EFFECT OF HOLD TIMES ON THE ELEVATED TEMPERATURE FATIGUE CRACK GROWTH BEHAVIOR OF INCONEL 718 ALLOY

J.P. Pedron and A. Pineau

Centre des Matériaux de
L'Ecole Nationale Supérieure des Mines de Paris
B.P. 87 - 91003 Evry Cédex, France
Equipe de recherche associée au C.N.R.S. ERA767

ABSTRACT

The effect of tensile hold times on the fatigue crack growth rate of Inconel 718 was studied at 923K. It was found that the superimposition of hold times (Th) can produce a drastic increase in the fatigue crack growth rate. Potential drop technique was used to analyse the crack propagation which takes place in certain conditions either during the cyclic part of the loading or during the dwell period. In this high strength and low ductility material it has been found that an upperbound of the crack growth rate can be written as $da/dN = Rp + \int_0^{Th} (da/dt)_{creep}\, dt$, where Rp is the monotonic plastic zone size, $(da/dt)_{creep}$ is the static crack growth rate.

KEYWORDS

High temperature crack growth; Fatigue-creep interaction.

INTRODUCTION

Inconel 718 alloy is a high strength nickel base alloy which is extensively used for the construction of turbine disks. Typical operation of disks of jet engines are such that hold times under peak stress are encountered. This work deals with the study of hold times effect on the crack propagation behavior of this alloy.

The fatigue crack growth rate (f.c.g.r.) behavior of this alloy has already been examined by several investigators. Popp and Coles (1969) have studied the influence of tensile hold time on the f.c.g.r. at 813K. These authors have shown that at this temperature the f.c.g.r. was increased when hold times were applied to the specimens. Their results were obtained from thin sheet specimens. More recently Coles, Johnson and Popp (1976) used 25.4 mm thick compact specimens and other types of specimens which contained surface flaws, to investigate the effect of tensile hold time on the f.c.g.r. at 813K. In that study they showed that in a range of f.c.g.r. larger than about 1 μm/cycle the hold time effect was more pronounced in the CT type specimens than in the other ones. More recently, Clavel and Pineau (1978) have used 7 mm thick CT type specimens to investigate the influence of the loading rate on the f.c.g.r. of alloy 718 at 823K, using sinusoïdal wave form signals ranging between 5.10^{-3} Hz and 20 Hz, triangular or square wave form signal with a frequency of 5.10^{-2} Hz. These authors showed that the f.c.g.r. was increased by a decrease in frequency. The comparison between the results obtained by using triangular wave form signal showed that this increase in crack propagation rate was essentially due to a strain rate effect. Still more recently the effects of stress ratio and hold time on the fatigue crack growth in Alloy 718 at 923K have been investigated by Shahinian and Sadananda (1979). These authors showed that the inclusion of a 1 mn hold at either the maximum or the minimum load increased the f.c.g.r.

The present study reports additionnal results on the f.c.g.r. behavior of Alloy 718 at 923K. This work was undertaken to extend the results previously obtained at 823K. The influence of frequency and hold time was investigated using static, cyclic and combined loadings.

EXPERIMENTAL PROCEDURE

The material used for this investigation was cut from a 35 mm diameter bar whose composition is given in Table 1. Ten millimeters thick CT type specimens were employed (Fig. 1). These specimens were cut in such a way that the notch was parallel to the bar axis. They were submitted to a conventional heat treatment applied to Inconel 718 alloy, i.e., annealing at 1223K for 1 hr, air cooling, aging at 993K for 8 hrs, furnace cooling to 893 K, aging at 893K for 8 hrs, air cooling to room temperature. This heat treatment leads to a duplex grain size microstructure, as especially noticed on longitudinal sections, and to the existence of β Ni_3 Nb phase precipitated along the grain boundaries (Fig. 2). The tensile properties of this alloy determined at room temperature and at 923K are shown in Table 2. The notch of the CT specimens was extended up to a/w ≃ 0.35 by fatigue precracking at room temperature. At the end of precracking the stress intensity factor range was maintained lower than 10 MPa$\sqrt{m}$.

