heat treatment studies. Al content remained essentially fixed on the basis of prior development work. Tests performed included thermal expansion, tensile, tensile and Charpy impact stability, stress rupture, creep, 538°C static crack growth, and microstructural analysis.

These studies showed, that for a given heat treatment cycle, a small amount of Cr combined with increased Co content in place of Ni provides a decrease in crack growth rate. Furthermore, the small Cr addition improves salt spray resistance, yet the addition is small enough as not to significantly affect thermal expansion performance. The crack growth rate was also reduced with increased Co content replacing Ni. The final alloy composition was designated INCONEL® alloy 783.

Crack growth rates were affected by heat treatment. Microstructural examinations showed heat treatment affected amounts of globular β phase present after hot working and annealing, and amounts of the phase re-precipitated within grain boundaries or intragranularly. Slower propagation rates correlated with increased volume percent of β phase with lower temperature anneals, or increased amounts of β phase precipitated in grain boundaries after high temperature anneals and " β -aging" at intermediate temperatures. A high temperature anneal was selected for compatibility with high temperature braze cycles without significantly coarsening grain structure. An appropriate β age was determined for good rupture and crack growth properties. Heat treatment studies further showed that higher yield strengths are achieved with treatments incorporating slow cooling within the γ'

precipitation range. A final aging treatment compatible with other superalloys, such as alloy 718 was therefore selected for optimum tensile strength.

Alloy 783 has been successfully produced as VIM-VAR large diameter forging billet, and hot rolled small rounds and flats. Sustained load crack growth data at 538°C obtained from seamless rolled turbine engine rings are presented in this paper. Alloy 783 has been successfully welded and fabricated into gas turbine engine components that are under evaluation by gas turbine manufacturers.

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Introduction

For over two decades research has been directed at developing controlled low thermal expansion superalloys. 1.2 These efforts were initially successful in the commercial development of INCOLOY® alloys 903, 907, 908, and 909. This class of superalloys have found significant commercial usage in industries as diverse as gas turbine engine static parts and superconducting magnets for fusion reactors. However, it has not been possible to fully exploit the advantages of high strength, low expansion materials in elevated temperature designs due to the poor general surface oxidation resistance and their susceptibility to fast crack growth under sustained loading in air at intermediate temperatures.

Procedure and Experimental Techniques

<u>Development Procedure.</u> The alloy development goal was to simultaneously optimize low thermal expansion, tensile strength and ductility at elevated temperatures, creep strength, stress rupture life and notch ductility, general oxidation and corrosion resistance, stability after long time exposure at intermediate service temperatures. Manufacturing and fabricating simplicity, and compatibility of heat treatments and joining parameters with other commonly used gas turbine superalloys were other factors that were considered advantageous and were evaluated throughout the development project.

In addition to the above superalloy characteristic goals, the primary goal was to achieve intermediate temperature, sustained load, crack growth resistance. Specifically, it was believed that a $\gamma\gamma'$ - β , controlled expansion superalloy should have da/dt at 538°C approaching that of thermomechanically processed, conventionally heat treated, INCONEL alloy 718. Past experience had shown that da/dt at 538°C was a critical alloy property to optimize if any new controlled expansion superalloy was to gain significant commercial usage. For static engine components, and other applications as well, it appeared feasible to achieve a commercial balance of physical, mechanical, thermal, manufacturing/fabricating, and crack growth properties within the $\gamma\gamma'$ - β alloy system.

Development of INCONEL alloy 783 was by necessity a concurrent development project. Compositions within the $\gamma\gamma$ - γ - β superalloy system were systematically explored via a series of interlocking factorial designs, and were screened for certain properties (such as da/dt). At appropriate points in the development process, certain compositional variations were also subjected to varying heat treatments using factorial designs to determine the compositional-heat treatment interactive and synergistic effects on selected properties. Response surface analyses were utilized to examine "the lay of the land", that is, the effect of two or more factors in combination on a given property. The significantly non-linear and interactive effects of Ni and Co on stress rupture life have been shown before, and demonstrate the need for this approach to alloy development.

