EFFECT OF INTERSTITIAL CONTENT ON HIGH TEMPERATURE

FATIGUE CRACK PROPAGATION AND LOW CYCLE FATIGUE OF ALLOY 720

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Abstract

Alloy 720 is a high strength cast and wrought turbine disc alloy now in use for up to about 1200°F in Allison's T800, T406, GMA 2100 and GMA 3007 engines. In the original composition intended for use as turbine blades, large carbide and boride stringers formed and acted as preferred crack initiators. The stringering was attributed to relatively higher boron and carbon levels. These interstitials are known to affect creep and ductility of superalloys, but the effects on low cycle fatigue and fatigue crack propagation have not been studied. Recent emphasis on the total-life approach in the design of turbine discs necessitates better understanding of the interactive fatigue crack propagation and low cycle fatigue behavior at high temperatures. The objective of this study was to improve the damage tolerance of Alloy 720 by systematically modifying boron and carbon levels in the master melt, without altering the low cycle fatigue and strength characteristics of the original composition.

Improvement in strain-controlled low cycle fatigue life was achieved by fragmenting the continuous stringers via composition modification. The fatigue crack propagation rate was reduced by a concurrent reduction of both carbon and boron levels to optimally low levels at which the frequency of brittle second phases was minimal. The changes in composition have been incorporated for production disc forgings.

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Introduction

In aerospace applications there is a continuous quest to reduce weight and to move to high strength materials with greater tolerance to higher design stresses and temperatures. Materials for critical rotating parts e.g. turbine discs, have been traditionally designed for burst margins, fatigue crack initiation, and creep strength. Since the early 80s regulatory evolutions by defense agencies and the Federal Aviation Administration (FAA) have put explicit demands on the total-life approach to ensure sufficient damage tolerance of the newer engines (1). The "retirement-for-cause" approach, for instance, resulted in fatigue crack propagation (FCP) programs like ESDADTA(2) and ENSIP(3).

Fatigue resistance of nickel base superalloys is affected by grain size, gamma prime (γ') size and morphology, carbides and other phases, and by the presence of processing defects like porosity and oxide inclusions (4,5,6,7). Chemical composition, material processing, and heat treatment may be altered to design a microstructure to derive desired properties. Composition control is the first step in this process. It is important to realize that major changes in microstructure and properties can be caused by relatively small changes in composition. Relatively better understanding of microstructure effects on creep and low cycle fatigue (LCF) of superalloys contrasts a similar systematic understanding of FCP behavior. Understanding of FCP behavior becomes even more important considering the increasingly extreme operating conditions encountered in modern jet engines.

Alloy 720 is a high strength cast and wrought turbine disc alloy now in use for up to about 1200°F in Allison's T800, T406, GMA 2100 and GMA 3007 engines. In the original composition intended for use as turbine blades (Table I), the carbon and boron levels resulted in carbide and boride stringering which acted as preferred fatigue crack initiation sites. These deliberately added interstitial elements are known to significantly alter creep and ductility of superalloys (8,9). However, the effects of these elements on FCP and LCF have not been studied. The objective of this study was to improve the damage tolerance of Alloy 720 by systematically modifying carbon and boron levels in the master melt, without altering the LCF and strength characteristics of the original composition.

Materials

Two experimental heats, 300 lb each, were VIM-VAR melted, homogenized and finished rolled to produce a uniform grain size of ASTM no. 10 -12, by the Special Metals Corporation, New Hartford, N.Y. These represent the two modified compositions, conditions A and B. For the baseline, disc forgings with identical grain size were used. The compositions are given in Table I. All specimen blanks were then identically heat treated as follows:

2020°F/2 hr/OQ; 1400°F/8 hr/AC; 1200°F/24 hr/AC.

Table I. Alloy compositions used in this study (wt. %).

