METALLOGRAPHIC ASPECTS OF CREEP FRACTURE IN A CAST Ni-Cr-BASE ALLOY

H R TIPLER
DIVISION OF MATERIALS APPLICATIONS
NATIONAL PHYSICAL LABORATORY
TEDDINGTON TW11 OLW, MIDDLESEX
UNITED KINGDOM

ABSTRACT

While a fairly extensive knowledge of the mechanisms responsible for failure during creep exists for wrought Ni-Cr-base alloys, this is not the case for cast alloys of this type. Consequently work has being carried out to investigate the types of damage which occur in the cast alloy IN738LC and the present paper describes some of the results obtained. Sections from specimens creep tested at 850 °C for varying proportions of their life to failure of 1000h approximately have been examined and two types of creep damage were identified: (i) internal cavities which nucleate at grain boundaries and increase in size and number to form cracks as creep progresses, and (ii) oxidised cracks which penetrate along grain boundaries from the surface and also increase in number and size as creep progresses but to a lesser extent. The mechanisms responsible for failure during creep of cast Ni-Cr-base alloys are considered to be the same as those in the wrought alloys despite the different microstructural characteristics, especially in the grain boundary regions.

KEYWORDS

Fracture, cast superalloys, cavitation, gas-turbine materials, creep.

INTRODUCTION

Processes responsible for failure in creep of wrought Ni-Cr-base alloys have been demonstrated to be those associated with the nucleation and growth of cavities at grain boundaries which coalesce to form internal grain boundary cracks. These processes continue until the grain boundaries are damaged to such an extent that the remaining load-bearing structure cannot withstand the applied load and failure ensues. The type and extent of such damage and the laws governing its accumulation are reasonably well established for wrought alloys and have been reviewed by Tipler, Lindblom and Davidson (1978). In cast alloys however, information on the nature and development of damage leading to failure in creep and on the influence of microstructural factors on the processes involved is relatively small. The general intergranular nature of the failure in cast IN738LC was noted, firstly, by Woodford and Frawley (1974) who showed that a change in failure mode from transgranular to intergranular occurred as the longitudinal axis of specimens taken from directionally solidified ingots changed from parallel to transverse to the direction of solidification, and secondly, by Scarlin (1977) in studies of crack growth. Dennison, Holmes and Wilshire (1978) considered that the role of cavitation, if present, in cast IN100 was negligible compared with the development of oxidised cracks along grain boundaries emanating from the surface. However, work at the National Physical Laboratory on two types of cast Ni-Cr-base alloys, MarM002 used for aero-engine blades (Thomas and Gibbons, 1980) and IN738LC used for land-based gas turbine blades (Tipler, 1979) has shown conclusively that cavitation occurs in cast alloys. The work reported here on IN738LC has been carried out as part of a larger programme within the European collaborative Project on gas turbine materials, COST 50, with the objective of obtaining a knowledge of the operative failure mechanisms in cast alloys and the factors which influence them. It was anticipated that a detailed knowledge of the mechanisms of the fracture process and the influence of microstructural factors thereon would have the important practical benefit of indicating methods for improving resistance to fracture, thereby contributing to increased component reliability.

MATERIAL SUPPLY AND TESTING

The composition of IN738LC is given below in weight per cent:

C = 0.12, Cr = 15.9, Co = 8.3, Ti = 3.3, Al = 3.4
Mo = 1.6, Nb = 0.96, W = 2.5, Ta = 1.72, Ni = Balance

Creep test pieces were cast slightly oversize by remelting and vacuum casting virgin IN738LC stock, and before machining were given the standard commercial heat treatment, viz., 2h/1120°C/AC + 24h/845°C/AC. The average grain size was 0.6mm

High sensitivity creep tests were carried out at 850 °C with an applied stress of 250 MPa using test pieces of the following dimensions: gauge diameter, 7.6mm, gauge length, 50.8mm and parallel portion, 80mm. Tests to fracture were supplemented by those in which the test was stopped at various fractions of the expected life so that the accumulation of damage at different stages of the creep life could be evaluated. After creep testing the specimens were sectioned longitudinally along a diameter and prepared in the usual way for metallographic examination.

CREEP DAMAGE

The term is used here to describe damage which originated at the surface of the specimen as well as that which occurred internally. The former is likely to be influenced by the environment in addition to the creep test parameters and is observed as cracks or oxide penetrating inwards from the surface along grain boundaries. The internal damage is normally influenced only by the creep test parameters and occurs as cavities or cracks of various lengths which form along the grain boundaries.

