FATIGUE AND CREEP-FATIGUE BEHAVIOUR OF HIGH-TEMPERATURE ALLOYS FOR HTR-APPLICATION

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Abstract

The development of High Temperature Gas Cooled Reactors requires the evaluation of the fatigue behaviour of those alloys which have been taken into account for possible use as structural materials. Comparative fatigue tests of six wrought alloys at 850°C revealed differences especially at low strain ranges. The influence of the coolant gas on Incoloy 800 H and Inconel 617 resulted in an increased fatigue life and for Incoloy 800 H in changes of the deformation behaviour. Hold times introduced at maximum tensile strain reduced fatigue life considerably. The hold time data have been evaluated following the rules of ASME Code Case N 47 and design curves for inelastic and elastic analysis are suggested.

1. Introduction

The development of a Prototype Plant for Nuclear Process Heat (PNP) is aimed at service temperatures up to 950°C. At high service temperatures fatigue and creep-fatigue interaction become design problems of great concern, especially for nuclear power plants. Many experience with creep-fatigue interaction have been made among with the development of the fast breeder reactors and can be applied for HTR projects. The extensive work on the austenitic stainless steels which are used as fast breeder structural materials has revealed that the fatigue behaviour is sensitive to parameters like temperature, strain range, type of material, and especially to the interaction with creep loads (1 - 4). Because of the interaction in between these parameters a correct description of the fatigue and creep-fatigue behaviour is very difficult. In the ASME Code Case N 47 e.g. creep-fatigue interaction is accounted for by a linear accumulation rule. But many experiments have shown that creep-fatigue interaction is far off from being linear. The other attempts to describe the creep-fatigue interaction are not satisfactory in all points, neither. As a consequence of these experiences and due to the lack of data for the materials of concern (6, 7) an extended programme of fatigue tests have been set up.

In a first step comparative tests have been performed with six wrought alloys at 850°C in air to get a general impression of the fatigue behaviour at high temperatures. The further tests concentrated on Incoloy 800 H and Inconel 617 which meanwhile turned out to be among the favourite alloys in the PNP project. These alloys have been tested in the temperature range from 750°C to 950°C in air as well as in helium with PNP specific impurities. For Incoloy 800 H the influence of hold times on the fatigue behaviour have been examined with emphasis at 850°C. The fatigue data have been evaluated following the linear damage rule of Code Case N 47 in order to check whether this rule is applicable at very high temperatures or not. Corresponding hold time tests on Inconel 617 are underway and will be reported later.

2. Materials and Experimental Procedure

Six wrought alloys have been tested, two of which are iron-based alloys and belong to the Incoloy series whereas the others are nickel based alloys and belong to the Hastelloy, Nimonic, and Inconel series, resp. The chemical composition and product forms are given in Table 1. All six alloys have been delivered in a solution annealed condition.
The tests have been performed with closed-loop, computer-controlled, servo-hydraulic systems in the strain controlled mode. The specimen used is shown in Fig. 1. The strains were measured axially on a gage length of 25 mm and varied between 0.3 % and 1.5 % total strain range. All tests were performed at a fixed strain rate of $4 \cdot 10^{-3}\ s^{-1}$. In the case of hold time experiments strain was kept constant either at maximum tensile or compressive strain. The hold times varied between 1 and 60 minutes. Test temperatures were 750°C, 850°C, and 950°C, resp., with an emphasis at 850°C. The air tests were performed in a three zone resistance furnace whereas the helium tests were performed in a pressure chamber with an induction heating. The helium atmosphere contained impurities specific for the primary circuit of a PNP plant (later on called PNP-helium). The composition of the helium atmosphere is shown in Fig. 2. The amount of the impurities was controlled continuously at the inlet and the outlet of the pressure chambers.

3. Results and Discussion

3.1 Comparative tests in air at 850°C

Experimental results plotted in Fig. 2 illustrate the fatigue behaviour of the six wrought alloys tested. Because only one heat of each alloy has been tested the discussion is restricted to the general trends observed.
For each alloy and each strain range the data points are close together and the scatter is less than a factor of two. This was observed during all other experiments, too.