	C	B	Zr	Ti	Al	Cr	Mo	Co	W	Ni
Baseline	0.03-	0.03-	0.025-	4.75-	2.25-	17.5-	2.75-	14.0-	1.10-	Bal
	0.04	0.04	0.050	5.25	2.75	18.5	3.25	15.5	1.40	Bal
Condition A	0.012	0.017	0.029	4.93	2.54	17.01	3.02	14.52	1.22	Bal
Condition B	0.011	0.029	0.030	4.95	2.55	17.14	3.03	14.54	1.22	Bal

Experimental Procedure

Metallography

Cross sections for optical and SEM metallography were polished to 1μ finish and analyzed in the as-polished condition for stringers and other phases. These were then electropolished and immersion etched per a procedure developed by Radavich (10). SEM analysis was conducted in the electropolished and also in the electropolished and etched condition. SEM fractography was conducted on FCP and LCF specimens.

Mechanical Testing

Tensile tests at room temperature and 1200°F were conducted on 0.5 in. dia. standard specimens per ASTM Standard E8. Smooth-bar longitudinal strain-controlled LCF tests were conducted on computer controlled servohydraulic system at 800°F, R = 0.0, at 20 cpm using triangular waveform. Compact tension specimens (1.5W x 0.25 in. thick) were used for fatigue crack propagation tests conducted per ASTM Standard E647 at 1200°F, R = 0.05 at 200 cpm. The crack extension was measured by a travelling microscope.

Results And Discussion

Microstructure

For the three conditions studied, the microstructures are shown in Figure 1. The grain size was identically uniform and averaged ASTM no. 10-12. Fine γ' averaged about 0.1 - 0.2μ. Due to the fineness of microstructure, high magnifications were needed in both optical and SEM metallography. The baseline microstructure consisted of boride and carbide stringers ranging in size from 4 to 20 mils (Figure 2a). Radavich (10) and Liu (11) have reported the phases present in Alloy 720 and are Mo and Cr rich M_3B_2 or MB_2 borides, Ti rich blocky MC carbides, $M_{23}C_6$ carbides, and occasional TiCN. Compared to the baseline, condition B in which carbon is 0.011% and boron is identical, the stringers were fewer and smaller ranging from 1 to 5 mils (Figure 2b). Mostly these were borides. For condition A with the lowest boron and carbon levels, the stringers were absent and the second phases were dispersed and finer.

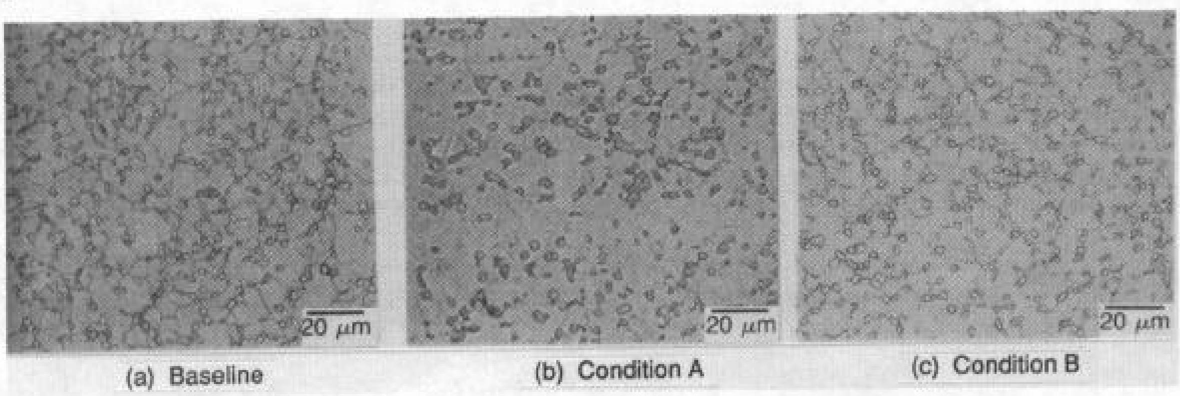


Figure 1. Optical micrographs of fully heat treated microstructures.