Since optimization factors included manufacturing and fabricating simplicity, full scale commercial-sized melts were produced using $\gamma\gamma'$ - β compositions which were known to be non-optimal in properties. These full scale melts were subjected to various manufacturing processes and evaluated for manufacturing feasibility. Some portions of this approach have been described.

This paper contains some examples of studies aimed at determining the effects of Co/Ni and Cr content, and the interaction of heat treatment on constant load crack growth, with discussion of other properties as relevant.

Compositions and Processing. The compositions evaluated in this paper are presented in Table I. Laboratory heats, designated by an HV prefix, were vacuum induction melted, 100 mm diameter, 22 kg ingots. These were homogenized, cut in half, and hot rolled on a 16 inch Birdsboro mill to 0.750 in diameter round bars and to 0.500 inch by 2 inch flats. Mechanical property test specimens were machined from the round bars and compact tension test specimens were

machined from the flats. A few flats and round bars were subjected to mechanical property tests and microstructural evaluations to verify that structure and properties were similar within a given ingot.

Full scale melts, designated with a Y prefix, were vacuum induction melted and vacuum arc remelted. The process history for Y9342Y is described elsewhere. Melt number Y9411Y was one of three vacuum arc remelted 457 mm diameter by 3810 mm long ingots. This ingot was homogenized and hot forged and rolled to 203, 254 and 305 mm diameter billets. Seamless rolled rings 50.8 mm thick by 101.6 mm high by 610 mm outside diameter were produced from a 203 mm diameter billet. These rings were subjected to property evaluations. Heat number Y9342Y is representative of non-commercially available Cr-free $\gamma\gamma$ - β superalloys. Heat number Y9411Y represents the commercial, Cr-alloyed $\gamma\gamma$ - β superalloy, INCONEL alloy 783.

<u>Testing</u>. Basic room and elevated temperature tensile, combination notch-smooth stress rupture, and thermal expansion testing were conducted in accordance with ASTM Standard Test Methods E8, E21, E139 and E228, respectively.

Static or constant load crack growth testing was conducted using standard compact tension specimens machined in conformance to ASTM E 647-91. Specifically, compact tension specimens were 7.6 mm thick by 25.4 mm wide. Overall outer dimensions were 30.5 mm by 31.8 mm. Specimens were fatigue pre-cracked in accordance with E647 to provide a starting nominal pre-crack plus notch length of 7.6 mm. Specimens satisfied the validity requirements of E 647-91 section 7.2.1. Static load crack growth testing was conducted at 538°C under induction heating in air at an initial stress intensity of nominally 27 MPa $\!\!\!\!/$ m.

Crack length measurements were recorded using traveling optical microscopes, electrical potential, and compliance techniques. The potential and compliance techniques were calibrated using optical microscopy measurements. Crack growth testing was predominantly conducted at Martest, Inc., where both optical and compliance techniques were used. Some testing was conducted at Inco Alloys International, Inc., using both electrical potential and optical techniques. Crack growth results were found to be reproducible between the two laboratories and across the three testing techniques.

Transient behavior at the initiation of the crack propagation test was typically observed which was comparable to that often observed in superalloy crack growth testing. This portion of the crack growth raw data was ignored for this analysis.

Table I Chemical compositions, weight %.