The differences in the fatigue behaviour are dependent on the strain range applied. Generally at strain ranges above 0.6 % materials with a good ductility as Incoloy 800 H show a better fatigue life. But since the correlation between fatigue life and ductility shows considerable scatter additional effects like corrosion are likely to influence the fatigue behaviour at high strain ranges.
At approximately 0.6 % total strain range the fatigue life of all six alloys is nearly identical. With further decreasing total strain range the differences in fatigue life are increasing. At 0.3 % the alloys with the highest UTS, Inconel 617, Nimonic 86, and Hastelloy S have been found to show a clearly better fatigue endurance. Furthermore the differences in fatigue life at low strain ranges are more pronounced than at high strain ranges, e.g. a factor of eight difference at 0.3 % total strain range compared to a factor of three difference at 1.5 % total strain range.

3.2 Influence of temperature and environment

The further tests in which the influence of the parameters temperature, environment, and hold time have been examined concentrated on Incoloy 800 H and Inconel 617 which are among the favoured alloys for a PNP plant. Inconel 617 may be used for those parts with the highest thermal loads whereas the use of Incoloy 800 H is restricted to lower temperatures.

In Fig. 3 the results of the continuous cycling tests of Incoloy 800 H at temperatures between 750°C and 950°C in air and in PNP-helium are shown. In air the continuous reduction of fatigue life with increasing temperature is dependent on the actual strain range. At 1.5 % total strain range a difference in temperature of 200°C makes hardly any difference in fatigue life whereas at 0.3 % total strain range the same temperature difference means a factor of ten in difference of fatigue life.
The fatigue tests in PNP-helium showed a much better behaviour than in air. At a strain range of $\Delta\varepsilon_t = 0.3$ % the cycles to failure in PNP-helium are at all temperatures approximately 5 times higher than in air. At high strain ranges it was found that fatigue life is increasing with increasing temperature opposite to what have been found during the air test.
As reported earlier (8) this effect is correlated to the ductility of Incoloy 800 H which increases with temperatures. The specimens tested in PNP-helium exhibited rhomboedrical deformation patterns on the surface, Fig. 4 a, which indicates a considerable yielding due to the high ductility of the material. It should be mentioned that the surface of the specimen is nearly free of oxide layers. On the surface of the specimens tested in air no deformation patterns, Fig. 4 b, but only solid oxide layers have been found. So it seems very likely that the oxide layers have suppressed a free yielding of the material at the surface during the air tests. Thus ductility will become significant for the fatigue behaviour only if the free yielding of the surface is not influenced by oxide layers.

The fatigue behaviour of Inconel 617 at temperatures between 750°C and 950°C in air and in PNP-helium is shown in Fig. 5. As in the case of Incoloy 800 H the results of the air tests indicate that the influence of temperature is dependent on the actual strain range. At $\Delta\varepsilon_t$ = 1.5 % nearly no influence of the temperature on fatigue life was found whereas at $\Delta\varepsilon_t$ = 0.3 % a difference in temperature of 200°C means a factor of ten difference in fatigue life.
Environment does influence fatigue life of Inconel 617 not so much as it was found for Incoloy 800 H. At a total strain range of 0.3 % fatigue life in PNP-helium is only a factor of two better than in air. At 1.5 % total strain range no significant influence of the environment on fatigue life was found. Especially at high strain ranges no increasing of fatigue life was found. The specimens tested in PNP-helium, Fig. 6 a, as well as in air, Fig. 6 b, showed no deformation pattern. The fracture path indicates that Inconel 617 is relatively brittle up to very high temperatures.
Furthermore it was observed that Inconel 617 is much more resistant to corrosion attack because in PNP-helium as well as in air the surfaces showed much less changes than Incoloy 800 H.

Comparing the fatigue behaviour of Incoloy 800 H and Inconel 617 the later is superior at low strain ranges. This is more pronounced in air than in helium and the differences in PNP-helium are larger at 750°C that at 950°C. At high strain ranges Incoloy 800 H has a better fatigue behaviour than Inconel 617, in air as well as in helium.