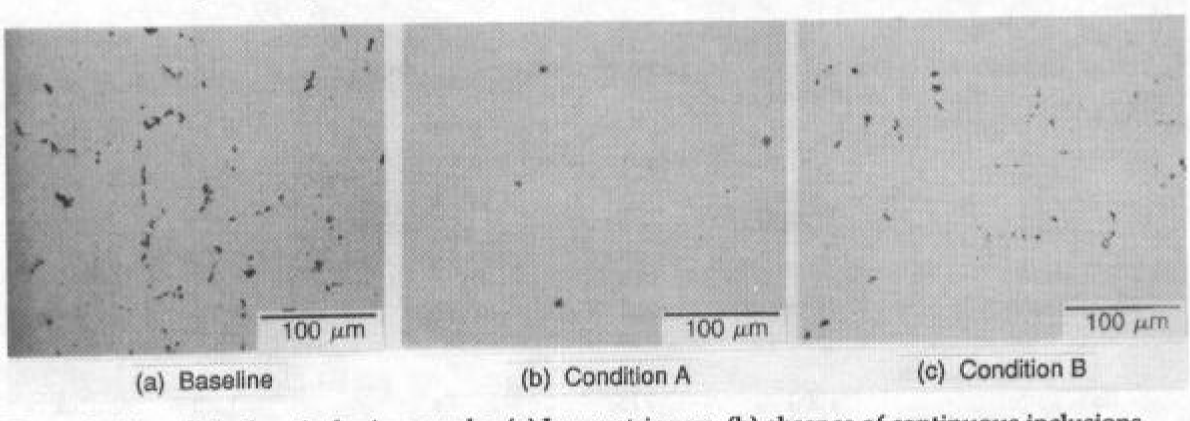


Figure 2. As-polished optical micrographs. (a) Large stringers, (b) absence of continuous inclusions, and (c) stringers broken into smaller lengths and individual particles.

Effects of Boron and Carbon

This section discusses the roles by which the controlled trace elements boron and carbon benefit nickel base superalloys. Both are added in the melt and have been reported to affect microstructures and properties of superalloys, stainless steels, and intermetallic compounds (12,13,14,15). Boron was originally added as a fluxing agent and in the late 50s, trace amounts of boron in melts improved hot workability and creep rupture properties of various steels (16). The amount required for property enhancement was very low. In Waspaloy only 15 ppm of boron was sufficient to double the stress rupture life (9). These improvements were attributed to stabilization of grain boundaries and phases present as a result of boron segregation to the boundaries. The segregation of boron is believed to (i) increase grain boundary cohesion, (ii) reduce grain boundary surface energy, (iii) lower grain boundary diffusion rates, and (iv) change γ, γ', and/or $M_{23}C_6$ morphologies. It also lowers the solidus temperature (14,17,18).

The solubility of boron in nickel is limited, and above the limit it forms complex Mo and Cr rich boride clusters and stringers as was also seen in this study. The continuous stringers are microstructural inhomogeneities which act as preferred crack initiators detrimental to LCF life. One way to eliminate the continuity and minimize the presence of stable, brittle borides is to reduce boron to below the solubility limit for a given material. This was achieved in the present study by systematically altering boron from 0.04 to 0.017%. The effects of this change in boron content on LCF and FCP are discussed in a later section.

In superalloys, carbon is added as a refiner during melting and generally results in the formation of MC, M_7C_3 and $M_{23}C_6$ carbides, and TiCN (19). Noncontinuous intergranular carbides improve creep resistance by grain boundary pinning, whereas continuous carbides are known to act as crack initiators and also degrade stress rupture properties (20). As expected both MC and $M_{23}C_6$ carbides were present in the microstructures studied. Relative to the baseline, the frequency of carbide clusters and also of discrete blocky carbides was less in conditions A and B.

