Time Dependent Effects on High Temperature Low Cycle Fatigue and Fatigue Crack Propagation of Nickel Base Superalloys

F. GABRIELLI*, M. MARCHIONNI and G. ONOFRIO
ITM–CNR, Via Induno 10 — 20092 Cinisello B., Italy

ABSTRACT

The influence of time dependent processes on high temperature fatigue behaviour was studied in wrought, cast and ODS mechanically alloyed nickel base superalloys. Fatigue tests were performed in air and in vacuum at different temperatures and strain rates. In LCF tests the disappearance of strain rate effect on fatigue life in vacuum indicates that fatigue damage is markedly affected by oxidation. In FCG tests the effect of oxidation in wrought alloy is stronger than in other alloys examined. Time dependent fatigue propagation micromechanisms are analyzed and discussed in detail.

KEYWORDS

Nickel superalloys; gas turbine; low cycle fatigue; fatigue crack propagation; air; vacuum; creep-fatigue interaction.

INTRODUCTION

Nickel base superalloys are typically used in high temperature components of gas turbines. In such applications they suffer from a large reduction in life by creep-fatigue-environment interactions under certain conditions and, from a designing view point, the analysis of the distribution of stresses has shown that low cycle fatigue, creep and vibrations are the main source of damage /1/.

Fatigue at high temperature, where time and strain rate effects are important, is often referred to as regime of time dependent fatigue and the

* Now at University of Ancona

fatigue process is frequently treated in separate components of initiation and of crack propagation. Furthermore high temperature fatigue resistance of alloys is profoundly affected by corrosion processes which influence the time to crack initiation and the growth mechanisms at the crack tip /2-5/. At high temperature such corrosion mechanisms take place synergistically with creep processes and lead to an acceleration of crack initiation and propagation and to a decrease of fatigue life.

The presence of time dependent processes in fatigue can dramatically modify the expected fatigue behaviour and complicate the extrapolation of laboratory data to the condition of the components in service. It is, thus, necessary to investigate the resistance to high temperature fatigue when time dependent processes are present in order to evaluate allowable flaw sizes and to improve life time prediction methods.

In air laboratory fatigue tests the corrosive action is mainly due to the oxygen. Many investigations of low cycle fatigue (LCF) and fatigue crack growth (FCG) were directed to separate the effect of oxidation by comparing results in air and in vacuum /6-9/. Other investigations were undertaken in order to separate the effect of fatigue and creep by tests with different strain rates or frequency and introducing hold times /10-13/.

This paper deals with an investigation of creep-fatigue environment effects on several nickel base superalloys. Primarly, attention will be given to the observations and interpretations obtained from experiments on smooth specimens subjected to uniaxial loading in the LCF range and then fatigue crack growth behaviour will be studied in the framework of linear elastic fracture mechanics.

The interplay of testing parameters will be considered in relation to the micromechanisms responsible for the nature of the failures observed.

MATERIALS AND EXPERIMENTAL PROCEDURES

The materials studied are the following nickel-base superalloys:
a) wrought alloys Inconel X-750, Inconel 718;
b) cast alloys, IN 792+Hf, IN 738 LC; IN 100;
c) mechanically alloyed ODS MA 6000.
Their chemical composition is reported in table 1.

The LCF tests were performed in the temperature range from 650°C to 1050°C in strain controlled conditions and in the strain rate range from 10^{-2} to 10^{-4} s^{-1}. The wave form was triangular symmetrical to zero (R=-1). More detailed procedure of experimental technique was described in previous reports /14,15/.

The FCG tests were performed in the temperature range from 650° to 950°C in load controlled conditions with the frequency varied between 0.01 and 10

TABLE 1. Nominal composition of the alloys (Wt%)

		Ni	Cr	Co	Mo	Fe	W	Ta	Nb	Al	Ti	Hf	C	Si	Y_2O_3
wrought	INCONEL X-750	73	15.5	-	0.5	7	-	-	1	0.7	2.5	-	0.04	0.2	-
	INCONEL 718	53	17.8	0.03	2.99	19.1	-	-	5.35	0.57	0.97	-	0.029	0.02	-
	IN 713 LC	75	12	-	4.5	-	-	-	2.0	5.9	0.6	-	0.05	-	-
	IN 792+Hf	61	12.4	9	1.9	-	3.0	3.9	-	3.1	4.5	1.0	0.12	-	-
cast	IN 738 LC	60	15.9	8.3	1.6	0.22	2.5	1.72	0.96	3.4	3.3	-	0.12	0.1	-
	IN 100	70	10	15	3.0	1	-	-	-	5.5	4.7	-	0.18	0.21	-
ODS	INCONEL MA 6000	69	15	-	2.0	-	4.0	2.0	-	4.5	2.5	-	0.05	-	1.1

Hz. The wave form was triangular with R ratio equal to 0.05. The experimental details were reported in a previous paper /16/.

