THE INTERACTION OF CREEP AND FATIGUE IN TWO WROUGHT SUPERALLOYS

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Two wrought superalloys were studied, one was a Nimonic 80A type nickel-base superalloy and the other was an Fe-Ni-Cr-base alloy Incoloy 901. The interaction of creep and fatigue experiments were conducted by cyclic creep and a pulsating stress superimposed on a steady creep load. It was found that in the temperature range of 550° and 720°C, most of the specimens were deviated from the linear cumulative relationship of fatigue and creep. The deviation is related to the creep ductility of the alloy, improvement of ductility will increase the cyclic creep life. This can be explained from the SEM fracture micrographs. The pulsating stress is very harmful to the creep rupture life, especially in presence of notches.

INTRODUCTION

Gas or other heat-cycle turbines are actually working in a state of periodic stressing, which can be considered as creep combined with low cycle fatigue and this can be called cyclic creep or cyclic creep-rupture. In addition, there may have some additional pulsating stress superimposed on static load such as stresses due to vibration of the rotating blades transmitted to the rotor disc of the turbine. These may cause premature failure of the machine parts all depending on the condition of the interaction of fatigue and creep, together with the influence of working medium. For this reason, it is inadequate to evaluate superalloys solely based on data from conventional test methods in atmosphere as stress rupture, creep or even cyclic fatigue tests. So more work to simulate the conditions as near as possible to the actual service condition should be done in order to get proper selection and reasonable utilization of materials. This is why this kind of work is very active in recent years (1,2,3). In our institute, some work was started at the beginning of seventies and tried to estimate the service life of a turbine wheel (4).

MATERIALS AND EXPERIMENTS

In this investigation, two wrought superalloys were studied, one was a Nimonic 80A type nickel-base alloy 437, and the other was an Fe-Ni-Cr base alloy whose composition is similar to Incoloy 901. The compositions and heat treatments are shown in Table 1.

Table 1. Chemical Compositions and Heat Treatments of the alloys

Alloy	C	Si	Cr	Ti	Al	Mo	B	Fe	Ni
437	0.03	0.22	20.58	2.66	0.94	--	0.005	0.54	bal.
901	0.03	0.21	12.62	2.35	0.31	5.56	0.011	bal.	43.75

437: 1080°C(8 hr)AC + 700°C(16 hr)AC
901: 1090°C(2 hr)WQ + 780°C(4 hr)AC + 720°C(24 hr)AC

The experiments of periodic cyclic creep were carried out on constant load creep testing machines which are actuated with automatic periodic loading and unloading devices. The periodicities at constant loading were 0, 3, 10 and 30 minutes at different temperatures of 350, 550, 650, 720 and 750°C under appropriate loads. Pulsating stresses with a frequency of 600 cycles per minute were superimposed coaxially on a creep load at different temperatures. Two types of specimens, smooth and notched, were tested, the calculated factor of elastic stress concentration Kt = 2.

EXPERIMENTAL RESULTS

(1) From the experimental results of alloy 901, it is shown that at lower testing temperature as 350°C, the rupture life of cyclic creep is mainly determined by the number of stress cycles and it is insensitive to the duration at which the peak load is sustained at each cycle. This is true for both notched and unnotched specimens, although the life of the former is much shorter.

(2) The cyclic creep test data of alloy 901 were shown in Figure 1, it is noted that there exists fatigue strengthening effect for the smooth specimens tested at 550, 650 and 720°C for the alloy, however, for the notched specimens, cyclic stressing weakens the alloy. Table 2 shows some data taken from the curves of Figure 1. It is shown that the strengthening effect is more pronounced with increase of temperature. For instance, the rupture life increased is only doubled at 550°C during loading and unloading by 10,000 cycles, while the rupture life is increased by eight-fold at 720°C with the same number of loading cycles. The weakening effect of the notched specimens is even more drastic, the rupture life at 550°C drops by a factor of nine during a cyclic life of 1,000. However, the notch sensitive effect is diminished at higher temperatures.