Similar to boron, the presence of carbon above a certain limit would form continuous carbides. In an earlier work on Waspaloy (21), carbon at 0.045% produced carbide clusters and stringers quite similar to our baseline condition. Reduction of carbon to 0.01-0.02% eliminated stringers without any degradation in strength or ductility. Recently it was reported that extra low carbon (about 0.01%) in IN-718 reduced the tendency of stringer formation and improved the LCF life (22). However, there is evidence that too low a carbon level in superalloys reduces creep properties (23).

Since a certain minimum amount of carbon is needed in superalloys for melt refining as well as carbide formation, it follows that an optimally low level of carbon is desirable. Our study has shown that to be at least 0.01% for Alloy 720.

Mechanical Properties

Tensile

Average monotonic tensile data for the three conditions are summarized in Table II. The tensile properties are identical at all temperatures.

Table II. Average monotonic tensile properties.

	Temp(°F)	UTS(ksi)	0.2% Y.S.(ksi)	% EL	% RA
Baseline	75	243	186	15.0	17
Condition A	75	241	183	16.5	18.7
Condition B	75	244	185	18.4	20
Baseline	1200	213	174	12.3	15.2
Condition A	1200	210	171	12.8	15.5
Condition B	1200	207	172	9.0	10.2

Low Cycle Fatigue

The strain-controlled low cycle fatigue data for the three conditions are compared in Figure 3. In the baseline condition, a majority of the cracks initiated at surface or near surface boride or carbide stringers. Figure 4 is characteristic of such an origin. As described earlier, the stringer length varied

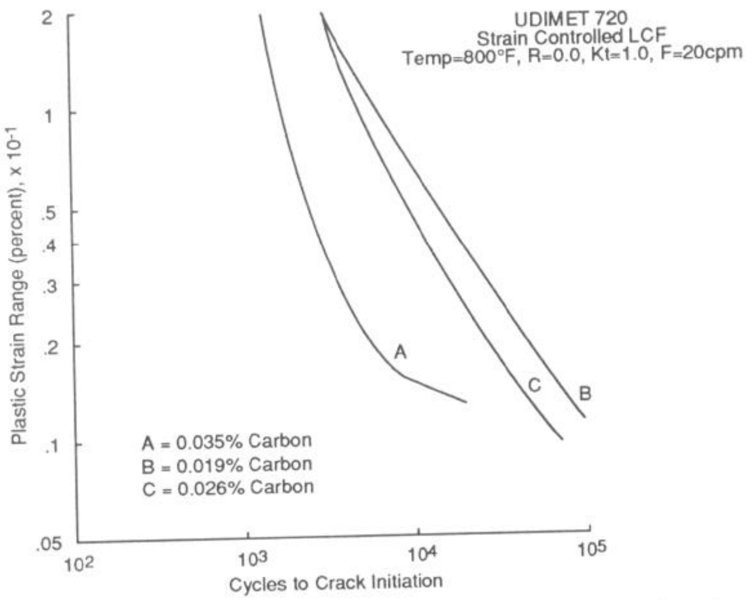


Figure 3. Strain-controlled LCF data shows the effect of carbon levels.

