POSTER REFERENCE: *ICF100799PR*

DAMAGE OF NICKEL BASE SUPERALLOY SUBJECTED TO LOW CYCLE FATIGUE WITH HOLD PERIODS

J. Zrník, J. Semenak and V. Vrchovinsky

Department of Materials Science, Technical University of Košice
Park Komenského 11, 040 01 Košice, Slovak Republic

ABSTRACT

The approach to a life time prediction presented in this paper is based on the review the of data received from laboratory realised low cyclic creep fatigue experiment with respective nickel base superalloy. The cyclic creep fatigue tests were run with relatively simple trapezoidal wave loading at temperature of 650°C. The tensile hold periods imposing on the fatigue stress have been introduced into load control low cycle fatigue. The time to failure, the time to failure corresponding to maximum applied load, and number of cycles to failure have been the criteria to evaluate the deformation behaviour of alloy subjected to creep fatigue loading. To make an attempt of alloy life prediction to the respective types of applied load the modified Kitagawa's the linear damage criterion has been used. The two regression functions for respecting applied hold time interval were expressed to calculate the time to failure. The formulae can be used to predict the life of nickel base superalloy subjected to cyclic creep loading.

KEYWORDS

Nickel superalloy, cyclic creep, tensile hold time, damage evaluation, life prediction, structure

INTRODUCTION

Various components of industrial gas turbines and aircraft experience periods of both fluctuating and steady stress, due to complex situation of mechanical and thermal stress. Those components are subjected to operate under complex stress conditions, involving creep, fatigue and thermal fatigue. In deformation process both creep and fatigue can contribute to material damage. It was recognised that static creep and/or conventional fatigue test conditions approach cannot always assess the deformation process and life of the component.

In the past two decades considerable effort has been brought to characterise the deformation process of nickel base superalloys that were stressed under the conditions of time-dependent load at elevated temperatures [1,2,3,4]. In such cases both creep and fatigue can contribute to degradation of the material The hold periods constitute the creep stress component in the fatigue cycle. Deformation characteristics under the creep-fatigue stress can differ considerably from those of the static creep.

The study presents results gathered at deformation process of wrought nickel base superalloy EI 698 VD subjected to creep fatigue loading. The evaluation of deformation process and the life prediction of the alloy were done in relation to the hold periods introduced into low fatigue stress cycle at upper stress level. The service life prediction in relation to the respective type of applied stress is expressed by modified Kitagawa's criterion being suitable for static and cyclic creep.

EXPERIMENTAL

The wrought nickel base superalloy EI 698 VD was selected as an experimental material. This alloy is suitable for manufacturing of discs and shafts of aircraft engines operated at temperatures up to 750°C. Chemical composition of the alloy in mass % is as follow: C max. 0.08, Cr 13-16, Mo 2.3-3.8, Nb 1.8-2.2, Ti 2.3-2.7, Al 1.3-1.7, Fe max. 0.2, balance Ni. Microstructure of alloy after finishing heat treatment consists of the equiaxed grain structure strengthened by coherent gamma prime precipitates. The alloy also contains MC and $M_{23}C_6$ carbides that do not contribute substantially to the strengthening.

The tensile stress cycling load controlled tests were conducted at temperature of 650°C. The cyclic creep tests were of trapezoidal wave pattern. The seven different hold times $\Delta t = 0$ (pure fatigue), 1, 3, 7.5, 15, 30, and 60 minutes at peak stress $\sigma = 740$ MPa were introduced in the tensile part of the load cycle. The net effect of these hold times is to systematically impose a creep stress component on the fatigue load cycling. The cycling frequency range was between 5.5×10^{-3} and 2.7×10^{-5} Hz and stress ratio $R = 0.027$. The stress ramp rate in one cycle, either during on-load or the off-load period, was 7.4 kN/min. No hold time was maintained at reduced load level of 20 MPa. The specimen longitudinal deformation, the failure lifetime or total time of the cyclic test, the number of cycles to failure, and the time at maximum load during cyclic test were recorded and compared with static creep.

