LIFETIME BEHAVIOUR OF THE WROUGHT NICKEL BASE SUPERALLOY SUBJECTED TO LOW CYCLE FATIGUE WITH HOLDS

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The deformation behaviour of the wrought nickel base superalloy EI698 VD has been investigated in condition of low cycle fatigue. The tensile hold periods, imposing a constant stress into fatigue loading, have been introduced at the maximum stress value. The individual hold periods were in the range of 1 minute to 10 hours. The fatigue tests were of tension-tension type defined by stress ratio $R = 0.027$ and were conducted at a temperature of 650 °C. The tests were performed up to fracture. The time to failure, corresponding to total load at amplitude peak, and number of cycles to failure have been the criteria for evaluation of the deformation behaviour of the alloy subjected to complex cyclic creep loading. In order to predict the lifetime of the alloy, regarding type of cyclic tests, the Kitagawa's modified linear cumulative damage criterion has been considered. Two regression functions for applied hold period interval were proposed to calculate the time to failure. The formulae can be used to predict the life of nickel base superalloy considering the specific conditions of low cycle fatigue without and with tensile holds period.

Key words: nickel base superalloy, fatigue, creep, hold time, lifetime prediction

1. Introduction

The nickel base superalloys have been developed for specific, specialized properties and applications where individual components of gas turbine are exposed to complex stress. Various components of industrial and aircraft gas turbines experience periods of both fluctuating and steady stress due to complex situation of mechanical and thermal stress originating from centrifugal force, high frequency vibrations, and temperature transients during engine service [1]. The structural

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components are subjected to complex stress conditions, resulting in creep, fatigue, and thermal fatigue. Extended work has been carried out on mechanical behaviour and microstructure Ni based superalloys in the past decade [2–6]. However, these investigations concern mainly creep and isothermal low cycle fatigue (LCF).

Considerable effort has been devoted to characterizing the deformation process of nickel base superalloys that were stressed under the conditions of time-dependent load at elevated temperatures [7–11]. Permanently increased attention has been paid to the study of creep and fatigue interaction under either isothermal or anisothermal fatigue condition. In such cases both creep and fatigue can contribute to degradation of the material. The creep-fatigue interaction can be judged as two specific cases in dependence on the way of stressing. The first case involves two subsequent simultaneous interactions with the creep and fatigue stress components separated in the process of loading which result in separate processes of damage. The second case involves subsequent simultaneous interactions with the presence of both components of damage in each single deformation or stress cycle. Simultaneous interactions are frequently applied at the fatigue cycle controlled through constant deformation while the holds are introduced into the fatigue cycle either at the tensile or compressive stress or at both simultaneously. The hold constitutes the creep stress component in the fatigue cycle.

The study presents results of analysis gathered on deformation process of wrought nickel base superalloy EI 698 VD subjected to LCF where creep stress component has been introduced imposing hold time into fatigue stress amplitude. The evaluation of deformation process and life prediction of the alloy was done in relation to the hold periods introduced into low fatigue stress cycle at tensile amplitude peaks.

2. Experimental

The creep resistant wrought nickel base superalloy EI 698 VD was selected for this experimental study. This alloy is suitable for the manufacturing of discs and shafts of aircraft engines and can be exposed to temperatures up to 760 ℃. Chemical composition of the alloy in mass % is given in Table 1. The alloy was given three step heat treatment to produce a uniform equiaxed grain structure. The alloyed nickel fcc matrix is strengthened by coherent gamma prime precipitates of the average size of about 60 nm and of the volume fraction of $\sim$ 40 % (Fig. 1).

The load controlled cyclic tests were conducted at temperature of 650 ℃ using microprocessor controlled hydraulic dynamic system INSTRON 8511. The cyclic

Table 1. Chemical composition of nickel base superalloy EI698 VD in mass %

C	Cr	Al	Ti	Mo	Fe	Nb	Mn	Ni
max. 0.08	13–16	1.3–17	2.3–27	2.3–3.8	max. 0.2	1.8–2.2	max. 0.4	balance

creep tests were of trapezoidal wave pattern shown schematically in Fig. 2. The nine different hold times $\Delta t = 0$ (pure fatigue), 1, 3, 7.5, 15, 30 min and $\Delta t =$ 1, 3, 5 and 10 hours were introduced at the maximum tensile stress of $\sigma = 740$ MPa. The net effect of these hold times is to impose a creep stress component into the fatigue load cycling. The cycling frequency range was between 5.5×10^{-3} and 2.7×10^{-5} Hz and the stress ratio was $R = 0.027$. The load ramp rate in one cycle, either during the on-load or the off-load period, was 7.4 kN/min. No hold time was introduced at the minimum, i.e. at the stress of 20 MPa. The specimen longitudinal deformation, the failure lifetime or total time of the cyclic test, the number of cycles to fracture, and the total time at maximum load were recorded and compared with appropriate static creep data. Creep tests, under the stress equal to maximum stress amplitude of $\sigma =$ 740 MPa were also carried out in this work.