HEAT	С	Fe	s	Si	Ni	Cr	Al	Ti	Nb	Co	В	
HV7340	0.007	Bal	0.0025	0.10	29.9	<0.1	5.4	0.14	3.1	34.1	0.006	
HV7341	0.006	Bal	0.0024	0.09	30.0	2.0	5.4	0.14	3.1	32.0	0.006	
HV7342	0.007	Bal	0.0024	0.08	30.0	3.0	5.4	0.14	3.1	31.0	0.006	
HV7346	0.017	Bal	0.0024	0.11	32.9	<0.1	5.4	0.13	3.1	31.0	0.007	
HV7347	0.009	Bal	0.0022	0.10	32.9	2.0	5.5	0.14	3.1	28.9	0.006	
HV7348	0.017	Bal	0.0022	0.08	33.0	3.0	5.4	0.14	3.1	27.9	0.006	
HV7361	0.004	Bal	0.0025	0.12	27.4	2.9	5.4	0.23	3.0	34.9	0.008	
HV7365	0.008	Bal	0.0025	0.10	27.0	4.0	5.4	0.10	3.1	33.1	0.008	
HV7369	0.015	Bal	0.0023	0.11	30.0	4.0	5.3	0.10	3.1	30.1	0.009	
HV7373	0.007	Bal	0.0020	0.10	33.0	4.0	5.4	0.09	3.1	27.0	0.008	
HV7498	0.009	Bal	0.0027	0.09	24.1	3.0	5.4	0.09	2.9	38.7	0.007	
HV7500	0.007	Bal	0.0037	0.10	26.9	3.0	5.4	0.10	3.0	35.8	0.007	
HV7502	0.008	Bal	0.0042	0.10	29.9	3.0	5.4	0.10	3.0	32.7	0.007	
HV7504	0.013	Bal	0.0029	0.10	33.1	3.1	5.3	0.09	2.9	29.6	0.008	
Y9342Y	0.005	Bal	0.0014	0.02	32.9	<0.1	5.3	0.58	3.0	31.0	0.006	
Y9411Y	0.004	Bal	0.001	0.03	28.6	3.0	5.4	0.01	3.0	33.9	0.004	

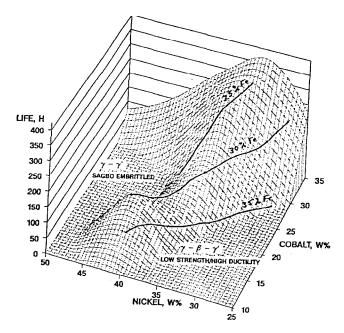


Figure 1 Effect of Ni and Co on the stress rupture life at 649°C and 510 MPa of Cr-free $\gamma\gamma$ - β alloys.³

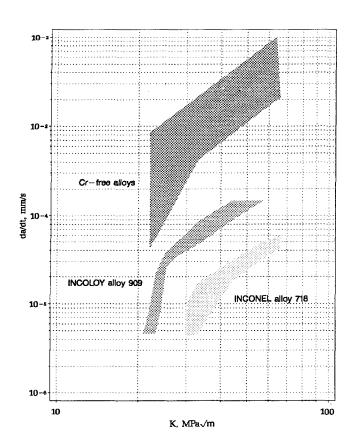


Figure 2 Comparison of da/dt at 538° C of Cr-free $\gamma\gamma$ - β alloys, INCOLOY alloy 909, and INCONEL alloy 718.

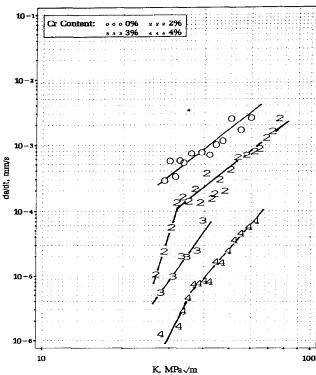


Figure 3 Effect of varying Cr content on da/dt at 538° C. Nominally 30% Ni, 27.5% Fe, 5.4% Al, 0.1% Ti, 3% Nb, balance Co. Cr added at expense of Co.

Results

<u>Crack Growth in Cr-Free yy'-\beta Superalloys.</u> Depending on the selected Ni and Co content, \(\gamma y'-\beta \) superalloys exhibited good 649°C stress rupture life, as shown in Figure 1. Notch rupture lives in excess of the targeted goal were achieved. The full large scale melt Y9342Y also showed good 538°C notch (K_1 = 2) rupture properties with lives exceeding 363 h under 827 MPa. These notch rupture properties were significant improvements over existing controlled thermal expansion superalloys and were thought to indicate probable resistance to sustained load crack growth.