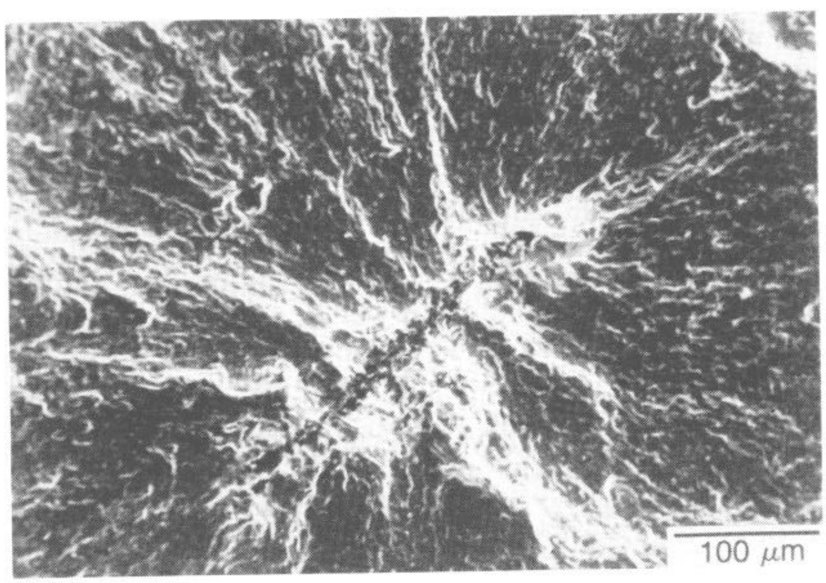


Figure 4. Characteristic LCF crack-initiation in the baseline composition at a near surface boride, for a test at $\Delta\varepsilon_t = 0.87\%$, T = 800°F, $K_t = 1.0$.

from 4 to 20 mils. There is evidence that the LCF life is related to the size of microstructural defects in superalloys (24,25,26). The probabilistic distribution and location of such defects increases the scatter of LCF life and they are relatively more detrimental when they are surface related (27,28). Tests were specifically conducted to investigate this behavior for the baseline condition. The conditions for the smooth-bar LCF tests were: 0-0.87%-0 total strain at 800°F, and 20 cpm. The life vs stringer-size data from these tests in Figure 5 show a noticeable scatter in life. Similar tests conducted on material with lower carbon levels of 0.025% and 0.019% (at constant boron) had shown less scatter and a gradual transition in initiation from surface related stringers to primarily crystallographic initiation.

Since the grain size, γ-size and major chemical elements, and the processing and heat treatment are identical for the three conditions, improvement in the LCF life is a result of the redistribution of phases due to small changes in the carbon and boron levels.

Fatigue Crack Propagation

From the da/dn vs delta K plot at 1200°F (Figure 6) the FCP resistance of condition B relative to the