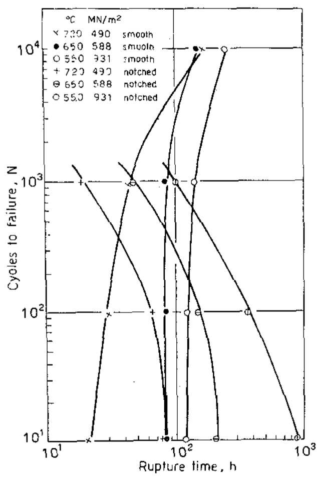


Figure 1. Fatigue-Creep Strengthening and Weakening of Alloy 901

Table 2. Relation of Life of Creep-rupture Tests and Number of Loading Cycles of Alloy 901

Temp. (°C)	Stress (MN/m^2)	Spec. Type	Stress Rupture Life(hr)	Rupture Life(hr) during Cycling at		
				100	1000	10000
550	932	smooth	80	82	86	150
"	"	notched	900	380	100	–
650	588	smooth	120	125	145	260
"	"	notched	200	150	45	–
720	490	smooth	20	28	42	160
"	"	notched	80	62	18	–

(3) The results of cyclic loading of notched specimens of alloy 437 are shown in Figure 2. It is shown that the creep-rupture life decreases with number of cycles as indicated on the normalized coordinates of N/N_f vs $N\Delta t/t_r$, in which N is number of cycles of loading, N_f is number of cycles of pure fatigue failure, Δt is duration at peak load of each cycle and t_r is the creep-rupture life. It is shown that the decrease of rupture life due to cyclic loading is different with different test condition: under the condition of 650°C and 588 MN/m^2 (85 ksi), the decrease of rupture life is most predominant, while under a condition of 550°C and 863 MN/m^2 (125 ksi), the decrease is the least and obeys a straight line relationship in the normalized coordinates.

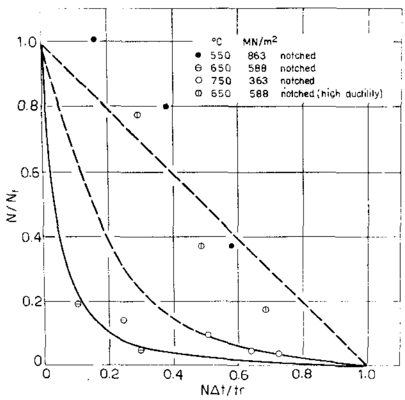


Figure 2. Creep and Fatigue Cumulative Damage of Alloy 437

(4) The creep-rupture life is very much shortened if a pulsating stress is superimposed on a steady creep load as shown in Figure 3. It is shown that the influence of the pulsating stress is more pronounced for alloy 437 compared to 901 at the temperature of 700°C. The decrease in rupture life is even more pronounced for the notched specimens compared to the unnotched ones. For instance, under the condition of 441 ± 196 MN/m^2 (639 ± 284 ksi),

the rupture life of the smooth specimens of the alloys 437 and 901 decreases to 40 and 30 hours respectively from about 100 hours of static creep-rupture life; and for notched specimens the rupture life is decreased to 70 and 30 hours respectively for the two alloys from about 400 hours, a decrease of more than ten-fold of the rupture life for the alloy 437. Therefore, any vibrational stress superimposed on the static creep load is very much harmful to the parts with notches working at elevated temperatures.

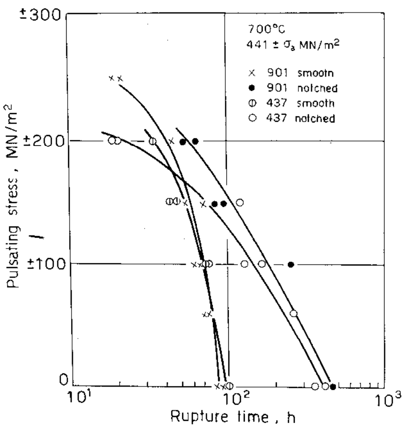


Figure 3. Rupture Life of Alloys 437 and 901 under Pulsating Loads Superimposed on a Constant Load of 441 MN/m^2 at 700°C.