Metallographic Characteristics

The damage generated during the creep tests was always located at grain boundaries and varied in type and intensity depending on the duration of creep or, in a fractured specimen, on the distance from the fracture surface. The examples given in Figs. 1 to 3 are typical of features observed at locations differing in distance from the fracture surface in a specimen which fractured after 1138h. Small cavities observed in an area remote from the fracture are shown in Figs. 1 and 2. In Fig. 1, apart from a triangular shaped pore, a number of cavities

about 1μm in size occur at different points along the grain boundary and adjacent to precipitate particles in some cases. In Fig. 2 it can be seen that the outline of individual cavities remains after they have coalesced but the groups of cavities have not joined up to form a continuous crack. There were many examples where inflections or relatively sharp radii of curvature in the boundary appeared to have assisted cavity nucleation. One example at an advanced stage of growth is seen in the "crack" in the lower part of Fig. 3. In this case, presumably, cavities had nucleated at the region of maximum curvature followed by further nucleation and coalescence in both directions to give the form shown in Fig. 3.

The progress in the growth and coalescence of cavities to form cracks along the grain boundaries is shown by comparing Figs. 1 and 4 which are typical of the damage at 30mm and 10mm respectively from the fracture surface. The intergranular nature of the failure and its propagation from points on the grain boundary well within the specimen is clearly demonstrated. A characteristic frequently observed was the arrest of a crack by a sharp change or reversal in direction of the grain boundary where the orientation changed from being approximately normal to the stress axis to one either at 45° or less to the stress axis. Examples may be observed at a number of positions along the grain boundary shown in Fig. 4. In addition to the advanced state of damage observed in Fig. 4, the same grain boundary also contains damage at an earlier stage, viz, in a number of cavities discernible at the bottom of the micrograph.

Two other forms of internal damage were present, i.e., casting porosity, Fig. 1 (triangular pore), and voids or thin cracks at the matrix/ γ-γ' eutectic interface, Fig. 5. Neither of these types of defect, which are present at the commencement of a test, appeared to act as sites for preferential growth of cracks. Thus the voids visible in Fig. 5 have not grown to a size comparable to that of the cavities which preceded the cracks visible in Fig. 4 although the former were a similar distance from the fracture. Compared with cavitation the presence of these types of defect does not appear to facilitate the fracture process beyond their contribution to the subsequent interlinkage of damage.

Quantitative Assessments

1. Surface cracking. Measurements of the amount of surface cracking were made in terms of the number of cracks and the depth to which they penetrated along the grain boundary from the surface

Fig. 1 x480
Cavitated grain boundary and large pore 30mm from fracture.

Fig. 2 x1200
Cavities remote from fracture.

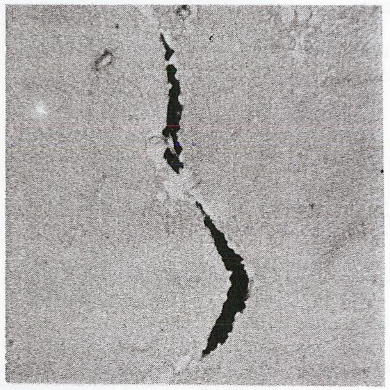

Fig. 3 x600
Cavities at grain boundary inflexions.

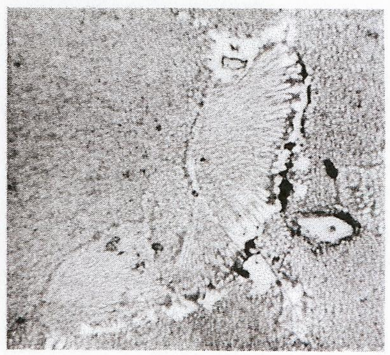

Fig. 5 x600
Voids on convex surface of γ-γ' eutectic 10mm from fracture.

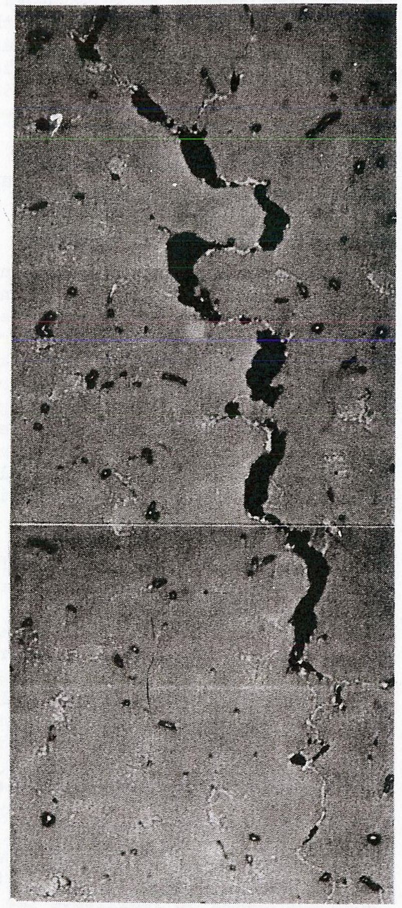

Fig. 4 x120
Cavitated and cracked internal grain boundary 10mm from fracture.

