THE INFLUENCE OF HEAT TREATMENT

ON THE MECHANICAL BEHAVIOR OF IN706

G. Härkegård*, W. Balbach, K. Stärk, and J. Rösler#

ABB Power Generation Ltd., CH-5401 Baden, Switzerland

* The Norwegian Institute of Technology, Trondheim, Norway

Technical University of Braunschweig, Germany

Abstract

Two different heat treatments have been proposed for IN706 to produce either (A) high stress rupture properties for applications up to 700°C or (B) high tensile properties for room and moderate temperature applications. This paper gives a brief account of the material properties obtained from the two heat treatments with emphasis on results from (slow) constant strain rate (CSR) testing and creep crack growth testing at temperatures between 550°C and 650°C. IN706B proved to be susceptible to stress assisted grain boundary oxidation with CSR rupture strains below 1% and with high creep crack growth rates. For IN706A, CSR ductility was considerably improved, and creep crack growth rates were reduced by up to three orders of magnitude. This improvement has been attributed to η-phase precipitation at grain boundaries causing increased resistance to oxidation induced intergranular cracking.

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Introduction

The majority of today's heavy duty industrial gas turbine discs are made of ferritic steel. With increasing turbine rotor diameter and inlet gas temperature, there is need for improved strength and toughness on one hand, improved high temperature properties one the other. From these points of view, the Ni-Fe class of superalloys offers an attractive alternative. A major obstacle for these alloys to become more widely used is their high cost. Other difficulties are related to their ultrasonic inspectability and their increased level of thermal stress due to a higher coefficient of thermal expansion and a lower thermal conductivity in comparison with ferritic steels. With increased strength and service temperature, the susceptibility to intergranular cracking has to be given due attention. This paper describes the effect of heat treatment on the high-temperature cracking behavior of IN706.

Chemical Composition, Heat Treatment and Tensile Properties

When IN706 was introduced by INCO in the early 70's, with a chemical composition as shown in Table I, two different heat treatments were proposed to produce either high stress rupture strength for applications up to 700°C or high-tensile strength and toughness for room- and moderate-temperature applications. The proposed heat treatments, referred to as A and B respectively, are given by Table II.

Table I. Chemical Composition of IN706 (Weight %)

	C	Mn	Si	Cr	Ni	Ti	Al	Nb	Fe
Min.	-	-	-	14.5	39	1.5	-	2.5	Bal.
Max.	0.06	0.35	0.35	17.5	44	2.0	0.40	3.3	

Table II. Heat Treatments for IN706

Heat Treatment	Solution Treatment	Stabilizing Treatment	Precipitation treatment I	Precipitation treatment II
A	925-1010°C, AC*	845°C/3 h, AC	720°C/8 h, FC	620°C/8 h, AC
B	925-1010°C, AC*	-	730°C/8 h, FC	620°C/8 h, AC

AC = air cool to room temperature
FC = furnace cool
*Oil quench recommended for large forgings

For large forgings, oil quenching is recommended after solution treatment to minimize precipitation and grain growth in deep-seated regions. The longer heating time required to attain a uniform stabilizing temperature in a large forging may be compensated for by reducing the temperature by 20-30 K. Minimum tensile properties of IN706 forged disc material (grain size ASTM 3-4) with heat treatments A and B are given in Table III.

Table III. Room Temperature Tangential Tensile Properties of IN706

Heat Treatment	Tensile Strength	0.2% Proof Strength	Elongation	Reduction of Area
A	1100 MPa	850 MPa	12%	15%
B	1135 MPa	930 MPa	12%	15%

Constant Extension Rate Testing

Notched creep rupture tests and relaxation tests on IN706B at 600°C gave rise to some unexpected low-ductility intergranular failures with a failure strain < 1% within the first 10 h of testing. Notched creep rupture lives two orders of magnitude below those of smooth creep specimens were observed. Since these low-ductility failures could not be consistently reproduced, alternative test methods, capable of more reliably revealing such embrittlement were sought. Based on estimated strain rates in the failed specimens, it was suggested that slow tensile tests with a (constant) strain rate in the interval $d\varepsilon/dt = 10^{-4}\text{-}10^{-3}\ h^{-1}$ be used. For lower strain rates (and stress levels), i.e. under intermediate and long-time creep conditions, creep rupture strains well above 1% were measured. For the higher creep rates used in standard tensile testing, failure strains are above 10%.

A series of constant strain rate (CSR) tests were carried out on IN706A and IN706B material at 600°C to find out, if there is a significant difference in their slow strain rate behavior. Smooth LCF type specimens (diameter 9 mm, gage length 25 mm) were tested at a strain rate of $5 \cdot 10^{-4}\ h^{-1}$. As can be seen from Figure 1, a very consistent picture emerged with respect to CSR ductility and heat treatment. For heat treatment B, rupture strains from about 1% down to 0.4% were measured, whereas for heat treatment A, rupture was not observed even at a permanent strain up to 5%.