3.3 Influence of hold times

For Incoloy 800 H a series of hold time tests have been performed in air, mainly at 850°C but some additional tests have been performed at 750°C. The main emphasis was put on tests at 850°C because other mechanical data possibly excludes the use of Incoloy 800 H at 950°C. The additional experiments at 750°C have been performed to study the temperature behaviour of creep-fatigue interaction. Parallel tests have been done in PNP-helium and will be reported when the numerical and metallographic evaluations are finished.

In pre-tests it was found at all temperatures that tensile hold times are more damaging than compressive hold times; this is valid for low strains as well as for high strains. Therefore the main test series has been performed at maximum tensile strain only.

The results of the hold time tests are presented in Fig. 7 and 8 in log N_f vs. log t_H plots. The introduction of 1 min hold time leads to a considerable drop in fatigue life which is more pronounced at small strain ranges. On a double logarithmic plot the data for hold times longer than 1 min show a linear decrease of fatigue life with hold times. Due to the scatter of some data it cannot definitely decided if a saturation occurs at longer hold times. But taking into account own but unpublished results in PNP-helium a saturation is expected only for hold times longer than 60 min and probably will occur earlier at high strain ranges than at low strain ranges.
The slopes of the decrease of fatigue life are not significantly influenced by strain range and temperature. But at low strain ranges the absolute values of fatigue are higher at 750°C than at 850°C. The independence of the slopes on strain range and temperature may be very helpfull for an extrapolation of the data to longer hold times.

3.4 Evaluation of the hold time experiments

The data have been evaluated with respect to the generation of design values. Following the ASME Code Case N 47 separate evaluations for elastic and inelastic analysis design data have been made.

Inelastic analysis

In the Code Case N 47 creep-fatigue interaction is accounted for by a linear summation rule:

$$\Sigma \frac{N}{N_f} + \Sigma \frac{\Delta t}{t_R} = D \qquad (1)$$

The first part of eq.(1) describes the fraction of fatigue loading (N: number of cycles during combined creep-fatigue loading, N_f: cycles to failure in a corresponding continuous cycling test). The second part of eq.(1) describes the creep loading (Δt: time at certain stress level, t_R: time to rupture at a corresponding stress level). For Incoloy 800 H and temperatures up to 760°C Code Case N 47 assumes the damage sum D to be 1.
To be able to compute the creep part of the damage sum creep experiments have been performed in air on the same heat of Incoloy 800 H as used for the fatigue experiments. The rupture times varied between 5 and 4300 hours. The results could be fitted very well to Norton's creep law with the following parameters: $\sigma_R = 106.4/\text{MPa} \cdot (t_R/h)^{-0.116}$.
The creep damage during the hold times was computed by integrating the fraction of rupture times during a relaxation period as proposed by Spera (9). The relaxation behaviour is strongly dependent on strain rate. At high strain rates very high peak stresses are generated which relax within a few seconds to the same stress level as at low strain rates. The peak stresses have been cut off when computing creep-fatigue damage because they are not representative for the actual loading of a component. More details of the evaluation are reported elsewhere (10).

The creep-fatigue damage interaction values are shown in Fig. 9. They generally decrease with increasing hold times and become less than one. Most of the data can be covered by a bilinear curve with a minimum damage value of D = 0.4. There are indications that for longer hold times the damage values will increase.