In all the tests performed in vacuum, the pressure was lower than 10^{-2} Pa.

EXPERIMENTAL RESULTS AND DISCUSSION

Low Cycle Fatigue Behaviour

High temperature fatigue failure occurs by initiation and propagation of one or more cracks until specimen separation occurs. In general, nucleation takes place at a free surface and the crack propagates subsequently in three stages: a) stage I growth which is an extension of the initiation process (it has a length of the order of 10 µm) and takes place along a crack tip shear plane and usually extends for a distance of the order of few grain diameters; b) stage II growth that is normal to the applied stress and is controlled by the continuous response of the material; c) stage III growth that occurs when static fracture, e.g. hole growth, contributes to crack advance and leads to final failure /17/

The part of area devoted to the various stages of failure depends on the applied stress level and on the type of material: for example, when the applied stress decreases, stage I increases and stage II decreases; in nickel superalloys at elevated temperature the stage I is well defined and crack initiation is due to heterogeneous planar slip bands /4/.

Following stage I, when cyclic conditions do not include creep, the stage II exhibits a transgranular path. Up to now the factors controlling the stage I-II transition have not been clearly identified. Stage I and stage II are also affected by temperature and environment.

Nickel-base superalloys show a strong decrease in fatigue life with increasing temperature. This behaviour is not accompanied by a corresponding decrease in short-time mechanical properties, viz. 0.2% yield strength or in the monotonic tensile ductility. Thus the pronounced decrease in fatigue life with increasing temperature has been ascribed to the effect of air environment in accelerating crack initiation and propagation /4/.

The low-cycle fatigue results in air and vacuum of IN 738 LC alloy at 850°C are shown in Fig. 1. The oxygen in the air environment reduces fatigue life by a factor 2 or 3 with respect to vacuum fatigue life. The decrease in strain rate enhances the environmental effects that play a fundamental role in reducing fatigue life. The presence of 60 s hold time in tension and compression determines a further reduction in fatigue life. In vacuum tests the strain rate influence disappears. This confirms that the damage in air is mainly due to oxidation effects and, consequently, fatigue life, in absence of air environment, is increased.

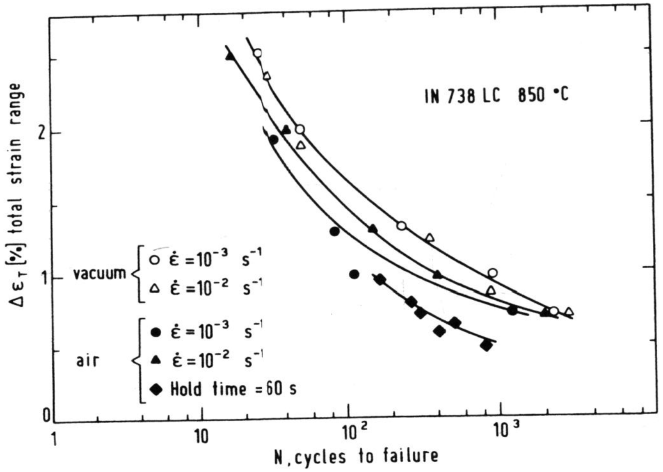

Fig. 1. Effect of strain rate, hold time and environment on LCF of IN 738 LC alloy.

The results at 750°C on IN 100 alloy (Fig. 2) support the previous observations too. The fatigue life increases in vacuum tests, where the strain rate effect disappears. In air the strain rate influence is stronger, but in this case the strain rate ratio is greater than in the other alloys.

From the viewpoint of strain rate effects in vacuum a slightly different behaviour is observed in Inconel 718 alloy. As matter of fact the low-cycle fatigue results in air and vacuum at 650°C (Fig. 3) show that the reduction of strain rate in air produces a strong reduction in fatigue life (4 or 5