It is well established that Ni and Ni-Fe base superalloys are susceptible to "stress assisted grain boundary oxidation", SAGBO, at temperatures above 550°C. In particular, this has been demonstrated for IN718 by Kang et al. [1], Gao et al. [2] and Andrieu et al. [3], who performed creep and dwell fatigue crack growth testing of this alloy at 650°C. By testing at partial oxygen pressures below 10^{-6} bar, a reduction of crack growth rates of up to four orders of magnitude has been observed. In the present investigation, oxygen was excluded from the surface of IN706B test specimens by applying a 0.25 mm nickel plating to its gage length. Two CSR test specimens were given

3-4% permanent strain at 600°C without failure, which is comparable to values obtained for stabilized IN706A. These results clearly demonstrate the embrittling influence on unstabilized IN706B of an oxidizing environment.

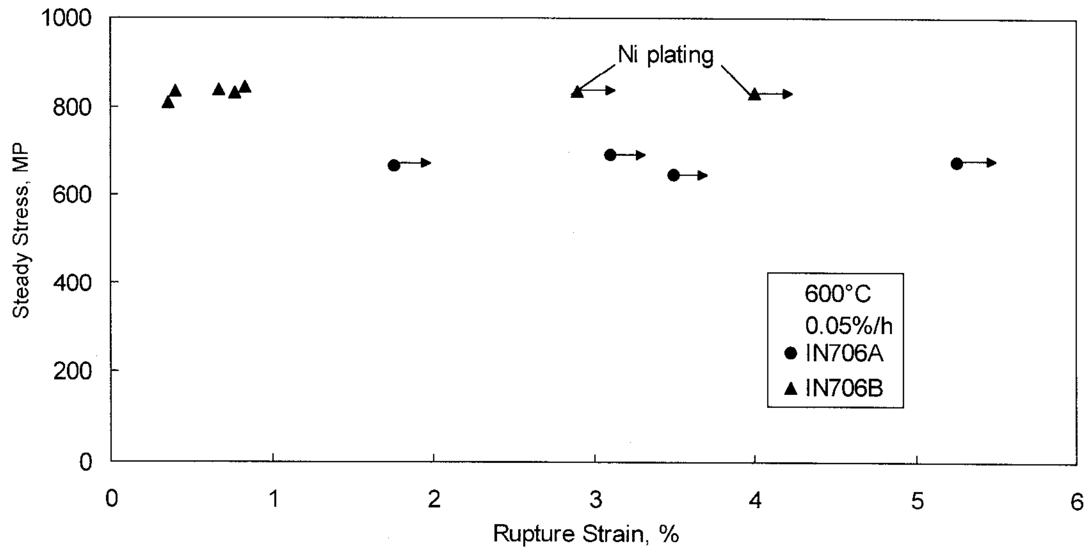

Figure 1 - Steady stress vs rupture strain in constant strain rate testing of IN706A and IN706B at 600°C and $d\varepsilon/dt = 5 \cdot 10^{-4}\ h^{-1}$.

Creep Crack Growth

For alloy systems to be used in the design of jet engine and industrial gas turbine discs, it is necessary to have accurate knowledge about the growth rate of defects under transient thermal loading and steady centrifugal and thermal loading. While fatigue crack growth rates as determined in the laboratory under normal test frequencies only rarely give rise to design life restrictions, the acceleration of crack growth often observed under hold-time fatigue testing has to be carefully considered. In particular, this is true for alloys susceptible to SAGBO. While slow CSR testing is a useful qualitative tool for screening different alloys and heat treatments with respect to SAGBO, only creep crack growth testing will give the designer the data required for a quantitative assessment of crack growth from pre-existing defects.

To this end, 25 mm thick compact tension specimens (CT25) were machined out of blocks of IN706 disc material, which had been subjected to heat treatments A and B respectively. The notch was in the tangential-radial plane with the crack growing in the tangential direction. Before creep crack growth testing, the machined notch was pre-cracked in fatigue. A simple dead-weight loading was applied and the crack opening displacement was continuously registered. When testing was interrupted and the specimen broken open after a crack length increment Δa < 1-2 mm, the average growth rate, $da/dt = \Delta a/\Delta t$, and the associated average stress intensity factor, $K(a+\Delta a/2)$, were determined. For larger crack length increments, an attempt was made to determine the crack growth as a function of time by means of the crack opening displacement.