RESULTS AND DISCUSSION

The results on the total time to fracture (TTF), time corresponding to maximum load (MLT), and numbers of cycles to failure (NCF) received at the cyclic creep experiment are summarised in Table 1.

TABLE 1
EXPERIMENTAL DATA RECEIVED AT CYCLIC TEST

Parameter	Hold time [minute]							
	fatigue	creep	1	3	7.5	15	30	60
TTF [min]	44 268	2 500	54 972	18 942	30 300	13 896	5 662	3 406
MLT [min]	-	2 500	10 741	8 003	19 591	10 911	4 981	3 188
NCF [min]	22 120	-	10 778	2 668	2 612	728	166	53
ε_f	3.2	6.3	3.3	3.5	3.6	3.1	3.9	6.9

The strain-time to failure dependencies, measured when strain was at the maximum load, corresponding to the initial stress of 740 MPa, for all hold times are illustrated in Figure 1. The low cycle fatigue test and static creep test results were conducted as well, and results are stated also in Table 1. As can be seen from the diagram in Figure 1 the introduction of stress reduction introduced into the creep process, and/or the introduction of cyclic stress component in static creep, resulted in life increase and decrease in the strain rate ε of the alloy in comparison with static creep. The time to failure was proportionally extended with decreasing of the hold period.

In order to evaluate the creep fatigue resistance of tested nickel base superalloy the time criteria, such as time to failure or time to failure corresponding only to the maximum applied load can be used for this purpose. The evaluation of deformation behaviour according to the time to failure corresponding to the sum of hold periods at maximum load (MLT) is presented in Figure 2. The corresponding hold period of $\Delta t = 7.5$ minutes at maximum load seems to have specific influence on the deformation behaviour of alloy. Probably, in the cyclic creep with the hold time shorter than 7.5 minutes, in damage process more fatigue would participate at crack nucleation and its propagation. If hold time is over this critical dwell the life prediction dominating role in damage process would be taken over by creep. Comparing these results with the results

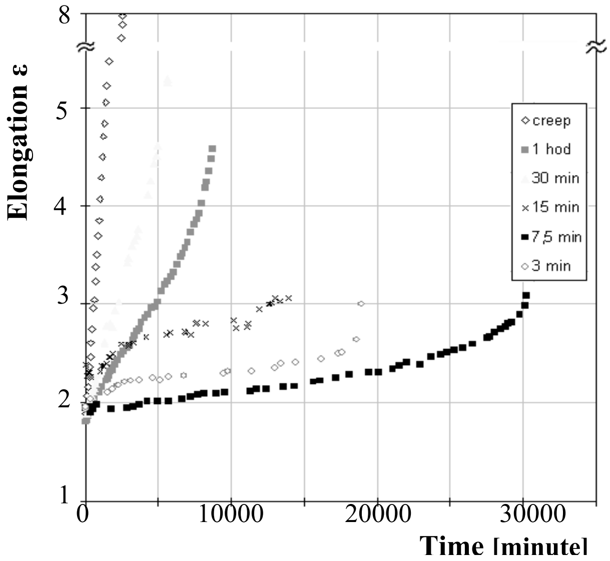

Figure 1: Strain-time to failure dependencies

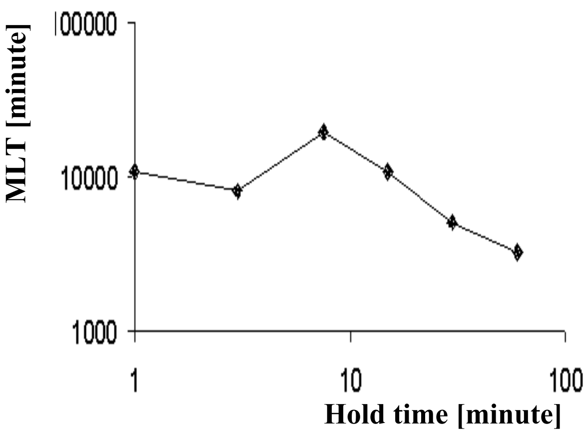

Figure 2: Plot of time to failure corresponding to applied load as the function of hold time