Elastic Analysis

The elastic analysis fatigue design curve is constructed on the basis of a fatigue life curve which takes into account all reductions of fatigue life due to time dependent effects. Because hold time experiments normally yield the highest reduction in fatigue life the elastic analysis fatigue design curve at 850°C is constructed on this type of test. The existing data have been extrapolated to 1000 h hold time in two ways: First, the linear damage rule with D = 0.4 has been used (symbol o in Fig. 10). This method has been chosen because following Majumdar (11) it leads to the most conservative extrapolation compared to other methods. Alternatively the linear decrease of log N_f vs. log t_H in Fig. 8.has been extrapolated to 1000 h hold time linearly, neglecting possible saturation effects (symbol o in Fig. 10). Both procedures yield nearly the same values. Because the procedure in both methods is very rigorous the resulting curve in Fig. 10 is expected to be the average minimum fatigue life curve including time dependent effects. For strain ranges lower than 0.3 % only a rough estimation can be made.
The corresponding design curve was generated by applying the factors 2/20 on the average of the expected minimum values of the hold time experiments. The suggested design curve

at 850°C is considerable lower than the design curve at 760°C, even at small numbers of cycles. In Code Case N 47 the allowable strains at 538°C - 760°C coincide at 10 cycles. At higher temperatures a decrease in allowable strains is expected at low numbers of cycles comparable to that found for 304-type steels at lower temperatures.

4. Summary and Conclusions

Fatigue tests at 850°C have been performed to study the behaviour of six different wrought alloys. For two alloys, namely Incoloy 800 H and Inconel 617, the influence of temperature, air and PNP-helium and for Incoloy 800 H additionally the influence of hold times have been evaluated in more detail. A first attempt has been made to extend the existing design rules for Incoloy 800 H to higher temperatures.

During the comparative tests in air it has been found that at high strain ranges the six alloys tested show a different behaviour from that at low strain ranges. The largest differences have been found at low strain ranges. Since low strain ranges are more design relevant low cycle fatigue testing should be extended to strain ranges as small as possible to grant reliable design data.
At low strain ranges UTS is a measure for the expected fatigue behaviour whereas at high strain ranges the influence of ductility may be obscured by other effects like corrosion.

The fatigue tests in air and in PNP-helium have demonstrated that in the case of Incoloy 800 H significant changes of the fatigue behaviour due to the environment may occur. For Inconel 617 the changes have not been that significant. The failure mechanism is strongly affected by the environment. Therefore the influence of the environment needs careful examination. This will include the testing of pre-conditioned specimens to simulate the fatigue behaviour after extended service times.

During the hold time experiments performed with Incoloy 800 H considerable reduction of fatigue life due to creep interaction was found. Up to 30 min hold time no clearly visible indication of a saturation of the hold time influence was found. The evaluation of the results at 850°C with the linear damage interaction rule, which is used in Code Case N 47 for inelastic analysis, yielded damage values less than one. Most of the damage values can be covered by a bilinear curve with 0.4 at the minimum. The evaluation was found to be very sensitive to small changes in stress. Therefore the linear damage rule seems to be of limited value and needs further improvement. The elastic design curve has been established with very conservative assumptions and falls below the values of Code Case N 47 at 760°C. Future experiments and computations will show how far this conservative treatment is justified.

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Table 1 Alloys tested, chemical composition, product form

Alloy	Chemical composition in weight percent										Product form
	C	Si	Mn	Cr	Ni	Mo	W	Co	Al	Ti	
Incoloy 800 H	0.071	0.33	0.9	19.95	30.47	0.22	0.01	0.05	0.32	0.42	plate
Incoloy 8002	0.32	0.24	0.79	20.19	31.55	0.23	0.01	0.03	0.32	0.82	bar
Hastelloy X	0.102	0.37	0.94	21.84	42.01	8.95	0.83	2.40	0.12	0.07	bar
Hastelloy S	0.008	0.19	0.51	15.79	65.80	14.65	0.1	0.49	0.24	0.01	plate
Nimonic 86	0.055	0.25	0.08	25.02	62.40	10.14	0.1	0.24	0.29	0.03	bar
Inconel 617	0.065	0.06	0.03	22.00	52.55	8.87	0.19	12.4	1.02	0.38	tube