TABLE 1 Inco 718 Composition (Wt%)

	Ni	C	Cr	Mo	Ti	Al	Nb	Fe
%	Bal	0.065	18.3	3	1.1	0.55	4.7	18.4

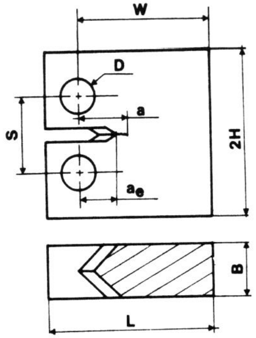
TABLE 2 Inco 718 Tensile properties

Temperature K	σ_{ys} Tensile Yield Strength (MPa)	σ_R Tensile Strength (MPa)	A% Tensile Ductility
293	1154	1408	23.5
923	967	1155	17.4

High temperature f.c.g.r. experiments were carried out at 923K under the following conditions :

- sinusoïdal wave shape signal, with ν = 20 Hz;
- triangular wave shape signal, with loading and unloading times of 10 s;
- trapezoïdal wave form signal including the same loading and unloading times as used in triangular signal and a superimposed hold time (Th), with Th ranging between 10 s and 5 mn. In all cases the R ratio ($R = K_{Min}/K_{Max}$) was constant and equal to 0.10. The maximum load (P_{Max}) was maintained approximately constant,

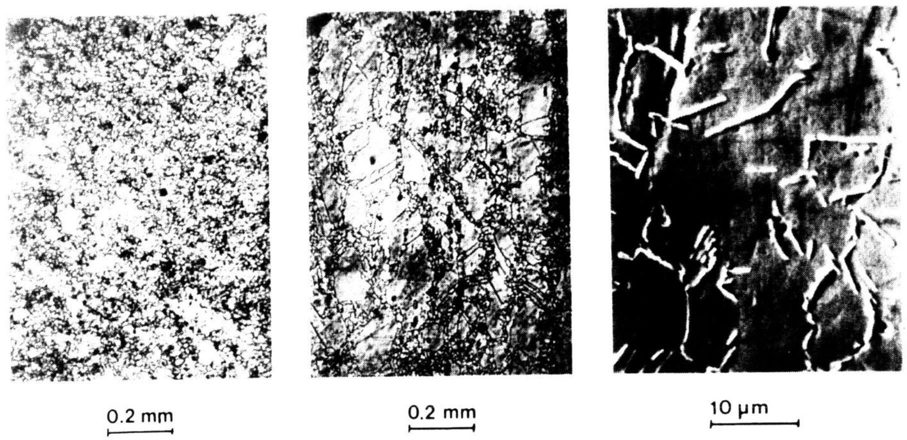
i.e. 250 daN < P_{Max} < 300 daN, since several studies have shown that this parameter could influence the high temperature f.c.g.r. (Shahinian and Sadananda, 1979; Sadananda and Shahinian, 1977; Koterazawa and Mori, 1977).



SYMBOL	NOMINAL DIMENSIONS (mm)
W	25.0
B	10.0
2H	30.0
L	31.25
a_e	7.25
D	6.5
S	13.75

Fig. 1. CT type specimen.

In tests at elevated temperature the crack was extended in the range corresponding to 0.35 < a/w < 0.70. The crack length was measured by using either a travelling microscope or a D.C. potential drop technique (I = 4.5A) which has previously been calibrated.



a) Cross section; optical micrograph.
b) Longitudinal section; Optical micrograph.
c) Scanning electron micrograph.

Fig. 2. Inco 718 - Microstructure.

EXPERIMENTAL RESULTS

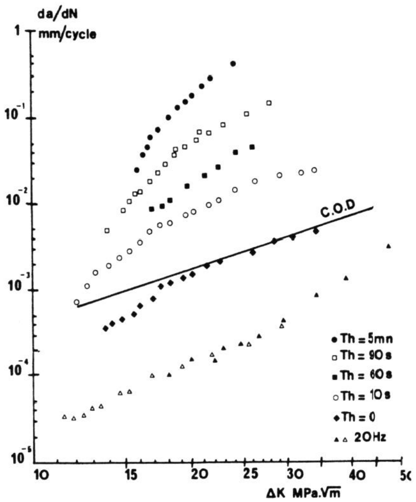
Figure 3 shows the results corresponding to the different wave shape signals used in this study. These results may be represented in terms of the Paris equation $da/dN = A(\Delta K)^n$ where the exponent n is given in Table 3. The value for n was calculated for $\Delta K > 18$ MPa $\sqrt{m}$.

The results corresponding to ν = 20 Hz are very close to those previously obtained at the same frequency on specimens cut from an another bar (Clavel, Levaillant and Pineau, 1979). It is also noted that a decrease in frequency from 20 Hz (sinusoïdal signal) down to 5.10^{-2} Hz (triangular signal) leads to a strong increase in f.c.g.r. Moreover these results show that the incorporation of a hold time strongly increases the f.c.g.r. This effect is quite significant since for instance at ΔK=20 MPa$\sqrt{m}$ the f.c.g.r. is increased by two orders of magnitude when the dwell period lasts 5 mn.