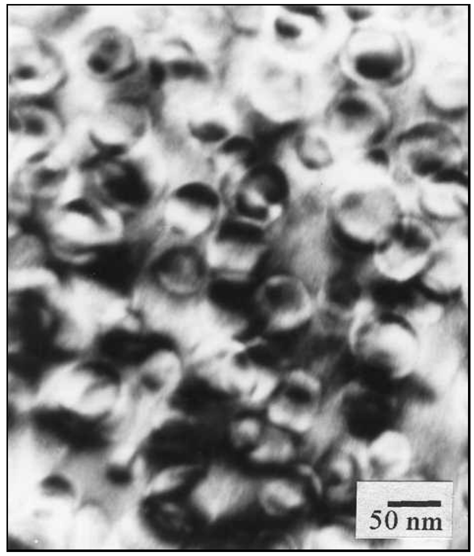

Fig. 1. TEM micrograph of the gamma prime distribution and morphology.

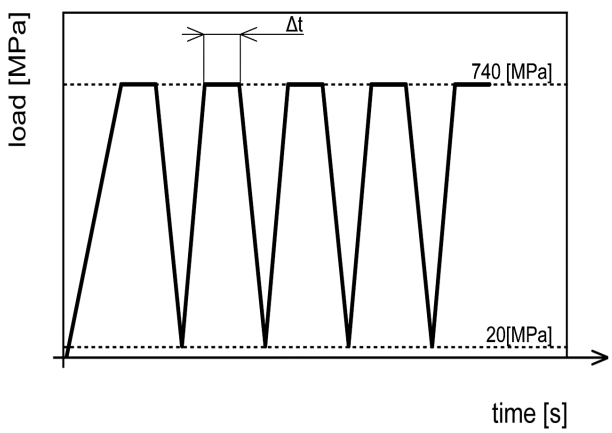

Fig. 2. Diagram of the fatigue loading schedule.

3. Results and discussion

The strain-time data, measured when strain was at the maximum load, corresponding to initial stress of 740 MPa, for isothermal cyclic creep tests for longer hold periods are presented in Fig. 3. The longer hold periods varied between 1 hour to 10 hours. The strain-time diagram for shorter hold periods in range of 1 minute to 30 min is presented in Fig. 4. Comparing the results of the cyclic tests with that of pure creep data the introduction of any hold period in cycling resulted in fracture life increase and decrease in creep strain rate $\dot{\varepsilon}$. There is only slight scattering of $\dot{\varepsilon}$ values observed for 10, 5, 3, 1, 0.5 hours of the hold periods, respectively. However, the introduction of the shorter hold periods caused the creep strain to drop down to more than half compared with that of the creep.

The results on the total time to failure (TTF), the time corresponding to total maximum (creep) load (MLT), numbers of cycles to failure (NCF), and fracture strain obtained in the cyclic creep experiments with the shorter hold periods, are summarized in Table 2. Evaluating the number of cycles N_{f} to failure vs. hold time Δt indicates sharp transient in the lifetime response corresponding to hold periods in the range of 7.5 to 15 min. These stated numbers do not include the N_{f} value obtained from the low cycle fatigue test of the same stress amplitude conducted without hold periods.

In order to evaluate the creep-fatigue resistance of this nickel base superalloy, the time criteria, such as time to failure and/or time to failure corresponding

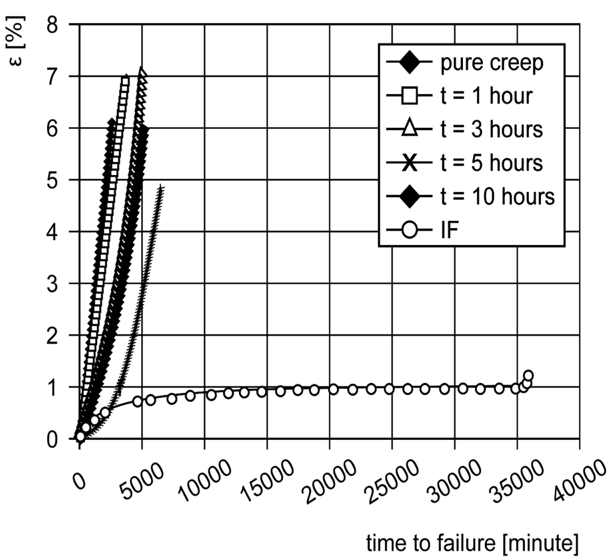

Fig. 3. Strain-time to failure dependences for longer holds.