Table 2 Composition of impurities in the helium atmosphere

H_2	CH_4	H_2O	CO	CO_2	N_2	
500 ± 50	20 ± 5	1.5 ± 1	15 ± 5	≈ 1	≤ 5	μbar

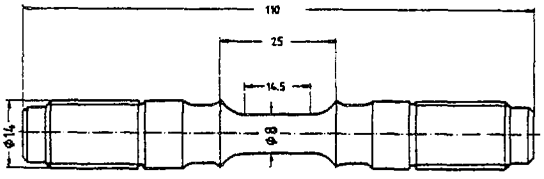


Fig. 1 Low-cycle fatigue specimen

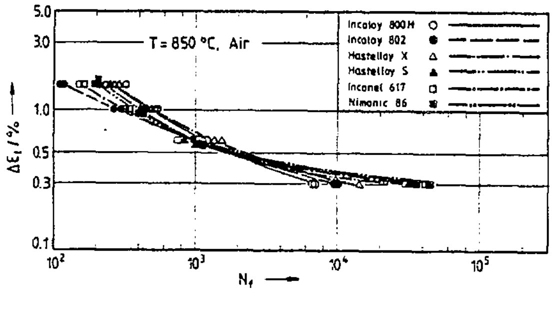


Fig. 2 LCF-behaviour of different alloys at 850°C in air

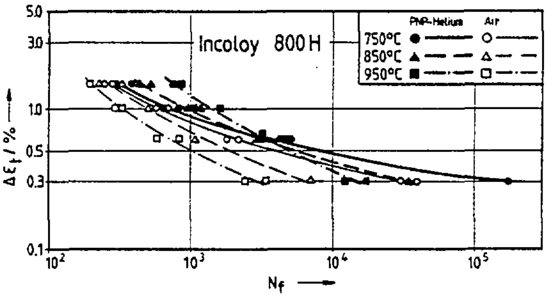


Fig. 3 Influence of temperature and environment on the fatigue behaviour of Incoloy 800 H

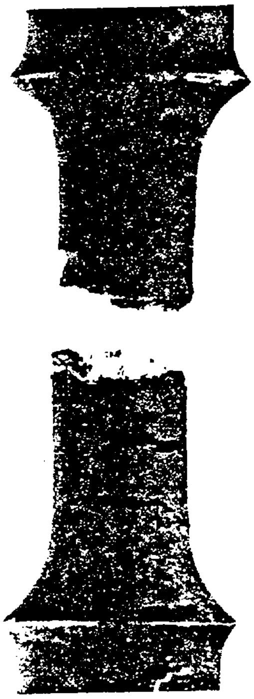


Fig. 4 a Fig. 4 b

Incoloy 800 H specimens tested at 950°C and 0.6 %

in air in PNP-helium

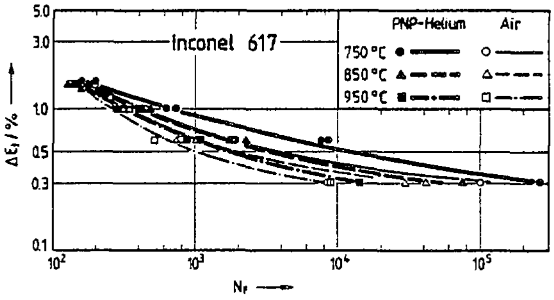
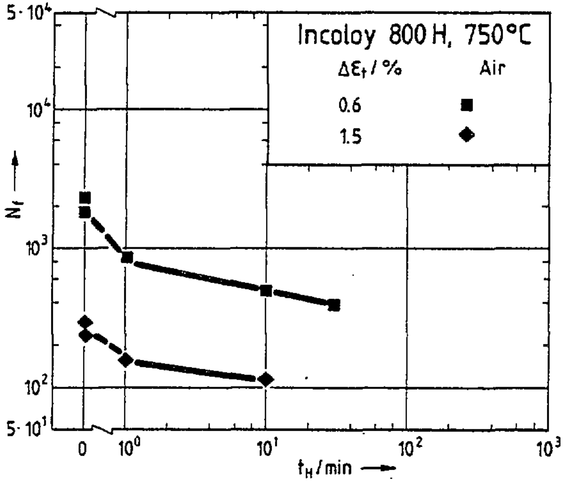


Fig. 5 Influence of temperature and environment on the fatigue behaviour of Inconel 617