received on total time to fracture, the contradiction appeared. The longest life was corresponding to the test with hold time of Δt =1minute. In case that total number of cycles to fracture was the criterion to evaluate the deformation behaviour of the alloy the plot representing the dependence is documented in Figure 3. Regardless the fact that there is observed continuous decrease in number of cycles to failure with increasing hold time Δt the relationship can not be interpreted generallyy as prior creep damage effect on the fatigue mechanisms and/or as influence of creep on cycles reduction. The main reason not to follow such interpretation is the fact that creep damage which is time-controlled process will simply dominate at longer hold times. That is why it would therefore be illogical to explain such behaviour to apply the concept of the major damage mechanism to influence the minor one. Besides that, the resulted number of cycles to failure which showed continuous decreasing tendency with increasing hold time just it does not need to be the result of creep fatigue interaction. It can be accepted only as pure mathematics relation between time to failure and corresponding cycles number causing the creep damage.

Another interesting result of experiment was observed in case of applied hold times of Δt =3 and 7.5 minutes. The resulted number of cycles to failure showed very small difference. To verify the finding these tests were repeated and results were proved to be correct and were not an effect of random data scattering. Considering this fact, the explanation on such deformation behaviour could be based on the balanced creep and fatigue participation in damage at these applied hold times.

The application of stress of reductions in creep turns the respective process into a cyclic deformation process where besides time-controlled creep process also fatigue process would participate in damage process. The life extension, observed when the hold periods were introduced in cyclic process would have been a result of several additional aspects contributing to deformation process and modifying it. Among these aspects might be included, the alternating stress higher and lower than the yield point for the respective stress amplitude, the effect of introducing the cyclic deformation onto the creep process and vice versa, repeated storage of reversible anelastic creep deformation preceding the process of irreversible creep, and recovery of the stored deformation energy and release of anelastic deformation in time of the offs of the load. In this respect these facts make more difficult the prediction of life for actual test condition. It is known that during the creep fatigue the each other stress component mutual interactions are involved in damage process. However, in order to predict the cyclic service life of structural part there is not need to have knowledge how to estimate the individual creep and fatigue stress contribution in deformation process. For effective evaluation of their contribution would be more convenient to incorporate both of them into the one parameter.

To predict creep fatigue life of an alloy under considered laboratory test condition the linear damage summation rule [5] would be hardly appropriate to use it in case when creep damage may arise due to the