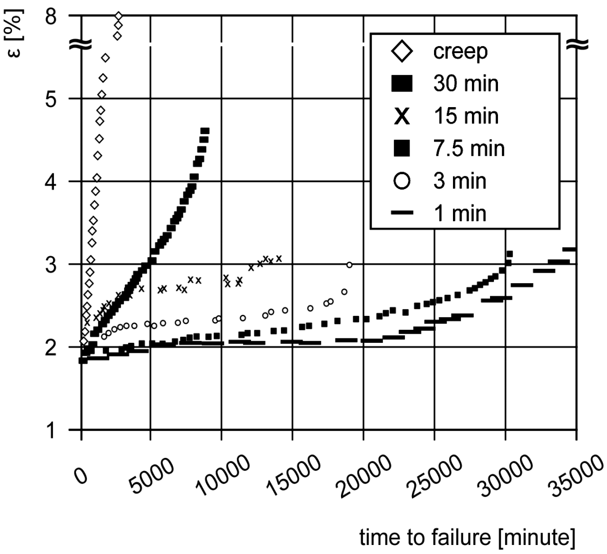

Fig. 4. Strain-time to failure dependences for shorter holds.

Table 2. Experimental data received from LCF and creep test

Parameter	Hold period [min]							
	fatigue	creep	1	3	7.5	15	30	60
TTF [min]	44 268	2 500	54 972	18 942	30 300	13 896	6 862	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	4.7	6.9

only to total sum of holds at the maximum applied load (MLT) can be used for this purpose. The evaluation of lifetime behaviour according to the time to failure corresponding to the sum of hold periods at maximum load is presented in Fig. 5. The corresponding hold period of $\Delta t = 7.5$ min at maximum load seems to have specific influence on the life time behaviour of alloy. Probably, in the cyclic creep with the hold period shorter than $\Delta t = 7.5$ min, in damage process more fatigue would contribute at crack nucleation and its propagation. If hold time is over this critical hold period in the life prediction dominating role in damage process would be taken over by creep. Comparing these results with those determined using the total time to fracture, a clear contradiction appears (see Table 2). The longest life corresponds to the test with the hold period of $\Delta t = 1$ minute. In case that total

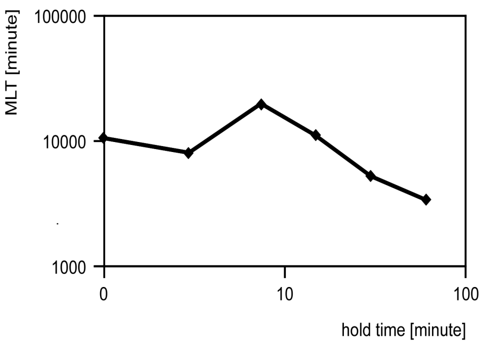

Fig. 5. Plot of the time to failure in terms of the sum of hold time at maximum load.

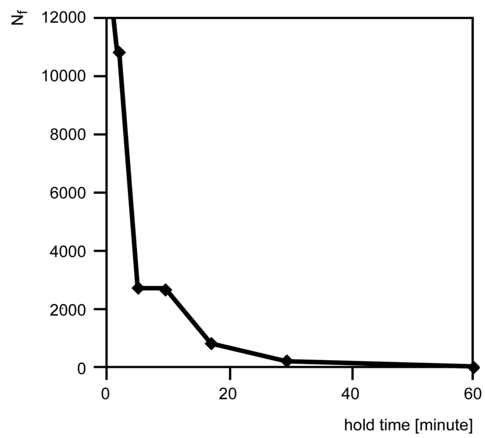

Fig. 6. The dependence of hold time and the number of cycles to failure.

number of cycles to fracture (NCF) is the criterion to evaluate the lifetime of the alloy, the plot representing the dependence is documented in Fig. 6. Regardless of the fact that with increasing hold period Δt there is observed continuous decrease in number of cycles to failure, the relationship can not be interpreted simply as the effect of prior damage on the fatigue mechanisms and/or as the influence of creep on cycles reduction. The main reason not to accept such interpretation is the fact that creep damage, which is time-controlled process, simply dominates in cyclic deformation process with longer hold periods introduced, i.e. when time needed for creep deformation advancement in one cycle would be sufficient.