Fig. 6 a Fig. 6 b

Inconel 617 specimens tested at 950°C and 0.6 %

in air in PNP-helium



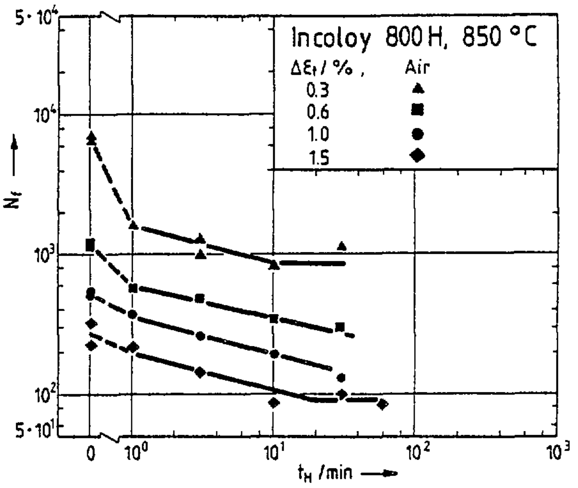


Fig. 7 Results of hold time tests at 750°C

Fig. 8 Results of hold time tests at 850°C

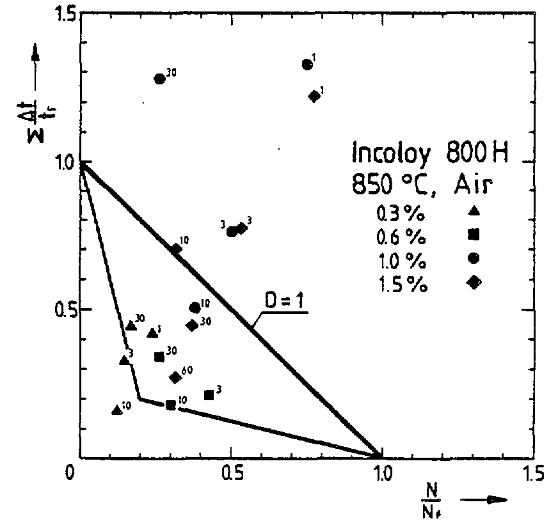


Fig. 9 Creep-fatigue interaction diagram

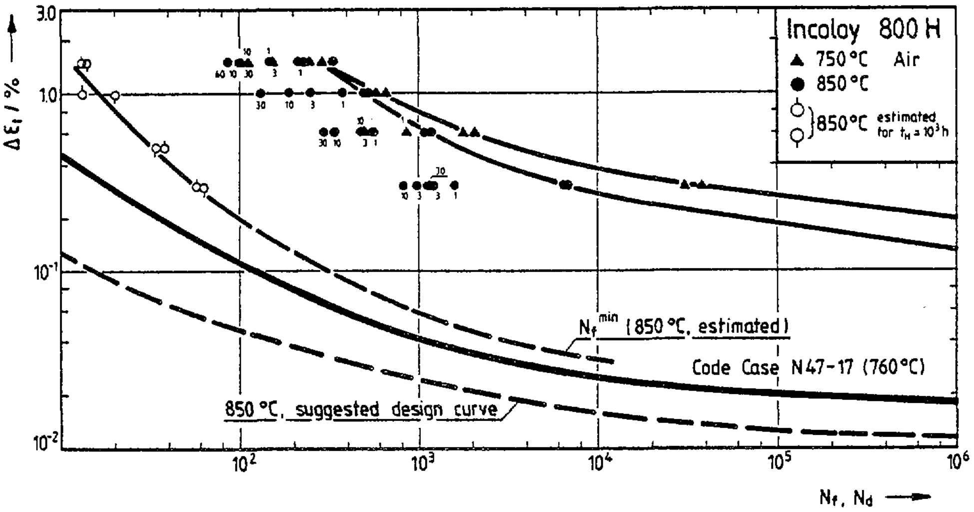


Fig. 10 Suggested fatigue design curve for elastic analysis and Incoloy 800 H at 850°C