TABLE 3

Hold time (Th)(s)	20 Hz	0	10	60	90	300
n	3,4	3,3	3,3	4	4	5,5

Further tests were performed in order to show that acceleration in f.c.g.r. observed with trapezoïdal signals was really associated with the effect of dwell period and not only with a decrease in frequency. A specimen was given the various wave shape signal programs shown in Fig. 4. These supplementary results clearly show the deleterious effect of a tensile hold time on the f.c.g.r. It is worth noting that this behavior is different from the situation observed at 923K where faster f.c.g.r. were found to be associated with a continuous signal (Clavel and Pineau, 1978).



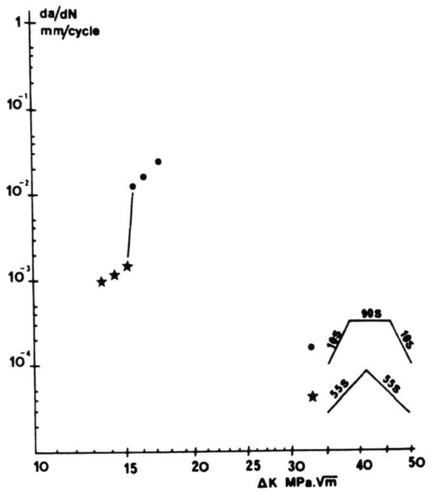


Fig. 3. Inco 718; 923K Hold Time effect. Fig. 4. Inco 718; 923K Wave Form effect.

In order to compare the f.c.g.r. measured at 923K to those which can be calculated from a C.O.D. model, the C.O.D. was calculated as C.O.D. = $1/2(\Delta K)^2 / E\sigma_{ys}$, where E is Young modulus (E = 165 GPa at 923K , (Clavel, Levaillant and Pineau, 1979)). In Fig. 3 it is observed that the C.O.D. model predicts f.c.g.r. larger than those experimentally measured at ν= 20 Hz. This conclusion is in agreement with previous results (Clavel, Levaillant and Pineau, 1979). It is presumably a casual fact that the calculated C.O.D. should be very close to the f.c.g.r. corresponding to $\nu = 5.10^{-2}$ Hz.

Fracture surfaces were observed by means of a scanning electron microscope. At high frequency (ν = 20 Hz) it was noted that the fracture mode was essentially transgranular and occurred by formation of ductile striations as soon as ΔK was larger than about 20 MPa$\sqrt{m}$. For lower values, crystallographic features typical of low f.c.g.r. were observed. In the range where striations could be identified it was noted that the striation spacing was close to the macroscopic f.c.g.r., (da/dN).

At lower frequency and even in the tests corresponding to triangular wave shape signal the fracture mode was partly intergranular. Observations of the fracture surfaces associated to trapezoïdal wave shape signal indicated that, for the same stress intensity factor range, the amount of intergranular decohesion was an increasing function of the dwell period. Although it has been difficult to measure whith accuracy the percentage of intergranular decohesion on the fracture surfaces, partly because of the complex grain microstructure of this alloy, the results corresponding to ΔK = 20 MPa $\sqrt{m}$ are given in Table 4.

TABLE 4 Percentage of intergranular decohesion

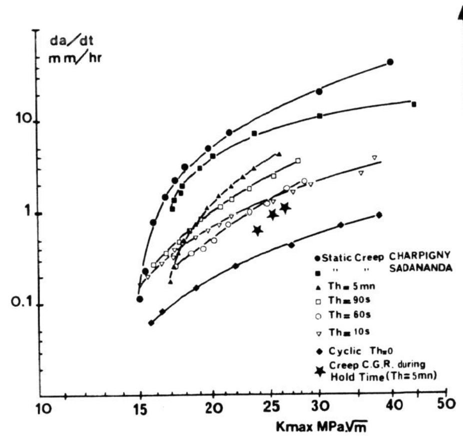
Th(s)	0	10	60	90	300
%	15	25	30	40	65

DISCUSSION

Several phenomena may occur in the acceleration of the f.c.g.r. which has been observed in the tests which included a tensile hold time. Among them, environment plays very likely an important role. It has been shown recently by Floreen and Kane (1979) that the f.c.g.r. of Inconel 718 alloy at 923K was strongly dependent on the chemical composition of environment. Moreover these authors have demonstrated that aggressive environments promoted intergranular crack growth. In the present experiments which have been carried out in air, oxidation might also have a detrimental effect on f.c.g.r. Earlier experiments carried out at 823K (Clavel and Pineau, 1978) showed that if oxidation damage takes place, it essentially occurs during the loading and/or unloading part of the cycling. It was pointed out that this behavior would have some analogy with that observed by Barsom (1971) in corrosion fatigue when ΔK is lower than KSCC, where KSCC is the threshold value for stress corrosion cracking. In the present study the results shown in Fig. 4 indicate that the most damaging effect is observed during a hold time cycling.