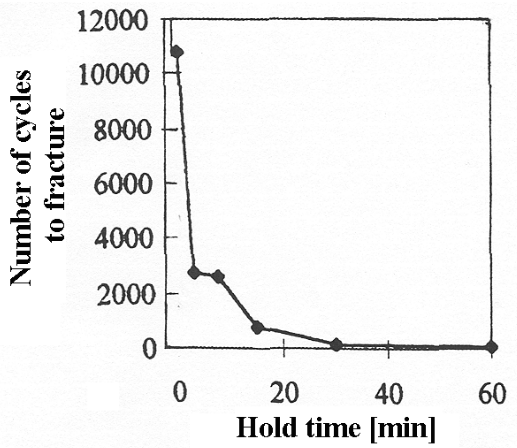

Figure 3: The dependence of hold time on the number of cycles to failure

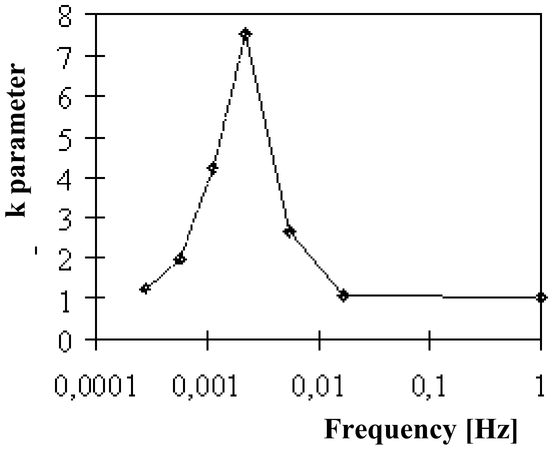

Figure 4: Frequency dependence of **k** parameter

cyclic loading condition. To separate the creep caused by the applied stress and the creep damage caused by the strain accumulation the equation of Kitagawa et al. [6] which is a modification of the linear rule of damage accumulation is more practical to use. The Kitagawa's equation can be written than in the following form where the frequency dependence of **a** parameter is assumed:

$$\left(\frac{N}{N_f}\right) + \left(\frac{t}{t_{rcyc}}\right) + \boldsymbol{a}\left(\frac{\varepsilon}{\varepsilon_{stat}}\right) = 1 \qquad (1)$$

where N is total number of cycles to failure, N_f is number of fatigue cycles to failure corresponding to pure fatigue, t is the total time to failure at cyclic creep, ε_{stat} is creep ductility, and **a** is Kitagawa parameter is considered to be frequency dependent, i.e. expressing a process frequency dependence.

This equation assumes explicitly that the creep life modification under the cyclic creep condition, however, it fails in evaluation of fatigue degradation by creep, i.e. by the time-dependent process. The parameter $\boldsymbol{a}$ can be expressed as $\boldsymbol{a} = 1 - 1/\boldsymbol{k}$. Parameter $\boldsymbol{k}$ determines the difference in a material life exposed in condition of cyclic creep and can be stated as $\boldsymbol{k} = t_{rcyc}/t_{stat.}$, where t_{rcyc} is the life corresponding to the conditions of cyclic creep when only creep process is considered, and t_{stat} is life corresponding to the course of static creep. Regarding these parameters the equation can be adjusted to the following form:

$$\left(\frac{N}{N_f}\right) + \left(\frac{t}{kt_{stat}}\right) + \left(1 - \frac{1}{k}\right)\left(\frac{\varepsilon}{\varepsilon_{stat}}\right) = 1 \qquad (2)$$

The equation expresses the simplest modification of the linear damage summation rule that enables to evaluate the creep fatigue interaction when life increase is involved. The only limitation of using it for life evaluation was an assumption that creep damage resulting from hold period and from on-load and off-load period in one cycle was taken equal. To summarise the creep damage resulting from fluctuating load, creep damage resulting from constant load and fatigue damage the modified equation can be written as:

$$\left(\frac{N}{N_f}\right) + \left(\frac{N}{kN_c}\right) + \left(\frac{t_h}{kt_f}\right) = 1 \qquad (3)$$

where N -applied cycles number, N_f -cycles to failure under fatigue, N_c -number of cycles representing pure creep when fluctuating load is applied, t_h -sum of holds at maximum load, t_f-time to failure at applied static creep, k –parameter to characterise the different behaviour of material under cyclic and static creep.

If we consider the cyclic creep as deformation process where fatigue and (cyclic) creep participate there with respect to time-controlled degradation, then the resulting degradation should arise due do superposition of these contributions. Of course, we cannot generalise this assumption to whole frequency reductions interval of the applied stress because at low frequencies of load reduction exclusively simple static creep would control the degradation process only. That is why any important changes between the parameters t_{cyc} and t_{stat} can not be expected and there a continuous transition them must exit due to the change in stress reduction frequency. Kitagawa resolved the problem of ***a*** parameter frequency dependence by introducing a third member into the equation 1. In order to validate this equation over the entire frequency interval the limitation on admission only a negligible contribution resulting from cyclic deformation to total deformation must be introduced. It would be therefore more advantageous, to satisfy above limitation, to use only the first two terms of Eqn. 2 and to assume the frequency dependence of the ***k*** parameter. However, in order to simplify the calculation procedure the creep process was separated in to the periods of hold time and periods of ramping time and the number of cycles was formally used as a parameter of damage, although time-controlled process was involved. After these adjustments and using the data for creep life corresponding to maximum load and data from pure fatigue test to calculated the number of cycles to fracture corresponding to fluctuating load the following equation was received for applied loading:

$$\left(\frac{N}{60000}\right)+\left(\frac{N}{k.13000}\right)+\left(\frac{t_h}{k.2500}\right)=1 \tag{4}$$