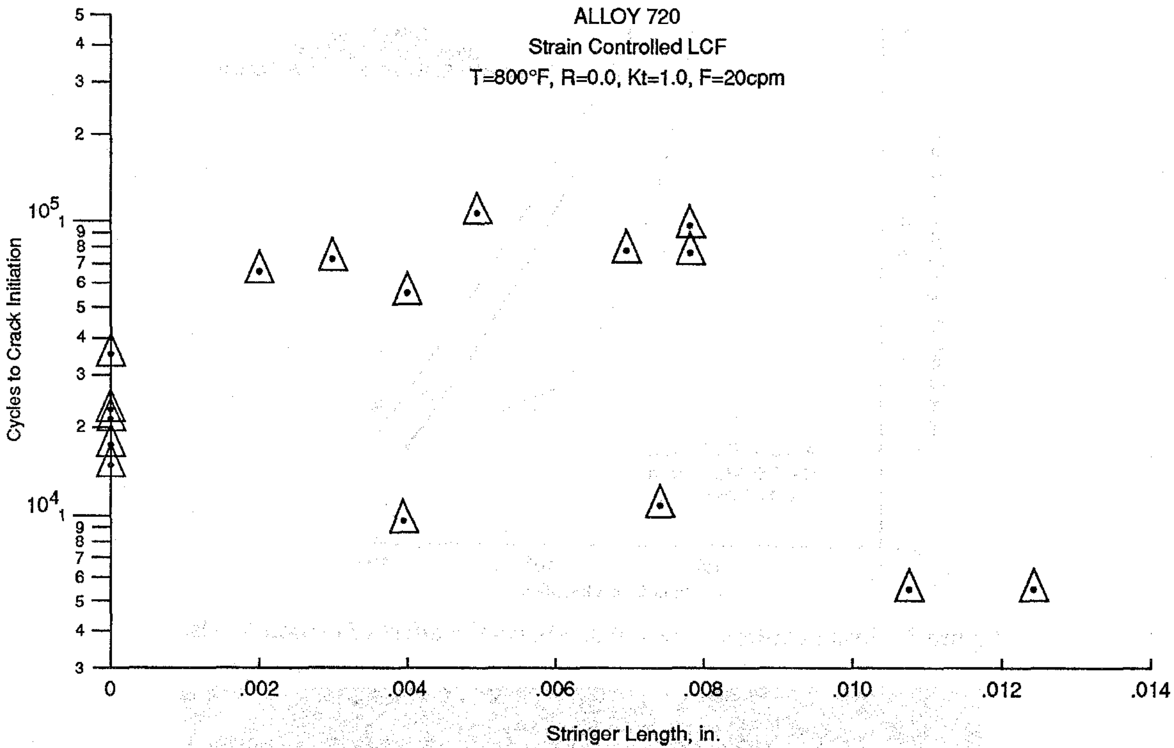


Figure 5. Stringer-size effect on strain-controlled LCF life in the baseline composition at constant $\Delta\varepsilon_t = 0.87\%$, T = 800°F, $K_t = 1.0$.

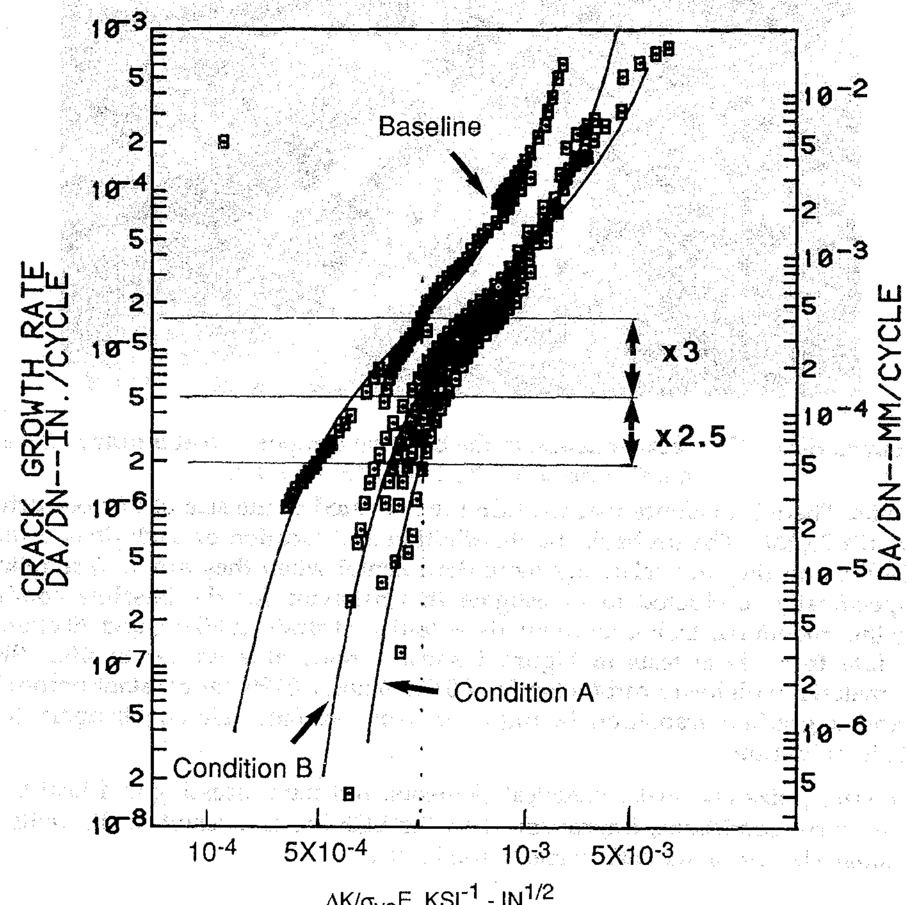


Figure 6. Fatigue crack growth rate normalized with yield strength and modulus at 1200°F, R = 0.05, F = 200 cpm.