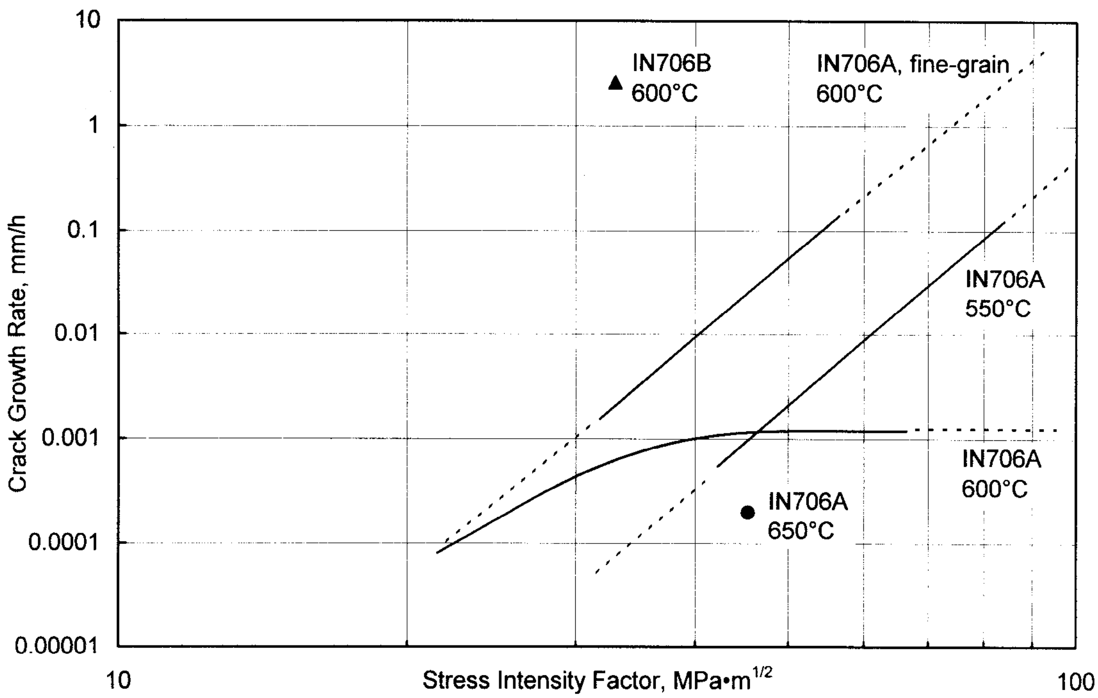

Figure 2 - Creep crack growth rate vs stress intensity factor for coarse-grained IN706 disc material and fine-grained IN706 bar material at 550-650°C.

The results have been summarized in Figure 2. It can be seen that the creep crack growth rate of IN706A is more than three orders of magnitude less than that of IN706B coarse-grained disc material (ASTM 3-4) at 600°C. In both cases fracture was intergranular. Fracture surfaces of IN706B were smooth, whereas IN706A showed grain boundary precipitation. This is in agreement with observations by Takahashi et al. [4]. Upon investigating the creep rupture surfaces of stabilized alloy 706, they found high density of micro-dimples along grain boundaries. These were considered to be originated from η-phase precipitates.

There appears to be a plateau in the growth rate of coarse-grained IN706A at 600°C for stress intensity factors above 40 MPa√m, whereas for IN706A fine-grained bar material (ASTM 7-8) at 600°C and for IN706A coarse-grained disc material at 550°C, *da/dt* is continuously rising with *K*. At 650°C, there is only 0.15 mm crack growth in 1000 h at *K* = 45 MPa√m. The observed decrease of crack growth rate with temperature at $K > 40$ MPa√m may be attributed to crack blunting and lower levels of stress at the tip of the crack due to the decreasing resistance against plastic deformation and creep.

In the absence of other investigations of IN706, it may be instructive to compare the crack growth behavior determined in this study with that of IN718. According to Gao et al. [2], the creep crack growth rate of IN718 can be expressed as a function of stress intensity factor (30-60 MPa√m) and temperature (600-700°C) by the equation:

$$\frac{da}{dt} = A \cdot K^n \cdot e^{-\frac{Q}{RT}}$$

Contrary to some of the results discussed above for IN706, this means that *da/dt* is continuously increasing with temperature. From tests carried out in pure oxygen were determined Q = 287 kJ/mol and n = 1.62. At 600°C and K = 40 MPa$\sqrt{m}$, the crack growth rate in pure oxygen was found to be 0.6 mm/h. At this temperature and stress intensity factor, tests in moist argon and earlier test results by Floreen [5] in air gave *da/dt* = 1-4 mm/h, i.e. about three orders of magnitude greater than what was observed for IN706A in the present investigation.

Conclusions

IN706B (not stabilized) is susceptible to oxidation induced cracking at temperatures above 550°C. This was demonstrated in slow tensile tests, where rupture strains below 1% were registered. At 600°C, a creep crack growth rate greater than 1 mm/h was observed for K = 40 MPa$\sqrt{m}$. This is comparable to growth rates obtained for IN718 under similar test conditions.

By including a stabilizing heat treatment at 800-850°C, whereby η-phase precipitates at grain boundaries, IN706A could be subjected to strains above 5% in slow tensile tests without rupture. Creep crack growth rates were reduced by up to three orders of magnitude in comparison with those of IN706B.

References

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