The realised laboratory test did not provide the satisfactory data for precise determination of the time during which the creep at static load does not contribute to damage accumulation. However, according to the deformation dependencies in Figure 2 it can be assumed that hold times of Δt =1 and 3 minutes are involved to comply with this assumption. In order to guarantee the stated prediction, the calculation was based on an extreme hold limit that is for Δt = 1 minute, when the effective period of static creep will be the longest. After subtracting this value from applied hold time the effective hold times related to maximum load were calculated and they are presented in Table 2.

TABLE 2
FRACTURE EFFECTIVE DWELL TIME AT THE MAXIMUM LOAD

Δt	1 min	3 min	7.5 min	15 min	30 min	60 min
MLT_{ef}	0	5 335	16 979	10 183	4 815	3 153

To substitute this effective hold time to Eqn. 4 and utilising additional experimentally obtained data the ***k*** parameter and ***a*** parameter as a function of hold time at the maximum load was determined. The results of this calculation are presented in Table 3.

TABLE 3
PARAMETERS ***k*** AND ***a*** AS A FUNCTION OF HOLD TIME

Δt	1 min	3 min	7.5 min	15 min	30 min	60 min
k	1.03	2.62	7.5	4.2	1.95	1.25
a	0.03	0.62	0.87	0.76	0.48	0.2

It was already stated that ***k*** and ***a*** parameters are frequency dependent. The frequency dependence of ***k*** parameter can be related to frequency dependent process corresponding to, for example, the ability of storing and recovery of anelastic creep deformation. It is possible to assume that, in process of cyclic creep it should be a defined frequency at which the maximum dissipation of deformation energy resulting from the storing and recovery of anelastic creep deformation will be reached, because the frequency effect was introduced into the loading process as a result of different hold periods. Another possible example of the ***k*** parameter frequency dependence is equilibrium frequency dependence of hardening and softening process due to stress relaxing in off-times. The frequency dependence of ***k*** parameter, which was introduced into process by load reduction or by introduction of hold time onto low cycle fatigue, is presented in Figure 4.

To model the life prediction behaviour of alloy the modified Eqn. 4 of the linear rule of damage was used. For applied load – temperature conditions to calculate the time to failure (MTF) as a function of the applied hold time t_h at the maximum load with respect to ***a*** and ***k*** parameters the following explicit formula was determined:

$$\text{MTF} = \frac{60937.5k(t_h)}{24.375(t_h-1)+4.6875}\,t_h \tag{5}$$

For other parameters, which may be suitable for life prediction, the following relations were calculated:

$$\text{NCF} = \text{MLT}/t_h \quad \text{and} \quad \text{TTF} = \text{MLT} + 4\ \text{NCF} \tag{6}$$

To calculate the ***k*** parameter values it is not easy to find the regression function, which would describe its value with good reliability for whole interval of the applied hold times. That is why for interval of used short hold times t_h < 7.5 minutes and for interval of longer hold times, interval t_h > 7.5 minutes the different regression function has been used. The discontinuity at the boundary of the interval corresponding to hold time of Δt = 7.5 minutes in plotted curve presenting the alloy model life prediction was the result. For the shorter hold time regression function of ***k*** = 1.0105 t_h – *0.1567* and for longer hold time ***k*** = 44.53 $t_h^{-0.8862}$ were determined.