baseline composition improved by a factor of 3 when carbon was lowered and boron was constant (at delta K of 20 ksi-in$^{1/2}$). The dominant crack propagation mode was intergranular (Figure 7) as would be expected for such fine grain structure. The cracks appeared to follow the continuous stringers in the baseline condition (Figure 8) and were also seen originating at cracked MC carbides (Figure 9). Better resistance to crack growth in condition B is due to fewer brittle stringers and blocky carbides, which if readily available as in the baseline condition, provide less accommodation for crack tip plasticity.

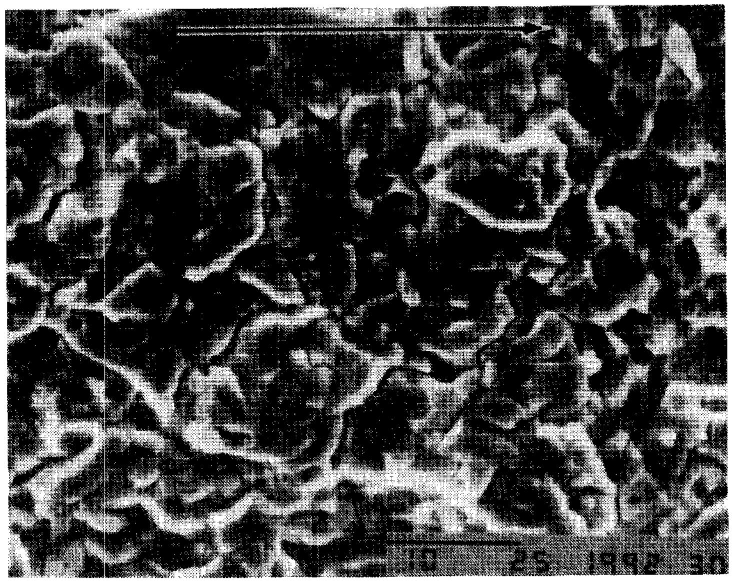
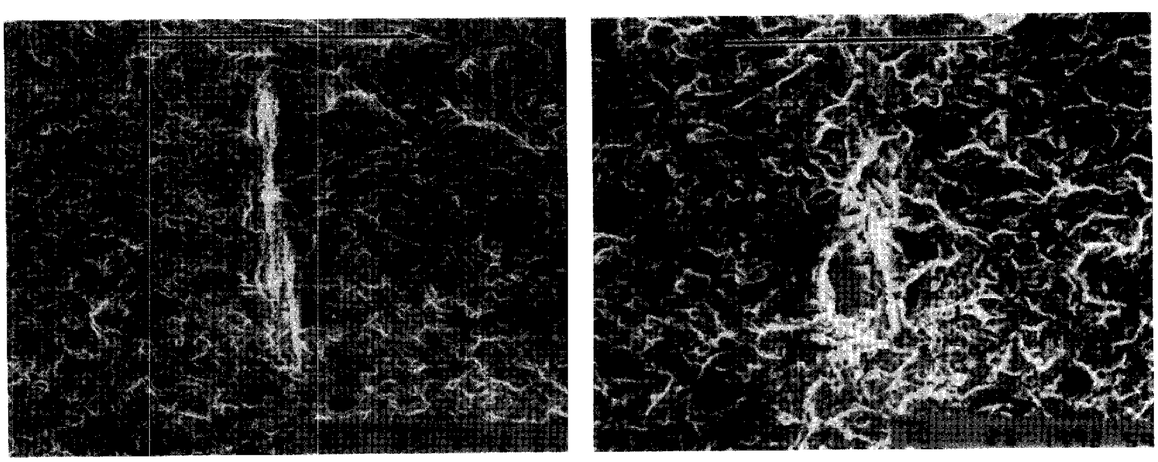


Figure 7. Intergranular cracking is the dominant crack propagation mode in all three conditions. Fractograph is from a test in condition B.