However, sustained load crack growth testing at 538° C revealed a different situation. As shown in Figure 2, the range of da/dt at 538° C for Cr-free $\gamma\gamma$ - β alloys was actually worse than INCOLOY alloy 909, despite these same alloys having superior notched stress rupture lives.

The crack growth rate was somewhat sensitive to heat treatment, but no significant improvements were found possible. This data illustrates the potential fallacy of using notched stress rupture data as indicators of sustained load crack growth resistance.

Effect of Cr on da/dt in $\gamma\gamma'$ - β Alloys. The effect of varying Cr content on da/dt at 538°C is shown in Figure 3. Cr was added at the expense of Co. Ni, Fe, Al, Ti and Nb contents were held constant at nominally 30%, 27.5%, 5.4%, 0.1% and 3%, respectively. Compact tension specimens were annealed at 1010°C for one hour and age hardened at 788°C for 16 hours, furnace cooled 55°C/h to 621°C, held for 8 h, and air cooled. Increasing Cr content from nil to 4% improved da/dt resistance by over 2 orders of magnitude.

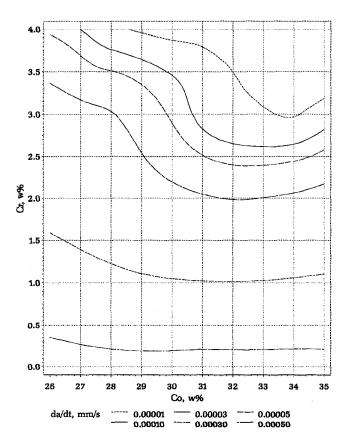


Figure 4 Effect of Cr and Co on da/dt at 538°C and 33 MPavm.

Response Surface Analysis: Cr-Co-da/dt. The preceding experiment led to expanded composition factorial studies to define the Cr-Co-da/dt response surface for alloy specimens annealed at 1010°C for one h, air cooled, and age hardened at 788°C for 16 h, furnace cooled 55°C/h to 621°C, held for 8 h and air cooled. The resulting da/dt isocontours versus Cr and Co, shown in Figure 4, reveal a Cr-Co interaction effect on da/dt in alloys containing greater than 2% Cr content. Da/dt decreases with Cr at all Co levels, but especially at Co contents greater than roughly 30%. The desired da/dt rates fell within a pocket of greater than 2.5% Cr and greater than about 30% Co content.

Response Surface Analysis: Cr-Co-E. The effect of Cr and Co on the secondary creep rate of specimens tested at 649°C under 380 MPa is shown in Figure 5, as creep rate isocontours. Heat treatment was the same as noted above. Creep rate varied as a bowl relationship with Cr and Co, with minima occurring between 26 and 30% Co and 2 to 4% Cr. While increasing Co content increased the creep rate for any given Cr content, increasing Cr content up to 3.5% decreased the creep rate. It was therefore possible to offset losses in creep strength due to increasing Co content (for added da/dt resistance) by also increasing Cr content.

Effect of Co/Ni content and heat treatment on da/dt. Table II summarizes the effect of varying the Co/Ni content for alloys containing 3% Cr simultaneously with heat treatment on sustained load da/dt at 538°C and 33 MPaVm. Fe, Al, Ti and Nb were held constant at nominally 26%, 5.4%, 0.1% and 3%, respectively.

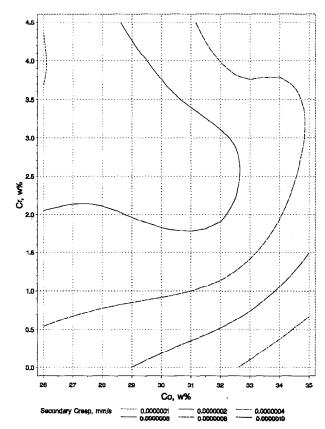


Figure 5 Effect of Cr and Co on secondary creep rate at 649°C under 380 MPa stress.