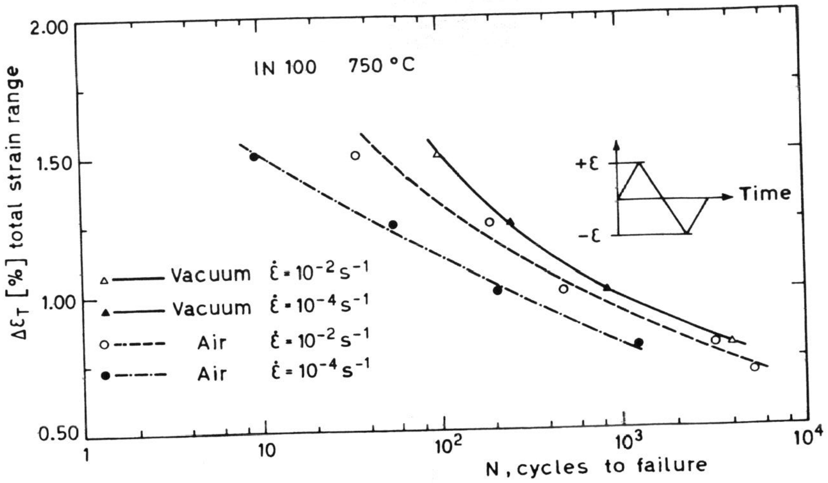

Fig. 2. Effect of strain rate and environment on LCF of IN 100 alloy.

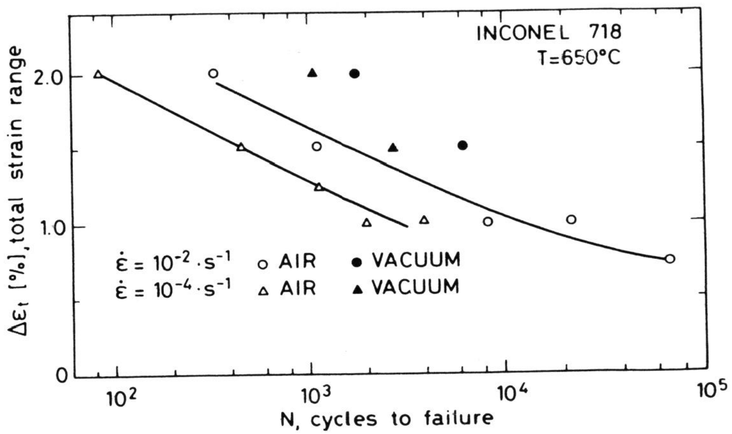

Fig. 3. Influence of strain rate and environment on LCF of Inconel 718 alloy.

times). When tests are performed in vacuum the number of cycles to failure increases markedly and the effect of strain rate on fatigue life, although reduced (a ratio of 2 or 3 times in endurance) is apparent. This indicates that a creep fatigue interaction is operative in vacuum at the lower strain rate examined. Such interaction in air operates in conjunction with oxidation producing an acceleration of fatigue damage.

Fig. 4 shows the influence of temperature on LCF of ODS MA 6000 alloy in air and in vacuum. In air, when temperature increases, fatigue life decreases and the effect is more remarkable at very high temperature: this is attributed to oxidative effects which become more relevant. The influence of oxidation is stronger at lower strains, when time to initiation represents a higher percentage of fatigue life, but it is negligible at higher strains, when crack initiation occurs in the early cycles.

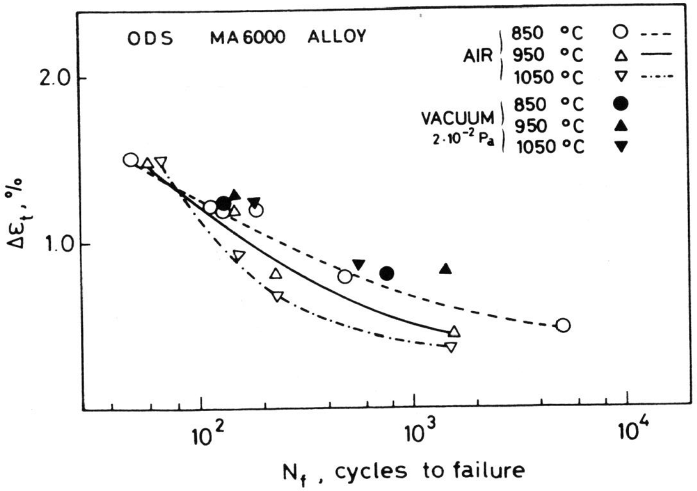

Fig. 4. Influence of temperature and environment on LCF of MA 6000 alloy.

The fractographic analysis of the LCF fracture surfaces shows typical micromechanisms of fatigue damage. In all the cases, air and vacuum, high and low strain rate, one or more cracks initiate at the external surface of the specimens and propagate in stage II transgranular mode. An example of crack initiation is shown in Fig. 5.

Fig. 6 gives a path of mixed transgranular and intergranular propagation mode that is observed only in one specimen at very high strain, even if the strain rate is great.