DISCUSSION AND CONCLUSION

(1) According to the results from Figure 2, the interaction coefficient of creep and fatigue can be expressed by B in Lagnebory and Attermo equation (5).

$$\frac{N}{N_f} + B\left(\frac{N}{N_f}\cdot\frac{N\Delta t}{t_r}\right)^{\frac{1}{2}} + \frac{N\Delta t}{t_r} = 1$$

When B = 0, the equation represents that the material obeys the linear cumulative damage, that is, there is no interaction between creep and fatigue, and they are simply additive. It will be a straight line in the normalized coordinates as the alloy tested at 550°C and 863 MN/m^2 (125 ksi).

When B > 0, the interaction of the creep and fatigue will weaken the material as most of the notched specimens, although these specimens all show notch strengthening under static creep tests.

When B < 0, the interaction strengthens the material as most of the unnotched specimens.

(2) In order to find out the relation of the parameter B with other mechanical properties of the alloy 437, specimens of the same alloy were prepared to a state of higher ductility. That is, after solution treatment at 1080°C (8 hr), then followed by 850°C (24 hr) ageing, furnace cooled to 700°C, kept for 16 hours, then air cooled. With this treatment, the creep ductility will be as high as 27% under 650°C, 588 MN/m^2 (85 ksi). If plot the creep ductility at different temperature against parameter B, a very good correlation is shown as indicated in Figure 4. The higher the ductility of the alloy, the lower is the B value. But it is not true for the ductility expressed by the elongation of the conventional tensile tests at a strain rate of 1.8×10^{-2} / min. If the strain rate is slow enough, as at a strain rate of 9×10^{-6} / min., the elongation data fit the same curve as of creep ductility quite well.

From the observations of the fracture surfaces by SEM, as shown in Figure 5, the variation of B value can be explained. It is found that the damage due to fatigue is mainly intragranular and the damage due to creep is by grain boundary sliding. If the ductility of the alloy is high enough, the above two types of deformation are compatible with each other and they are additive, so the damage due to cyclic creep will be linearly cumulative, that is B = 0. If the stress rupture ductility is low, crevices along grain boundaries will easily

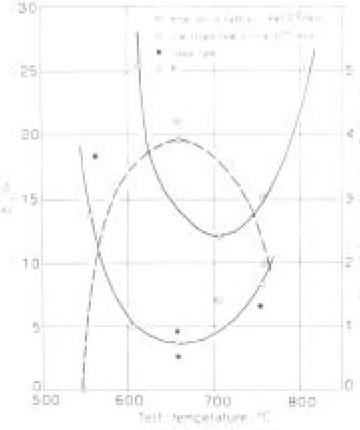
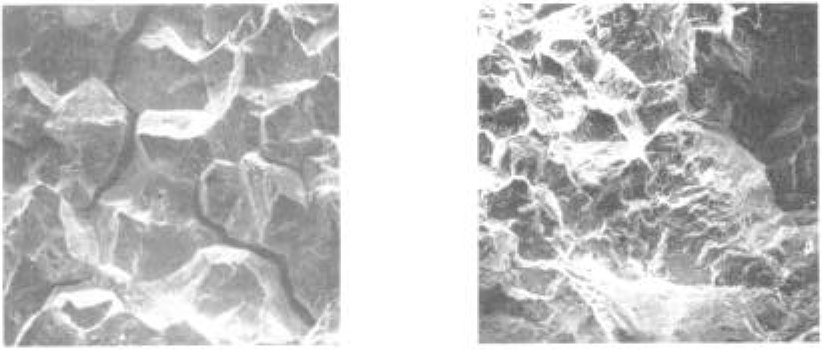


Figure 4. Relation of Ductility of Alloy 437 with Creep-fatigue Interaction Factor B



(a) Low Ductility
Mag. x124

(b) High Ductility
Mag. x124

Figure 5. SEM Fracture Micrographs of Fatigue-Creep Specimens Tested at 650°C, 588 MN/m^2, Periodic Cycling of 3 min. 20 sec.

be formed, fatigue will enhance the creep damage and the fracture is accelerated.

(3) The creep rupture strength is seriously reduced if a vibrational force is superimposed on a steady creep stress, especially for those parts with notches or slots such as dovetail root of blades. So measures must be taken in design and production to avoid the disastrous failure of some key parts as blades or discs of the gas turbine engine.

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