Annealing heat treatments were conducted at 982 and 1038°C for one hour and air cooled. Aging heat treatments were conducted at 732, 788, and 843°C for 16 h then furnace cooled 55°C/h to 621°C for 8 h and air cooled. Additionally, specimens were given a high temperature solution anneal at 1121°C for one hour and air cooled, followed by an intermediate heat treatment at 843°C for 2 h, air cooled, and age hardened at 732°C for 8 h furnace cooled to 621°C held for 8 h, and air cooled.

Sustained load crack growth was a strong function of the Co/Ni content and the heat treatment, as well as interactions between the composition and heat treatment. Regardless of the heat treatment, increasing the Co/Ni ratio reduced crack growth rates, though the amount of reduction in da/dt depended on both the anneal and aging temperatures. Specimens of 24% Ni content consistently failed to sustain crack growth, with cracking repeatedly stalling. When da/dt was measurable, rates were less than 0.9×10^6 mm/s. In most cases, the creep crack threshold was above 33 MPa $\!\!\!\!/$ m. On the other hand, specimens of 33% Ni content consistently had the highest da/dt for any given combination of annealing and aging temperatures.

Both annealing and aging temperatures had significant effects on da/dt. Annealing at 982°C resulted in lowest crack growth rates for all aging temperatures. Crack growth rates increased significantly in specimens annealed at 1038°C, by nearly an order of magnitude in specimens containing 30% or more Ni content. Increasing the aging heat treatment temperature consistently decreased da/dt for all annealing temperatures and at all Ni contents, except for those specimens containing 24% Ni.

Table II Effect of Co/Ni content and heat treatment on da/dt (106 mm/s) at 538°C and 33 MPa/m.

Anneal:		982°C			1121°C			
Aging Temperatures:	732°C, FC 621°C, AC	788°C, FC 621°C, AC	843°C, FC 621°C, AC	732°C, FC 621°C, AC	788°C, FC 621°C, AC	843°C, FC 621°C, AC	843°C, AC 732°C, FC 621°C, AC	
24% Ni (HV7498)	crack growth stalled	<0.2	crack growth stalled	crack growth stalled	crack growth stalled	not tested	crack growth stalled	
27% Ni (HV7501)	0.7	precrack fractured	<1	5	1.8	0.5	2	
30% Ni (HV7503)	2	1.3	<0.1	15	9	5	11	
33% Ni (HV7505)	5.8	crack growth stalled	1.5	30	35	10	32	

Notes:

- 1) Annealed at temperature shown for one hour, air cooled.
- 2) Two-step ages: Initial temperature held for 16 h, furnace cooled 55°C/h, to 621°C held for 8 h, air cooled.
- 3) Three-step age: 843°C held for 2 h, air cooled. 732°C held for 8 h, furnace cooled 55°C/h to 621°C held for 8 h, air cooled.

The da/dt of the solutionized, intermediate and age hardened specimens also showed strong sensitivity to Ni content. This study demonstrated that da/dt performance is controlled by the judicious use of combined heat treatment temperatures and times. Exposing specimens to the 843°C heat treatment permitted the use of high temperature, solutionizing and grain coarsening anneal.

INCONEL alloy 718 da/dt. There is a considerable amount of da/dt data at 649°C published for alloy 718, but little da/dt data at 538°C. This was data determined by Sadananda and Shahinian from plate using non-optimal composition and thermomechanical processing. To generate more relevant da/dt data, a fully heat treated turbine engine ring of 38.1 mm thick by 50.8 mm high was sacrificed for specimens.

The da/dt in the axial and radial orientations were determined at 538°C and are shown in Figure 6. Also plotted on this figure are the da/dt results obtained from fully heat treated plate. Compact tension specimens from both the ring and from the plate were heat treated at 954°C for 1 h, air cooled, 718°C for 8 h furnace cooled to 621°C, held for 8 h, and air cooled.