An example of stage II transgranular propagation mode with ductile fatigue striations is shown in Fig. 7. The striations are present almost in all the alloys even if not always well defined and covered by oxide layer. However in fracture surfaces of specimen fatigued in vacuum, striations are less clear than in air.

The influence of strain rate on crack propagation mode on Inconel 718 alloy is shown in Figs 8 and 9. At higher strain rate the character of the fracture is transgranular with the presence of fatigue striations. At lower strain rate a mixed transgranular-intergranular fracture mode is evident and no striations are observed.

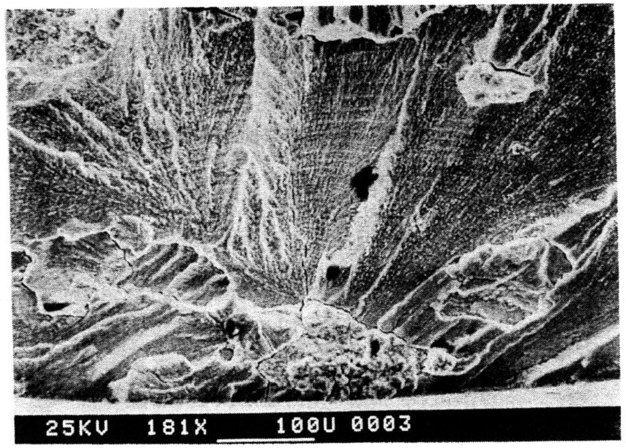

Fig. 5. Example of crack initiation in a specimen of MA 6000 alloy tested in air: T=1050°C, $\dot{\varepsilon}=10^{-2}s^{-1}$, $\Delta\varepsilon_t$=1.23%, N=65.

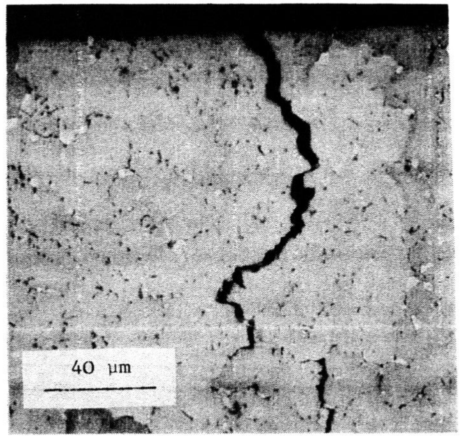

Fig. 6. Mixed transgranular-intergranular fracture of IN 100 alloy fatigued in air: $\dot{\varepsilon}=10^{-2}s^{-1}$, $\Delta\varepsilon_t$=1.5%, N=35.

Fatigue Crack Growth Behaviour

The effect of oxidation at different frequencies on FCG rates of Inconel X-750 is shown in Fig. 10. The contribution of creep effects is indicated by the difference in FCG rates between vacuum data at 0.01 and 10 Hz. In air tests both creep and oxidation mechanisms are operative. The rôle of time dependent processes in increasing FCG rates was already analyzed versus frequency /7/. It was observed that at high frequency (10 Hz)

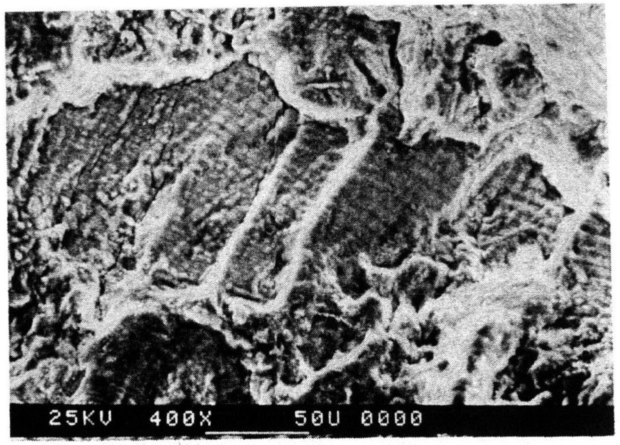

Fig. 7. Example of transgranular fatigue propagation of IN 738 LC alloy: T=850°C, $\dot{\varepsilon}=10^{-2}s^{-1}$, HT=60 s, $\Delta\varepsilon_t=0.8\%$, N=260.