This observation suggests that, contrary to the situation observed at 823K, creep damage is predominant at 923K . This conclusion can equally be inferred from the comparison of the f.c.g.r. results on a time basis, and no longer on a cycle basis (Fig. 5). In this figure, the static creep crack growth rates measured by Sadananda and Shahinian (1977) and by Charpigny and Hénon (1980) are included. It is worth emphasizing the fact that Charpigny and Hénon have employed for their study the same type of specimens as those used in this investigation (and cut from the same bar). Therefore their results can directly be used to derive the static creep crack growth resistance of our material. In this figure the results are reported in terms of the maximum stress intensity factor, i.e. $K_{Max} = \Delta K/(1-R)$ although it is not yet clear whether the elevated temperature crack growth behavior can be related to this loading parameter or to other parameters such as net ligament stress or C* parameter (Harper and Ellison, 1977; Sadananda and Shahinian, 1977; Koterazawa and Mori, 1977).

Figure 5 shows that all data corresponding to a hold time are bounded by the static curve (upper bound) and the cyclic behavior (Th = 0, lower bound). It is worth noting that the cyclic curve and the static curve are in reverse order of the one observed at lower temperatures, i.e. 823K and 698K, by other investigators (Popp and Coles, 1969; Sadananda and Shahinian, 1978). At these temperatures, it was observed that the upper bound corresponded to the cyclic curve whilst the lower bound was associated to the static curve. It is also worth noting that the curves corresponding to the longest hold times, i.e. Th = 90s and Th = 5 mn are close to the creep crack growth curve. All these observations strongly suggest that in the conditions of this study the effect of hold time on the f.c.g.r. is closely associated with the creep crack growth resistance.



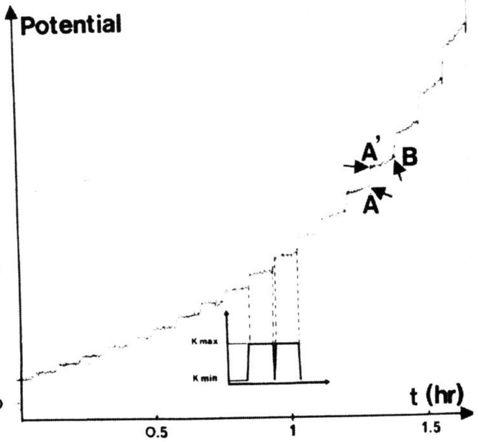


Fig. 5 Inco 718, 923K, Hold time effect. Fig. 6 Inco 718, 650°C, Potential drop recording.

This conclusion would imply that crack propagation occurs not only during the fatigue cycling but also during the dwell period. It has been possible to effectively observe this behavior by using the potential drop technique. Fig. 6 shows with more details an example of an electrical signal recorded during an experiment which included 5 mn hold time. This figure indicates that the electrical potential increases during the hold time which is imposed every cycle (Part A'B). This variation in potential A'B was observed only at high ΔK, i.e. $\Delta K > 25$ MPa $\sqrt{m}$. It is possible to convert this increase in potential A'B into a static crack growth rate by using the calibration curves. This procedure leads to values of the static crack growth rate lower than those reported by Charpigny and Henon (Fig. 5). This difference might be related to the fact that, unlike pure static creep experiments, our tests, which include periodic unloading of the specimens, do not provide a steady creep crack growth rate.

The curves shown in Fig. 6 also show another interesting phenomenom. An abrupt increase in electrical potential, AA', is observed during the fatigue cycling.