If these regression functions expressing the ***k*** parameter dependence on hold time would be substituted into the equation (5) the following formulae for life prediction, to differentiate the effect of shorter and longer hold time on superalloy behaviour subjected to cyclic creep would be resulting:

$$\text{MTF} = \frac{\check{z}60937.5(1.0105\ t_h - 0.1567)}{24.357(t_h-1)+4.6875+(1.0105t_h-0.1567)}\,t_h \quad \text{for } t_h < 7.5 \text{ minutes} \tag{6}$$

$$\text{MTF} = \frac{60937.5(44.53t_h^{-0.8862})}{24.375(t_h-1)=4.6875+(44.53t_h^{-0.8862})}\,t_h \quad \text{for } t_h > 7.5 \text{ minutes} \tag{7}$$

The graphic presentation of the model life parameters prediction MTF and NCF for defined testing condition of cyclic creep using the Eqn. 6 and Eqn.7 are shown in Figure 5 and Figure 6.

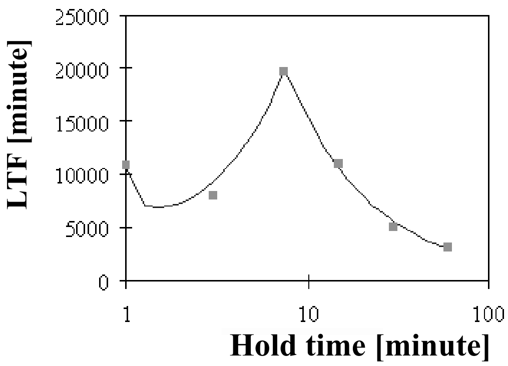

Figure 5: The plot of alloy model life prediction in condition of cyclic creep

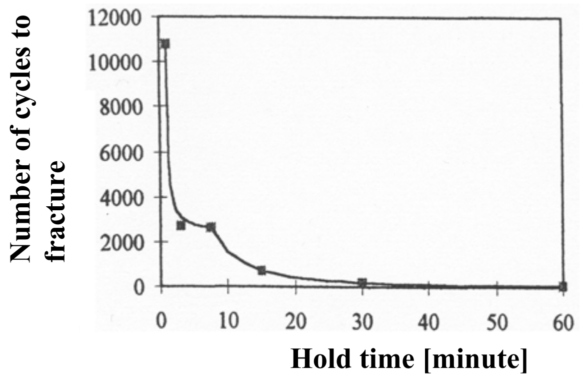

Figure 6: Model prediction dependence of number cycles to fracture as function of hold time

CONCLUSION

The application of short repeated reductions of the applied stress of 740 MPa to reduced stress level of 20 MPa resulted in change of deformation behaviour of alloy. By introduction of stress reductions onto creep the decrease of strain rate was observed and it was followed with life increase in comparison to static creep. For the laboratory tests condition the modified linear rule of damage summation was used to model the life prediction. The formulae differenting the effect of hold time at the applied maximum load with respect to ***a*** and ***k*** frequency dependent parameters to calculate time to failure were determined. These formulae respecting the applied hold time interval and introducing limitations they can be used to predict the life of nickel base superalloy subjected to cyclic creep loading.

References

1. Härkgard, G. and Guedon, J.Y. (1998). In: Proceedings of the 6^{th} Liege Conference on Materials for Advanced Power Engineering, Belgium, 913.
2. Gabb, T.G. and Welsch, G., (1998) Acta Metall. 37, 2507
3. Portela, P.D., Bertram, A., Fahlbusch, E., Frenz, H. and Kinder, J. (1996). In: Fatigue'96, 795, Lütjering, G., Nowack, H. (Eds). Beijing.
4. Bosimer, D.A. and Sheitogolu, H. (1989) Trans. ASME, 112, 205.
5. Taira, S. (1962). Creep in structures, pp. 96, Nicholas, H. J. (Eds). Academic Press, N.Y.
6. Kitagawa,M., Tamura, K. and Ohtomo, A. (1983) J. of SMSJ, 32-357, 662