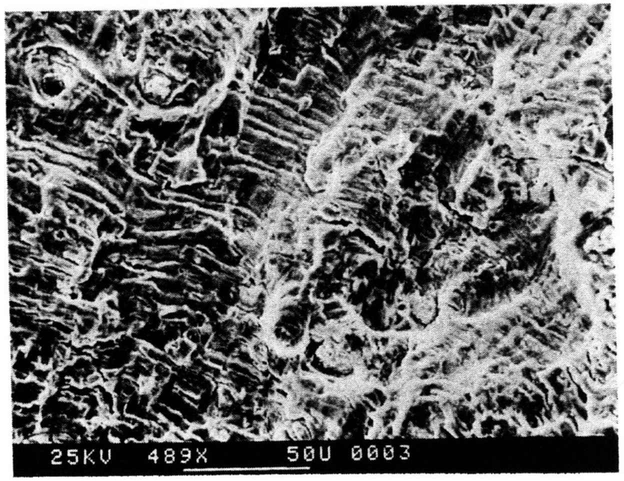

Fig. 8. Fracture surface of Inconel 718 alloy fatigued in air at 650°C and $10^{-2}s^{-1}$.

oxidation is the main mechanism responsible for the increase of the FCG rates when temperature is increased from the room value (Fig. 11). Furthermore, at 0.01 Hz, oxidation operates in conjunction with creep processes and both time dependent mechanisms are responsible for the change of the propagation mechanisms from transgranular with fatigue striations at 10 Hz to intergranular with grain boundary creep cavities at 0.01 Hz (Fig. 12).

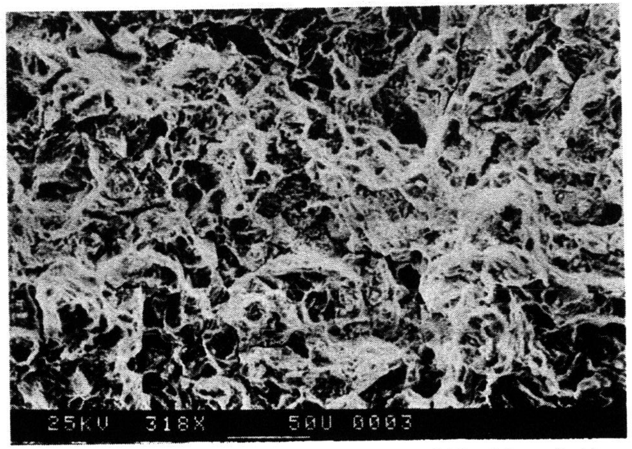

Fig. 9. Fracture surface of Inconel 718 alloy fatigued in air at 650°C and $10^{-4}s^{-1}$.

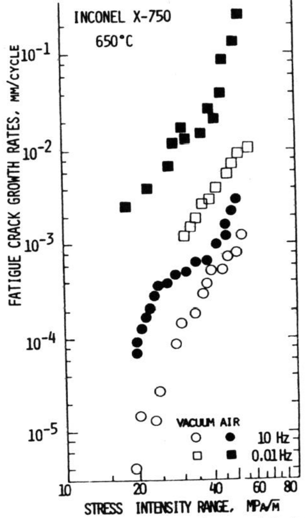

FIGURE 10. Effect of oxidation of different frequencies on FCG rates of Inconel X-750 at 650°C.

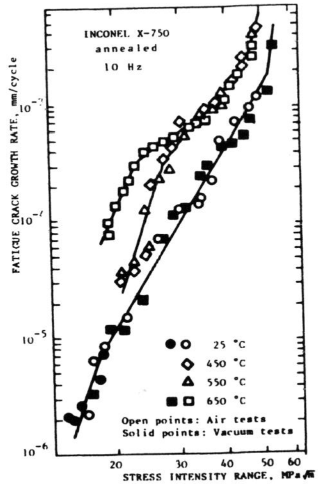

FIGURE 11. Temperature effect in air and in vacuum on FCG rates of Inconel X-750

In all cases experimental FCG rates of this alloy show the important rôle of the ambient air in enhancing the crack rate.

The role of air in increasing high temperature FCGR has been observed also in the wrought nickel base alloy Inconel 718 (Fig. 13).In air tests, at 650°C,FGC rate strongly increase when frequency decreases in the range from

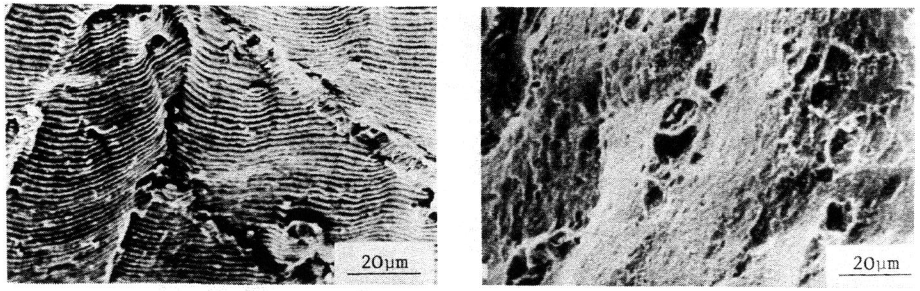

Fig. 12. Fracture surfaces of Inconel X-750 fatigued at 650°C and at a) 10 Hz and b) 0.01 Hz.