The da/dt of the engine ring was dependent on orientation to some degree, with the axial da/dt being lower than the radial da/dt. The ring had significantly better da/dt versus the plate. This was the result of the controlled thermomechanical ring-rolling process and composition intended to result in a controlled microstructure and good crack growth resistance. The da/dt of this ring matched the da/dt of a 50.8 mm diameter rod hot rolled and fully heat treated as produced at Inco Alloys International. This range of da/dt at 538°C was adopted as the goal.

Alloy 783 Engine Ring, Effect of Anneal Temperature. Based on the above examples and several other studies, a composition was selected for evaluating the large scale manufacturing feasibility. The aimpoint composition was 28.5% Ni, 34% Co, 5.4% Al, 3% Cr, 3% Nb, 0.006% B, with Ti and Si each less than 0.2%, and Fe being the balance. The actual composition of heat Y9411Y is given in Table I.

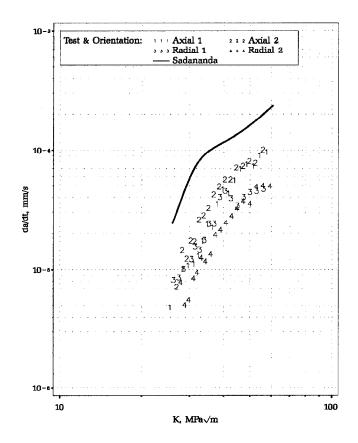


Figure 6 INCONEL alloy 718 da/dt at 538°C. Data determined from engine ring and from plate (Sadananda⁵).

Effect of Heat Treatment. Sustained load crack growth performance of INCONEL alloy 783 is also dependent on the heat treatment. This dependency is illustrated by the annealing temperature-aging temperature-da/dt mean response surface shown in Figure 11. This response surface was constructed from the examples shown in this paper combined with data from other developmental studies, and is valid for compositions nominally containing 28% Ni, 34% Co, 3% Cr, 5.4% Al, 3% Nb, and balance Fe. The annealing time at temperature is one hour, and air cooled. The aging heat treatments are based on specimens aged at the temperatures shown for 8 to 16 h, furnace cooled 55°C/h to 621°C, held for 8 h, and air cooled. The da/dt shown is at 538°C and 33 MPa√m and represents mean values for the heat treatments.

The da/dt is maximized when annealed between about 1040 to 1080°C regardless of the aging temperature. However, the maximum da/dt is highest at aging temperatures around 750°C or lower, dropping significantly above 800°C. The minimum da/dt occurs after annealing below 1020°C or above 1100°C and aged at temperatures above 800°C.

A wide variety of heat treatment combinations may be used to achieve good da/dt resistance in alloy 783. Solution annealing at 1120°C followed by an intermediate β age at 845°C for 2 to 4 h, followed by a conventional γ' precipitation two-step heat treatment of 718°C for 8 h furnace cooling to 621°C , held for 8 h, and air cooling, has been found to offer a good combination of properties. This heat treatment provides for coarser grain size (ASTM #5 to #3) for creep resistance, reduces thermomechanically induced anisotropy, and provides for more uniform and controlled fine β precipitation throughout the grain boundaries and the microstructural matrix as a whole.

Microstructure. Low da/dt rates in low temperature (< 1020° C) annealed alloy 783 is associated with fine grain and an abundance of globular and intergranular β in the microstructure. The microstructure for a specimen from a turbine ring heat treated at 1010° C for one

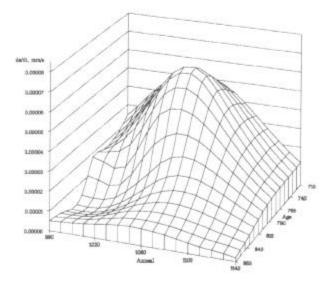


Figure 11 Effect of annealing and aging temperatures on the da/dt at 538°C and 33 MPavm of INCONEL alloy 783.