It has been checked that this abrupt increase in potential took place during the loading part of the cycling. This type of phenomenom was observed for ΔK ranging from 17 MPa $\sqrt{m}$ to 30 MPa $\sqrt{m}$ in those tests which involved the longest hold time. This discontinuous variation per cycle in electrical potential was used to evaluate the crack growth which takes place every cycle. The results are given in Fig. 7. In this figure we have also plotted the monotonic plastic zone size which can be calculated as follows :

$$R_p = 1/3\pi \, (K_{Max}/\sigma_{yc})^2; \qquad (1)$$

where σ_{yc} = 675 MPa is the cyclic yield strength. It is observed that, in the range of f.c.g.r. in which this discontinuous phenomenon occurs, the crack advance per cycle is of the same order of magnitude as the monotonic plastic zone size. It is suggested that this behavior corresponds to the accumulation of creep damage by formation of intergranular cracks or intergranular cavities in front of the crack tip. When the damage reaches a critical value, local instable crack propagation occurs over a distance where the applied stress reaches a critical value. This interpretation is close to that recently proposed by Lloyd and Wareing (1979) in their analysis of stable and unstable fatigue crack propagation during high temperature creep fatigue in austenitic steels. In our case which corresponds to a high strength and low ductility material, as compared to stainless steels, the critical distance is of the order of the monotonic plastic zone size.

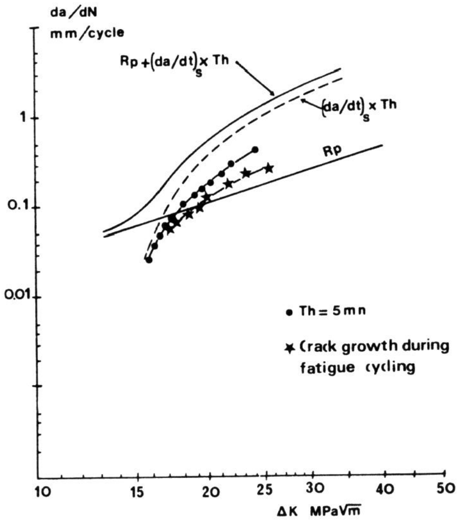


Fig. 7. Inco 718, 923K.

This analysis can be used to determine an upperbound for the crack propagation rate in creep-fatigue. This upperbound can be written as follows :

$$da/dN = (da/dt)_{creep} \times Th + R_p \qquad (2)$$

where $(da/dt)_{creep}$ is the static crack growth rate measured in static creep tests. It is believed that this relationship corresponds to an upperbound, since, as shown previously, the steady creep crack growth rate is higher than the growth rates which could be evaluated from the non steady behavior observed during each hold time. In Fig. 7 where the f.c.g.r. are shown on a cycle basis, we have plotted the two curves corresponding to $(da/dt)_{creep} \times Th$ and to $(da/dt)_{creep} \times Th + Rp$. These two curves are plotted for Th = 5 min. This figure shows that equation (2) is indeed an upperbound for the f.c.g.r.

SUMMARY AND CONCLUSIONS

1. Fatigue crack growth rate in Inconel 718 at 923K is strongly increased when hold times are superimposed to fatigue cycling.

2. The acceleration in crack growth rate is associated with the occurrence of intergranular cracking.

3. An upperbound for the fatigue crack growth rate in creep fatigue is given as follows:

$$da/dN = (da/dt)_{creep} \times Th + Rp,$$

where $(da/dt)_{creep}$ is the static creep crack growth rate and Rp is the monotonic plastic zone size.

REFERENCES

Barsom, J.M. (1971). Corrosion Fatigue Conference, University of Connecticut, 424, NACE 2, 1971.
Charpigny, J. and J.P. Hénon (1980). Proceeding of the international Conference of Sheffield.
Clavel, M. and A. Pineau (1978). Met. Trans., 9A, 471-480.
Clavel, M. C. Levaillant and A. Pineau (1979). To be published in T.M.S. AIME Fall Meeting, Milwaukee (Wisconsin).
Coles, A. R.E. Johnson and H.G. Popp (1976). Journal of Eng. Mat. and Tech. 305-315.
Floreen, S. and R.H. Kane (1979). Met. Trans. 10A, 1745-1751.
Harper, M.P., E.G. Ellison (1977). Journal of Strain Ana. 12, n°3, 167-179.
Koterazawa, R. and T. Mori (1977). Journal of Eng. Mat. and Tech . 298-305.
Lloyd, G.J. and J. Wareing (1979). Journal of Eng. Mat. and Tech. 101, 275.
Popp, H.G. and A. Coles (1969). Proceeding of the Air Force Conference on Fatigue and Fracture of Aircraft Structures and Materials, 71-86.
Sadananda, K. and P. Shahinian (1977). Met. Trans. 8A, 439-449.
Sadananda, K. and P. Shahinian (1978). Trans. of the ASME, Journal of Eng. Mat.and Tech., 1-7.
Shahinian, P. and K. Sadananda (1979). Journal of Eng. Mat. and Tech., 224-230.