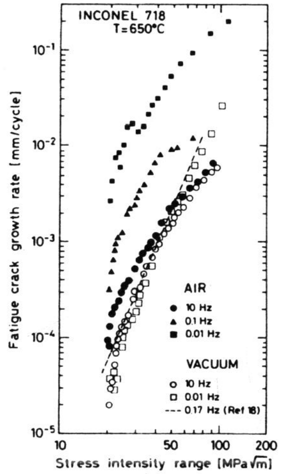

Fig. 13. Frequency effect on FCG resistance of Inconel 718 alloy at 650°C in air and in vacuum.

10 to 0.01 Hz. Vacuum tests, performed at the same temperature and in the same frequency range, have shown that, in vacuum, frequency effect is negligible and the FCG rate results are in agreement with experimental data from reference /18/.

The comparison of air and vacuum results shows that the effect of oxidation in enhancing FCG rate at 10 Hz is less remarkable than at lower frequencies. This indicates that, when frequency decreases, crack tip oxidation is more effective in producing the strong frequency effects observed in air at high temperature. Furthermore, a threshold stress intensity range, that is independent of test conditions, is apparent at 20 MPa $\sqrt{m}$.

The combined effects of frequency and oxidation on FCG rates of IN

792+Hf and IN 713 LC are illustrated in Figs 14 a and b, respectively. FCG rates at 750°C in both air and vacuum increase significantly when frequency is decreased from 10 to 0.01 Hz. However, in each case the increase of FCG rates with decreasing of the frequency is lower than in the Inconel X-750 wrought alloy even with this alloy tested at a lower temperature. In the IN 792+Hf oxidation effects are more remarkable at higher ΔK and the effect at 10 Hz is stronger than at 0.01 Hz.

In the IN 713 LC cast alloy, oxidation effects are less significant than in IN 792+Hf. At 10 Hz there is no apparent effect at $\Delta K < 25$ MPa $\sqrt{m}$, while at higher ΔK, vacuum FCG rates are lower than in air. The comparison of FCG rates in vacuum at 10 Hz and 0.01 Hz indicates that creep effects are more significant in IN 792+Hf than in IN 713 LC. In this latter case, however, the creep contribution to FCG rates appears dependent on stress intensity range.

Fractographic analysis has shown that in air the crack was proceeding along a transgranular path which is perpendicular to the direction of the applied stress with no influence of the microstructural features in all cases examined.

In the ODS MA 6000, FCG rates were measured in air and in vacuum at 850°C (Fig. 15). For a given ΔK the FCG rates increase when frequency decreases from 10 to 0.01 Hz both in air and in vacuum. However the extent of FCG rates increase with decreasing of the frequency, in the ΔK range examined, is less pronounced than in the previous alloys analyzed.

As far as the rôle of oxidation is concerned, experimental results have shown that the FCG rates of MA 6000 in vacuum are significantly higher than in air at the same experimental conditions (Fig. 15). This behaviour was formerly found in the cast alloy IN 738 and attributed to mechanisms of branching at the crack tip in air tests /19,20/. In MA 6000 at high frequency, no branching was observed and, at low frequency, branching was apparent in both air and vacuum tests. However, thick fragments of oxides were observed by SEM in specimens tested in air. Probably they produce blocking at crack tip. This is consistent with the experimental observation that in high temperature fatigue test at 0.01 Hz in vacuum a cyclic potential drop is continuously monitored with relative maxima when the crack is completely open and minima when completely closed. This effect was insignificant in air tests at the same frequency: in fact, in vacuum, the potential drop range, at a given crack length, is ten times higher than in air. Oxide blocking can lead to a decrease of the effective ΔK at crack tip and explain why the FCG rates in vacuum are higher than in air. However, for a detailed interpretation of this phenomenon more experiments are necessary.