hour, air cooled, $760^{\circ}C$ for 12 h furnace cooled $55^{\circ}C/h$ to $621^{\circ}C$, held for 8 h, air cooled, is illustrated in Figure 12. The globular β precipitates are abundant and uniformly distributed, and effectively pin grain boundaries. Intergranular β precipitation is also present. Overaged γ' is apparently darkening the grain interiors. Since the aging heat treatment temperatures for this specimen were below $800^{\circ}C$, the observed β is predominantly that which precipitated during the turbine ring thermomechanical processing.

The microstructure of an alloy 783 specimen given a high temperature anneal (1121°C for one hour, air cooled) and a γ' aging heat treatment (718°C for 8 h furnace cooled to 621°C, held for 8 h, air cooled), is shown in Figure 13. The microstructure of an alloy 783 specimen given the same heat treatment except with an intermediate β aging heat treatment, is shown in Figure 14. The microstructure of an alloy 718 compact tension specimen obtained from the engine ring is shown in Figure 15.

The annealed and γ' aged only alloy 783 specimen has essentially "clean" grain boundaries with some undissolved primary β particles scattered throughout the microstructure. In contrast, the annealed, β -and γ' -aged specimen contains extensive intergranular precipitates, as well as uniformly distributed intragranular lenticular β . The optical microstructure of the alloy 718 specimen is similar in appearance except the intergranular phase in this alloy is primarily δ (Ni₃Nb,Ti).

<u>Fractographs</u>. The fractographs of the latter three fractured compact tension specimens are also revealing. Creep resistant superalloys fracture intergranularly at 538°C when subjected to sustained loading in air. Likewise, fracture in all three specimens, alloy 783 in both heat treated conditions and alloy 718, followed an intergranular crack path, accompanied with frequent secondary intergranular branch cracks.

The fracture surface of the annealed and γ -aged alloy 783 specimen, in Figure 16, has very clean grain facets devoid of any significant ductility. Nevertheless, this specimen had da/dt rates superior to alloy 909 (see Table III). The annealed, β - and γ -aged alloy 783 specimen had significantly improved da/dt, yet the crack path remained the same, see Figure 17. However, the grain facets are rougher in appearance. The grain facet features are probably a combination of

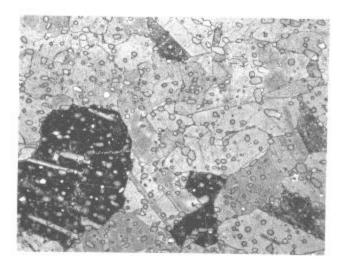


Figure 12 Alloy 783 heat treated 1010°C for 1 h, air cooled, 760°C for 12 h, cooled 55°/h to 621°C for 8 h, air cooled. Specimen from turbine ring, circumferential view, 500x.



Figure 13 Alloy 783 annealed at 1121°C for 1 h, air cooled, aged 718°C for 8 h cooled 55°/h to 621°C for 8 h, air cooled. Specimen from turbine ring, circumferential view, 500x.

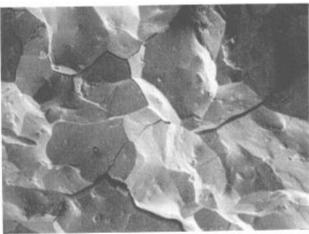


Figure 16 Alloy 783 da/dt at 538°C fracture surface. Heat treated at 1121°C for 1 h, air cooled, aged 718°C for 8 h, cooled 55°/h to 621°C for 8 h, air cooled. 500x.

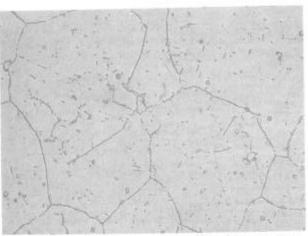


Figure 14 Alloy 783 heat treated 1121°C for 1 h, air cooled, 843°C for 2 h, air cooled, 718°C for 8 h cooled 55°C/h to 621°C for 8 h, air cooled. Specimen from turbine ring, circumferential view, 500x.