Another interesting experimental result was observed in case of the applied hold times of $\Delta t = 3$ and 7.5 min. The recorded number of cycles to failure showed very small difference. To verify these findings the tests were repeated, however no difference was obtained, hence discounting the possibility of scatter. Considering this fact, the explanation of such lifetime behaviour could be based on the mutual contribution to damage from creep and fatigue in these two specific hold periods.

At the application of the stress reductions, the respective creep process may turn into a cyclic deformation process where besides time-controlled creep process the fatigue process contributes to damage process at the same time also. The life extension observed when the hold periods were introduced in fatigue process could have been a result of several additional aspects contributing to deformation process and modifying the course. Among these aspects, the alternating stress higher and lower than the yield point for the respective stress amplitude, the introduction of the cyclic deformation onto the creep process and vice versa, repeated storage of reversible anelastic creep deformation preceding the process of irreversible creep, the recovery of the stored deformation energy and release of anelastic deformation in time of the load off periods might be included. Regarding these influences the prediction of lifetime for actual test conditions makes it therefore more complex and more difficult. It is known that during the creep-fatigue loading the mutual interactions of stress components are involved in damage process. However, in order to predict the service life of structural part subjected to creep-fatigue loading there is no need to have knowledge in estimating of the individual creep and fatigue stress contribution in deformation process. At an effective evaluation of the both stress components contribution, the incorporation of stress components into one parameter would be more effective.

To predict creep fatigue life of the alloy under considered laboratory test condition, the linear damage summation rule [12] would be hardly appropriate to employ in case when creep damage may arise due to the cyclic loading condition. However, to separate the creep caused by the applied stress and the creep damage caused by the strain accumulation in time of test the equation of Kitagawa et al. [13], which is a modification of the linear rule of damage accumulation, appears to be more practical in using. The Kitagawa's equation where a parameter is assumed as the frequency dependent is given by

$$\left(\frac{N}{N_{\mathrm{f}}}\right) + \left(\frac{t}{t_{\mathrm{rcyc}}}\right) + a\left(\frac{\varepsilon}{\varepsilon_{\mathrm{stat}}}\right) = 1, \tag{1}$$

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, $\varepsilon_{\mathrm{stat}}$ is creep ductility, and a is Kitagawa's parameter, expressing the frequency dependence of process.

This equation considers explicitly 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 a can be expressed as $a = 1 - 1/k$ and parameter k determines the difference in a material lifetime exposed in condition of cyclic creep and can be given as $k = t_{\mathrm{rcyc}}/t_{\mathrm{stat}}$, 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. Substituting these parameters in (1) the equation can be adjusted to the following form:

$$\left(\frac{N}{N_{\mathrm{f}}}\right) + \left(\frac{t}{kt_{\mathrm{stat}}}\right) + \left(1 - \frac{1}{k}\right)\left(\frac{\varepsilon}{\varepsilon_{\mathrm{stat}}}\right) = 1. \tag{2}$$

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

$$\left(\frac{N}{N_\mathrm{f}}\right) + \left(\frac{N}{kN_\mathrm{c}}\right) + \left(\frac{t_\mathrm{h}}{kt_\mathrm{f}}\right) = 1, \tag{3}$$

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

Considering the cyclic creep deformation process where fatigue and creep (cyclic) contribute to damage process then the resulting degradation should arise due to superposition of both these contributions. Of course this assumption cannot be generalized to whole interval of applied stress frequency reductions 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 there.

The problem with cycling frequency dependence of the a parameter Kitagawa resolved by introducing a third member into the Eq. (1). In order to validate this equation over the entire frequency interval, the limitation on a negligible contribution resulting from cyclic deformation to total deformation must be admitted. In order to satisfy this limitation, it would be more advantageous to use only the first two terms of Eq. (2) and to assume the frequency dependence of the parameter k. However, in order to simplify the calculation 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 the parameter of damage though time-controlled process was involved. Applying these adjustments and using the obtained experimental data for creep life (total sum of holds at amplitude peaks) and data from pure fatigue to calculate the number of cycles to fracture corresponding to fluctuating load the following equation was received for applied loading cycle:

$$\left(\frac{N}{60000}\right) + \left(\frac{N}{k \cdot 13000}\right) + \left(\frac{t_\mathrm{h}}{k \cdot 2500}\right) = 1, \tag{4}$$

where t_h is hold time at maximum load.