The micromechanisms of fatigue crack propagation were transgranular in all cases. In the fracture surfaces of MA 6000 alloy tested in air at 850°C, 10 Hz, a very limited region with fatigue striations associated with secondary cracks was observed at high ΔK. Voids around inclusions were also

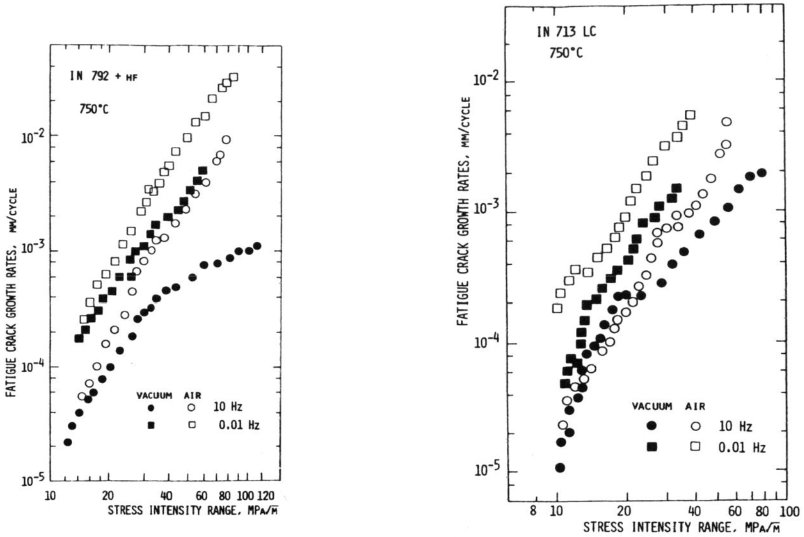

Fig. 14. Combined effects of oxidation and frequency at 750°C on FCG resistance of a) IN 792+Hf and b) IN 713 LC.

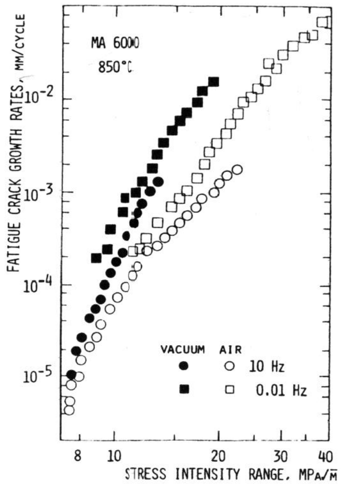

Fig. 15. Frequency effect on FCG resistance of MA 6000 alloy at 850°C in air and vacuum

apparent and when the frequency is decreased to 0.01 Hz, secondary cracks appear at grain boundaries.

All the experimental results presented emphatise the importance of the frequency influence. In general, at high temperature, a clear transition between high frequency and low frequency behaviour, associated with the transition of propagation mechanisms from transgranular to intergranular is evident.

Independent of cracking mode, with the exception of the alloy ODS MA 6000 where oxide blocking effects seem very important, the fatigue processes appear to enhance the environmental effects at the crack tip /19/ by favoring oxygen transport ahead of the crack tip during fatigue /20/. At elevated temperatures, in the case of transgranular fracture, oxygen will diffuse along slip bands to enhance stage I cracking or ahead of the crack tip to enhance the stage II type growth. These transgranular oxidation mechanisms do not appear to change the morphology of the fracture surface.

In the intergranular cracking, the fracture surface features will change from cavitated boundaries to pure brittle decohesion depending upon the relative contributions of cavitation and oxidation. Intergranular cavitation in the plastic zone ahead of the crack tip involves grain boundary sliding, void growth and coalescence. The diffusion of oxygen at grain boundaries will lead to reactions with grain boundary phases and it may enhance the flux of vacancies promoting rapid nucleation and growth of cavities /21/. Diffusion of oxygen may also cause embrittlement, and contribute to the debonding and brittle decohesion of grain boundaries.

CONCLUSIONS

The influence of time dependent processes on high temperature fatigue behaviour is analyzed in several nickel base superalloys. Fatigue tests were carried out at high temperatures in air and vacuum at different frequencies and strain rates. The experimental results lead to the following conclusions:

- The fatigue resistance in air is markedly reduced by the increase of temperature and the decrease of strain rate or frequency.
- In LCF tests, surface crack initiation results accelerated by oxidation that reduces greatly fatigue life; this effect is more marked at lower strain rates and is confirmed by vacuum tests where LCF life is increased and strain rate influence disappears;
- the influence of strain rate on vacuum fatigue life in Inconel 718 alloy can be ascribed to the presence of creep damage that operates in air in conjunction with oxidation effects.
- The alloys investigated show a different crack growth behaviour versus oxidation. Oxidation effects are very strong in Inconel X-750 and Inconel 718 and the comparison of air tests with vacuum tests show that vacuum FCG rates are significantly lower than those in air. The cast alloys IN 792+Hf and IN 713 LC exhibit a lower sensitivity to oxidation than the

wrought alloys. The FCG rates of the ODS alloy MA 6000 in vacuum are higher than in air in all the experimental conditions studied. This is probably due to oxide blocking effects at the crack tip in air tests. The different behaviour versus oxidation in LCF and FCG tests can be attributed to different strain range levels which are higher in LCF tests and prevent oxide blocking effects.