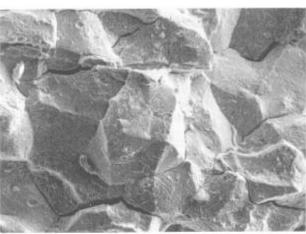


Figure 17 Alloy 783 da/dt at 538°C fracture surface. Heat treated 1121°C for 1 h, air cooled, 843°C for 2 h, air cooled, 718°C for 8 h cooled 55°C/h to 621°C for 8 h, air cooled. 500x.



Figure 15 Alloy 718 heat treated at 954°C for 1 h, air cooled, 718°C for 8 h cooled 55°/h to 621°C for 8 h, air cooled. Specimen from turbine ring, circumferential view, 500x.

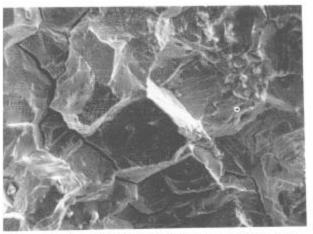


Figure 18 Alloy 718 da/dt at 538°C fracture surface. Heat treated at 954°C for 1 h, air cooled, 718°C for 8 h cooled 55°/h to 621°C for 8 h, air cooled. 500x.

the oxidation of the grain boundary phases and localized deformation. The alloy 718 specimen fracture surface, shown in Figure 18, is also rougher in comparison with the annealed and γ -aged alloy 783 fracture surface, with perhaps some slight grain facet deformation observable.

Concluding Comments. It has been demonstrated that sustained load crack growth in air at temperatures between 450°C and 700°C is strongly driven by oxygen from the environment in most, if not all, superalloys. Although inert environmental da/dt performance was not been shown here, the same is true for INCONEL alloy 783. It is clear from these microstructures and fractographs that alloy 783 da/dt performance at 538°C is largely a result of grain boundary phase formation (or lack of it) and the interaction with the environment. Resistance to sustained load cracking in air is achieved by grain boundary phase engineering in these superalloys.

Secondly, it was also concluded that "high intergranular stresses resulting from strain incompatibilities due to either slip character or microstructural inhomogeneities, or both" were also a requirement for a strong environmental effect. The presence of intergranular precipitates as different in composition and structure as β (ordered BCC) in alloy 783 and δ (orthorhombic) in alloy 718 provide increased environmental da/dt resistance over that of precipitate-free grain boundaries in these alloys. It has been demonstrated in INCONEL alloy X-750 that even grain boundary M23C6 phases can aid in the reduction of environmental sensitivity to oxygen as measured by sustained load crack growth.9 With intergranular precipitates so diverse in composition and morphologies, one is led to conjecture that some of the beneficial effect on da/dt at 538°C is due to altered (ie, reduced) intergranular strain incompatibilities. These observations offer future guidance (eg, the need for increased attention to practical grain boundary micro-engineering in elevated temperature superalloy development) and hope for new superalloys having improved environmental crack growth resistance.

Summary

INCONEL alloy 783 is a controlled low thermal expansion, oxidation resistant $\gamma\gamma'$ - β superalloy having sustained load crack growth resistance in air environments. Crack growth resistance was achieved by composition (optimized Co/Ni and Cr content) and heat treatment control, and is essentially equivalent to that of INCONEL alloy 718 in stress intensity ranges of 20 to 60 MPa·lm. Crack growth resistance is attained by the controlled precipitation of fine β particulates in grain boundaries, either by thermomechanical processing with fine grain annealing (980°C), or preferrably by solution annealing (1120°C) and using intermediate β re-precipitation heat treatments (845°C for 2 to 4 h, air cool). Primary strengthening is achieved by γ' aging heat treatment at 718°C for 8 h furnace cooled to 621°C, held for 8 h, and air cooled.

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