(i.e. from the edge of the section-hence edge cracks); the distribution of the cracks along the edges of the section was also noted. There was no discernible symmetry in crack lengths or distribution, either longitudinally or circumferentially, in any of the specimens and in some cases edge cracks were observed outside the gauge length. The lengths of the edge cracks were divided into four size groups and their frequency in specimens which had been tested to different times and strains is shown in Fig. 6.

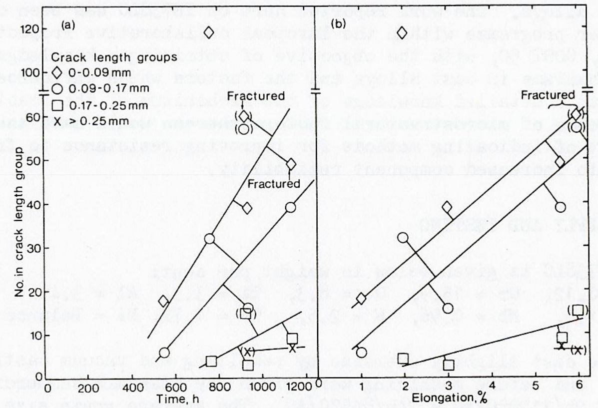

Fig. 6
Effect of (a) creep duration and (b) creep extension on frequency of edge crack lengths for specimens tested at 850°C at 250MPa.

The data in this figure relate to the total amount of cracking which occurred along the whole of the gauge length in each specimen. The data points which have been bracketed are exceptional as these are values taken from only one portion of a fractured specimen. In spite of a certain amount of scatter the peak frequency generally occurred in the same crack-length group irrespective of creep duration or strain and the rate of increase in the number of edge cracks decreased as their size increased. This indicates that new cracks were forming faster than the existing ones were growing and that crack growth was less rapid in the later stages of crack formation. Also, at any time, there was a tendency for the number of cracks > 0.09 mm in length to decrease as the size of the cracks increased.

2. <u>Cavitation and internal cracking</u>. In previous work (Tipler and others, 1978) in which creep damage in wrought IN597 alloy was characterised, assessments were made in terms of (a) the proportion of affected grain boundaries and (b) the number of cavities per unit area, but for the current alloy because of the larger grain size and the convoluted nature of the boundaries the former type of assessment, i.e. (a), has not been used and to complement assessment (b) the size and number of cavities and cracks has been measured. As creep progressed the growth and accumulation of cavities resulted in the formation of cracks and it was no longer possible to discern the outline of individual cavities. Consequently an artitrary length of 0.03mm was set below which grain boundary damage was specified as cavitation and the size of individual or coalesced cavities has been divided into five groups. The number in each grouping has been determined for the different specimens and as almost identical areas were examined in each case, valid comparisons between one specimen and another may be made. The results of the measurements are given in Fig. 7 where it may be observed that the peak frequency occurred at the same size group (approximately 2-6µm) throughout the creep test and the value increased with the duration of test up to rupture. The rate of increase in cavitation was similar for all size groupings below about 9µm but for

larger cavities the rate decreased, as did the number of cavities for given test conditions.

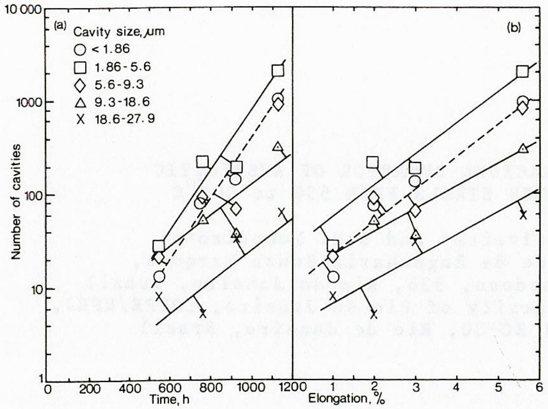

Fig. 7
Effect of (a) creep duration and (b) creep strain on frequency of cavity size for specimenstested at 850°C and at 250MPa

Coalesced cavities which had reached a length of greater than 0.03mm were classified as internal cracks and these have also been measured and divided into various size groupings. The results are shown in Fig. 8. Internal cracks did not appear beyond the gauge length as did the edge cracks, but their length and distribution along the gauge length showed no symmetry either longitudinally or circumferentially, and in this respect their behaviour was similar to that of the edge cracks. In the specimens removed from test prior to failure cracks in only the smallest size group, viz 0.03-0.09mm were observed. For all the results the scatter was considerable and the data points are insufficient to provide a good correlation with either strain or time. The symbols in brackets relate again to the specimen which fractured after 923h and for which only one part was examined.