- The fatigue crack propagation mechanisms in Inconel X-750 were changing from transgranular with ductile fatigue striations at 10 Hz to intergranular with creep cavities at 0.01 Hz. In the other alloys, the propagation mechanisms were transgranular in all cases in both air and vacuum.

ACKNOWLEDGEMENT

The authors wish to thank Mr. E. Picco, Mr. D. Ranucci, Mr. E. Signorelli and Mr. G. Vimercati for help with experimental work.

REFERENCES

1. Senechal P: Fatigue and creep consideration in the design of turbine components. "High temperature alloys for gas turbines 1982". R. Brunetaud et al. Editors. D. Reidel Publishing Company, 1982, p. 273.
2. Coffin LF: Metall. Trans. 3, 1972, p. 1777.
3. Gell M and Leverant GR: Fatigue at elevated temperatures, STP 520, Philadelphia, Pa, American Society for Testing and Materials, 1973, p. 37.
4. Runkle JC and Pelloux RM: Fatigue mechanisms, (ed. J.T. Fong), STP 675, Philadelphia, Pa, American Society for Testing and Materials, 1979, p. 501.
5. Marcus HL: Fatigue and microstructure, Metals Park, Ohio, American Society for Metals, 1979, p. 365.
6. Smith HH, Shahinian P and Achter MR: Transactions of AIME, Vol. 245, 1969, p. 947.
7. Gabrielli F. and Pelloux RM: Metallurgical Transactions, 13A, 1982, p. 1083.
8. Marchionni M, Ranucci D and Picco E: High-temperature low-cycle fatigue behaviour of IN 738 LC alloy in air and in vacuum. "High Temperature alloys for gas turbines 1982", Edited by R. Brunetaud et al., D. Reidel Publishing Company, London, 1982, p. 791.
9. Sidey D and Coffin Jr. LF: Cycle fatigue damage mechanisms at high temperature. "Fatigue Mechanisms", J.T. Fong Editor, ASTM STP 675, 1979, p. 528.
10 Meurer HP, Breitling H and Dietz W: Influence of hold time and strain rate on the LCF behaviour of alloy 617 at 950°C. "Low cycle fatigue and elasto-plastic behaviour of materials", K.T.Rie Editor, Elsevier Applied Science, Munich, 1987, p. 246.
11. Golwalkar S, Stoloff NS and Duquette DJ: The effects of frequency and hold time on fatigue crack propagation rates in a nickel base

superalloy. Proceedings of 6th International Conference on the strength of metals and alloys. Melbourne, Vol. 2, 1982, p. 879.
12. Marchionni M, Ranucci D and Picco E: Effect of strain rate and hold time on high-temperature low-cycle fatigue behaviour of a nickel-base superalloy. Advances in surface treatments. A. Niku-Lari Editor, Vol. 1, Pergamon Press Publishers, 1984, p. 45.
13. Pedron JP and Pineau A: Effect of hold time on the elevated temperature fatigue crack growth behaviour of Inconel 718 alloy. Proceedings of ICF5, Cannes, Pergamon Press, Vol. 5, 1980, p. 2385.
14. Massarelli L, Ranucci D and Picco E.: COST 50, Round II, final report R-80/12, 1980.
15. Marchionni M, Ranucci D and Picco E: COST 50, Round III, progress report R-82/13, 1982.
16. Gabrielli F, Vimercati G and Lupinc V.: Environmental effects on high temperature fatigue crack growth behaviour of nickel base superalloys. Mechanical behaviour of materials-V, Proceedings of Fifth Intern. Conf., China, Pergamon Press, 1987, p. 811.
17. Fujita FE: Fracture of Solids, Vol. 20, Interscience, 1963, p. 657.
18. Sadamanda K and Shahinian P: Metals Technology, January 1982, p. 18.
19. Scarlin RB: 'Fracture 1977', Taplin Ed., University of Waterloo Press, Waterloo, vol. 2, 1977, p. 849.
20. Scarlin RB and Speidel MO: Fatigue crack growth in nickel base alloys, COST 50, final report, Brown Boveri Research Centre, July 1976.
21. Sadananda K and Shahinian P: Journal of Engineering Materials Technology, vol. 100, 1978, p. 381.