(a) (b)

Figure 8. Fractograph from an FCP test in the baseline composition; (a) Mo rich boride, (b) Ti rich carbide.

A further improvement by 2.5X in the FCP resistance is achieved by lowering the boron level (at constant carbon) as shown in Figure 6. The crack propagation mode was similar to the other two conditions at this stress-intensity. As described earlier lower carbon and boron levels formed smaller dispersed second phase particles compared to the large continuous stringers in the baseline condition. Smaller particles in condition A tend to deflect the crack front thus improving the resistance to crack advance.

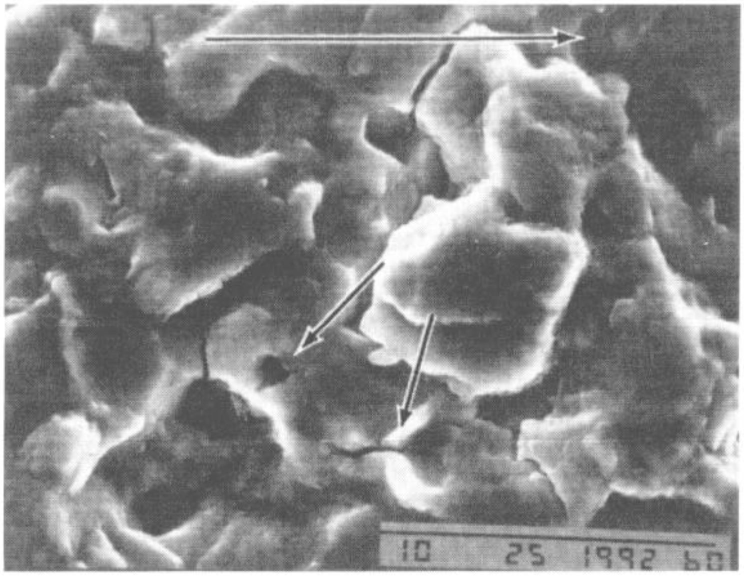


Figure 9. Cracks seen at carbides. Fractograph is from an FCP test in condition B.

At very high temperature i.e. 1200°F, intergranular crack propagation in fine grained turbine disc alloys has been largely attributed to environmental embrittlement of grain boundaries, although the exact mechanism is still being debated. Some of the proposed modifications for improving FCP resistance of superalloys include changes in grain size, γ' size, strength, and chemistry. However, it is known that improvements in FCP generally affect the competing LCF and creep behavior. In our study only chemistry was modified while all other variables were kept constant.

The present work on Alloy 720 clearly identifies a practical solution for improving FCP resistance without altering LCF. Carefully controlled amounts of the interstitial elements boron and carbon in the melt have concurrent benefits of improving the FCP resistance without affecting other properties. Of particular importance is the fact that these improvements have been achieved without requiring changes to the heat treatment or the fabrication process. Similar potent improvements, we believe, may be obtained in other turbine disc alloys by the relatively inexpensive and simple method of controlling minor elements in the melt.

Conclusions

- Trace elements can significantly alter the microstructure and mechanical behavior of superalloys.
- Improvements in high temperature fatigue crack propagation are possible without altering the low cycle fatigue properties.
- Boron and carbon are beneficial to superalloys in carefully controlled trace quantities. Excessive amounts result in microstructural inhomogeneities whereas too low amounts could degrade creep capability and producibility.
- A much greater emphasis on understanding fatigue crack propagation is needed in the design of turbine disc alloys.
- The development and improvements in advanced materials requires a multi-faceted approach. Chemistry, processing, and microstructure are equal contributors to the mechanical behavior and must be understood in systematic fundamental ways. Without this full capabilities of materials will never be achieved.

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