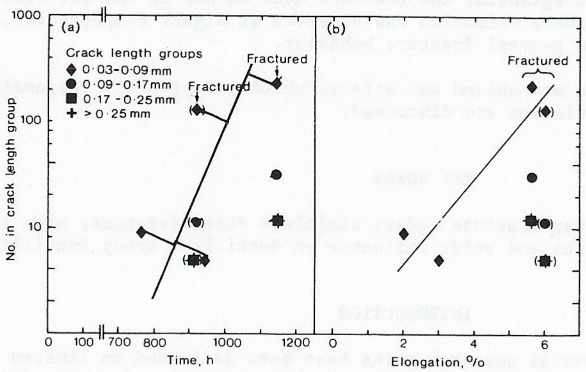

Fig. 8 Effect of
(a) creep duration and
(b) creep extension on frequency of internal crack lengths for specimens tested at 850°C at 250 MPa

Table 1 Development of intensity of cavitation during creep at 250 MPa and 850°C

Time, h	Elongation, %	Mean creep damage cavities/mm^2
549-S	1.0	0.24
764-S	2.0	1.21
932-S	3.02	1.65
923-F	6.0	14.94
1138-F	5.6	16.9

S = stopped F = fractured

The mean creep damage, which includes identifiable cavities and cracks expressed as equivalent numbers of cavities for each specimen is given in terms of cavities per mm^2 in Table 1. These values were obtained from the total gauge length in each case except for the specimen fractured after 923 hours. The abnormally high intensity of damage in this specimen compared with that which had reached 932 hours without failure is due to the difference in creep behaviour between the two, the former accumulating creep strain at a much faster rate.

DISCUSSION

In cast alloys the positive identification of creep cavitation is complicated by the occurrence of casting porosity. In the present work careful observation of the morphology and location of both types of feature has enabled clear distinction to be made so that the quantitative assessments of creep damage are reasonably reliable. The problem of discrimination is greatest with very small voids but with experience porosity can be readily identified by the shape, size and location of individual pores. It was noticeable that cracks did not appear to originate at micropores suggesting that porosity at the levels observed in the specimens used did not make a significant contribution to the fracture process except where creep cavities joined with a conveniently positioned micropore to form a crack.

The results provide conclusive evidence that in this particular alloy cracks formed by the growth and coalescence of cavities which nucleated continuously at grain boundaries throughout the test. Thus, although at the begining of tertiary creep i.e. after about 75% of creep life cracks of about 0.03mm in length began to appear as a result of the coalescence of cavities, the number of large cavities was always exceeded by those in the smaller size ranges. However edge cracks also occurred extensively and although for sizes greater than 0.1mm they appeared earlier in the creep life than internal cracks the total numbers of both types were similar at longer times.

From the results presented the relative importance of the two types of damage viz. edge cracks and internal cracks and cavities in controlling the fracture process cannot readily be specified and further work is in progress to provide additional clarification. It may well be that the "mean creep damage" has a greater acumulative effect in weakening the structure.

CONCLUSIONS

1. During creep of the cast Ni-Cr-base alloy, IN738LC, it has been established that internal damage in the form of cavities at grain boundaries developed in a way similar to that commonly found in wrought alloys of this type, and therefore contributed to the failure process.
2. The peak frequency in cavity size groups occurred at the same size irrespective of creep duration, while the magnitude of this peak frequency increased with

duration of test. Continuous nucleation of cavities therefore occurred throughout the creep life, so that in this respect also the cast alloy was similar to the wrought alloys.

3. The grain boundaries in the cast alloy were considerably more convoluted than those of a wrought alloy so that cracks along a grain boundary were often discontinuous and could be arrested at sharp inflections in the boundary.

4. Oxidised cracks penetrated along grain boundaries from the specimen surface as a result of creep deformation under the applied stress. These cracks continued to grow in number and size with duration of test but further work is in progress to determine to what extent this form of damage influences final failure.

5. Porosity at the low levels present in the cast specimens used in this work did not appear to contribute to the failure process except where linking with adjoining cavities occurred to form the final fracture path.

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