Evaluation of the obtained data from laboratory testing shows that they are not very satisfactory for precise determination of the period during which the creep at static load does not contribute to damage accumulation. However, according

Table 3. Fracture effective hold periods at the maximum load

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

Table 4. Parameters k and a as a function of hold period

Δt [min]	1	3	7.5	15	30	60
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

to the deformation dependence in Fig. 6 it can be assumed that hold periods of Δt =1 and 3 min are only involved to comply with this assumption. In order to guarantee the stated prediction, the calculation was based on an extreme hold limit of $\Delta t = 1$ minute, when the effective period of static creep will be the longest. After subtracting this value from applied hold period the effective holds related to maximum load were calculated and they are presented in Table 3. Substituting this effective hold time to Eq. (4) and employing additional experimentally obtained data the parameter k and parameter a as a function of hold time at the maximum load was determined. The results of this calculation are presented in Table 4.

It was already stated that k and a parameters are frequency dependent. The frequency dependence of parameter k 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 supporting of the parameter k frequency dependence is equilibrium frequency dependence of hardening and softening process due to stress relaxing within the load off-times. The frequency dependence of the parameter k, which was introduced into process by load reduction or by introduction of hold time onto low cycle fatigue, is presented in Fig. 7.

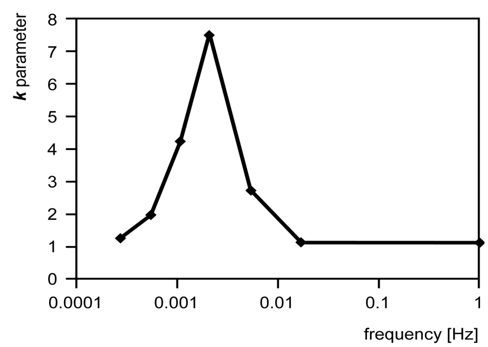

Fig. 7. Frequency dependence of parameter k.

To model the life prediction behaviour of alloy the modified Eq. (4) of the linear rule of damage accumulation was used. For the applied load – temperature condition 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:

$$\mathrm{MTF} = \frac{60937.5k\,(t_\mathrm{h})}{24.375\,(t_\mathrm{h}-1)+4.6875}t_\mathrm{h}. \tag{5}$$

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

$$\mathrm{NCF} = \mathrm{MLT}/t_\mathrm{h} \quad \text{and} \quad \mathrm{TTF} = \mathrm{MLT} + 4\mathrm{NCF}. \tag{6}$$

To calculate the parameter k values it is not easy to find the regression function, which would describe its value with good reliability for whole long interval of the applied hold periods. That is why for interval of used short hold times $t_\mathrm{h} < 7.5$ min and for interval of longer hold times, interval $t_\mathrm{h} > 7.5$ min the different regression function has been proposed. For the shorter hold time regression function of $k = 1.0105t_\mathrm{h} - 0.1567$ and for longer hold time $k = 44.53t_\mathrm{h}^{-0.8862}$ were calculated. If these regression functions expressing the parameter k dependence on hold time would be substituted into Eq. (5) the following formulae for life prediction, to differentiate the effect of shorter and longer hold time on lifetime behaviour, would be resulting:

$$\mathrm{MTF} = \frac{60937.5\,(1.0105t_\mathrm{h}-0.1567)}{24.357\,(t_\mathrm{h}-1)+4.6875+(1.0105t_\mathrm{h}-0.1567)}t_\mathrm{h} \quad \text{for holds of } t_\mathrm{h} < 7.5 \text{ min}, \tag{7}$$

$$\mathrm{MTF} = \frac{60937.5\left(44.53t_\mathrm{h}^{-0.8862}\right)}{24.375\,(t_\mathrm{h}-1)=4.6875+\left(44.53t_\mathrm{h}^{-0.8862}\right)}t_\mathrm{h} \quad \text{for holds } t_\mathrm{h} > 7.5 \text{ min}. \tag{8}$$

The graphic presentations of the model life parameters prediction MTF and NCF for defined testing condition of cyclic creep using the Eq. (7) and Eq. (8) are shown in Fig. 8 and Fig. 9.

4. Conclusions

The mechanisms of deformation and damage at high temperature in wrought nickel base superalloy subjected to low cycle fatigue where creep stress component have been imposed at amplitude peak were investigated. The obtained results serve to demonstrate that introduction of creep deformation into fatigue process or vice versa resulted in modification of the lifetime behaviour of superalloy in dependence

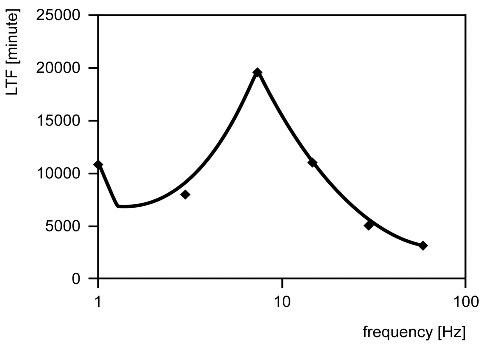

Fig. 8. Plot of alloy model life prediction in condition of cyclic creep.

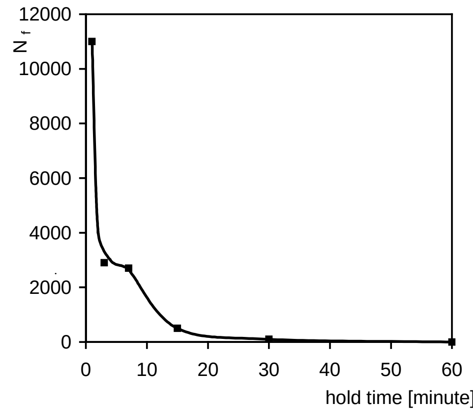

Fig. 9. Model prediction dependence of N_f as the function of hold time.

of the introduced parameters representing individual loading regime. The following conclusions can be drawn from the present study:

1. The creep-fatigue interaction represented by tensile hold period introduced into low cycle fatigue regime showed detrimental effect in fatigue life no matter what periods of holds have been used.

2. Introduction of tensile hold period has been shown to result in decrease in the number of cycles to failure as hold period prolonged. The increase in the strain rate resulted from creep participation in deformation process. The more pronounced strain rate increase can be related to more active creep participation in deformation process.

3. The presence of fatigue stress participation became dominant in deformation process when hold period was below 0.25 h.

4. For the laboratory test condition of low cycle fatigue where creep process was involved the modified linear damage summation rule was used to model life prediction in dependence on hold periods, representing the creep stress in fatigue cycle, introduced.

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REFERENCES

[1] HARKGARD, G.—GUEDON, J. Y.: In: Proc. of the 6th Liege Conf. on Materials for Advanced Power Engineering. Liege, Belgium, Jülich, GmbH 1998, p. 913.

[2] OTT, M.—MUGHRABI, H.: Mater. Sci. Eng. A., *272*, 1999, p. 24.
[3] EGGLER, G.—DLOUHÝ, A.: Acta Mater., *45*, 1997, p. 4251.
[4] POLLOCK, T. M.—ARGON, A. S.: Acta Metall. Mater., *40*, 1992, p. 987.
[5] GABB, T. P.—WELSCH, G.: Acta Met., *37*, 1998, p. 2507.
[6] LUKÁŠ, P.—OBRTLÍK, K.—KUNZ, L.—ČADEK, J.: Kovove Mater., *36*, 1998, p. 205.
[7] PORTELLA, P. D.—BERTRAM, A.—FAHLBUSCH, E.—FRENZ, H.—KINDER, J.: In: Fatigue'96. Eds.: Lütjering, G., Nowack, H. Beijing, Elsevier 1996, p. 795.
[8] ZRNÍK, J.—WANG, J. A.—PEIJING, Y. L.—HORŇAK, P.: Mater. Sci. Eng. A, 1987, p. 884.
[9] BOSIMER, D. A.—SHEITOGOLU, H.: Trans. ASME, *112*, 1989, p. 68.
[10] WANG, J. Y.—CHEN, W.—MUKHERJI, D.—KUTNER, T.—WAHI, R. P: Z. Metallkd., *86*, 1995, p. 365.
[11] MALDINI, M.—LUPINC, V.—ANGELLA, G.: Kovove Mater., *42*, 2004, p. 21.
[12] TAIRA, S.: Creep in Structures. Ed.: Nicholas, H. J. N.Y., Academic Press 1962, p. 99.
[13] KITAGAWA, M.—TAMURA, K.—OHTOMO, A.: J. of SMSJ, *32*, 1983, p. 662.