AN INTERNAL VARIABLE APPROACH TO CREEP, FATIGUE AND THEIR INTERACTION AT ELEVATED TEMPERATURES

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ABSTRACT

Service-failure at high temperature is known to occur mostly under creep conditions. A constitutive equation with one internal variable that is experimentally determined, is used in predicting the creep behaviour from results obtained in short term tests. Applications of the extrapolation procedure are described and its extension to LCF conditions is briefly discussed.

KEYWORDS

Creep, low cycle fatigue, internal variable, constitutive equation.

GENERAL CONSIDERATIONS

Materials used at high temperatures are subjected to severe loads such as creep, mechanical or thermal fatigue, thermal shock, environmental attack and their interaction. In the present paper, the mechanical loading of the material at elevated temperature will be considered. No attention will be paid to the influences the environment can exert on the material behaviour at high temperature, although it is recognized that such influences may be very important.

One of the main difficulties involved in the investigation of the behaviour of high temperature materials is the problem of extrapolation. In most applications (except perhaps some gasturbines) high temperature plant is designed for a long life time, typically up to 30 years. So, it is apparent that an extrapolation from laboratory conditions to service conditions has to be made when predicting the behaviour of the material.

At high temperatures a distinction is normally made between pure monotonic (creep) and pure cyclic loading and their interaction. Therefore extrapolation procedures for both sollicitations have been proposed. Creep-extrapolation procedures range from time-temperature parameter approaches (Goldhoff, 1959) to mechanistic creep crack propagation models (Christian and others, 1981). The experimental data necessary for their application have been obtained on virgin material, while it is common knowledge that most materials are metallurgically unstable at high temperature. This seriously limits the applicability of these approaches and highlights the fact that the microstructural evolution has to be taken into account in order to make accurate life predictions.

Life prediction under LCF and creep-fatigue interaction conditions has received much interest recently. The necessary acceleration in the laboratory testing is achieved by testing at increased strain ranges, shorter dwell times and higher frequencies than those encountered in service. Under such conditions, however, the dominating deformation and fracture mechanisms can be different from those in service. Indeed, it has been shown (Hales, 1980; Miller, 1982), based on ample metallographic and fractographic examinations, that under service conditions (low strain ranges, long dwell times and low frequencies) the failure mechanism is dominated by creep, while the interaction only takes place in a relatively narrow range of experimental conditions. This means that the "fatigue-oriented" approach to the creep-fatigue interaction phenomenon should be replaced by a "creep-oriented" approach.

OUTLINE OF THE METHOD

From the foregoing it follows that a creep based approach is probably the most appropriate for the investigation of the material behaviour at elevated temperature. Further it has been emphasized that the microstructural evolution should be taken into account. One way of doing this is by incorporating a structure parameter in the relations that describe the material behaviour under creep conditions (constitutive equations). In this way a mechanical equation of state with one internal variable is obtained (Grant, 1974). The time evolution of this internal variable reflects the changes that are taking place on the scale of the microstructure. From knowledge of the current value of the internal structure variable and the external variables such as temperature and stress, the subsequent behaviour of the material can then be described (Swearengen and Rohde, 1977). The approach adopted here does not specify a constitutive equation for the rate of the internal variable from the outset, but consists of experimentally determining it using appropriate short-term tests and obtaining the value of the internal variable under service conditions by extrapolation from these tests.

The method is based on the following constitutive relationship that describes the creep rate $\dot{\varepsilon}$ for a creep mechanism based on the glide and climb of dislocations, but where the climb step is rate-controlling :

$$\dot{\varepsilon} = \frac{A\, D_o G b}{kT} \exp\left(- \frac{\Delta H}{RT}\right) (\sigma - \sigma_i)^{n_o} \qquad (1)$$

In this expression σ means the externally applied stress, ΔH is the activation enthalpy, D_o is a diffusion coëfficient, A and n_o are constants, and σ_i, the internal structure parameter, is called the internal or friction stress. The value of σ_i can experimentally be determined in a number of ways, among which the most recent is by performing tensile tests at service temperature at several low strainrates ranging from 10^{-4} to 10^{-8} s^{-1} .The saturation stress obtained in such tests is equal to the internal stress corresponding to the imposed strainrate (Steen, 1983b).

By choosing the test temperature equal to the service temperature, the functional dependence of σ_i can be written as : $\sigma_i = \sigma_i(\sigma,t)$ where t stands for time. For a creep test under constant stress, we obtain $\sigma_i = \sigma_i(t)$. The evolution of $\sigma_i(t)$ thus determines the shape of the constant stress creep curve. Primary creep is characterized by an increasing internal stress, secondary or steady state creep by a constant internal stress. The increasing creep rate in the tertiary stage is mainly due to the presence of cavities and necking of the specimen, although a decreasing σ_i can also contribute to it. If it is assumed that in a constant stress creep test the microstructure evolves to its thermodynamic equilibrium, the occurrence of a constant σ_i means that this equilibrium has been reached. However in many cases a secondary or stationary creep stage is not observed, but a continuous transition from primary to tertiary creep takes place, which is a reflection of a continuously changing structure (Williams and Wilshire, 1977).

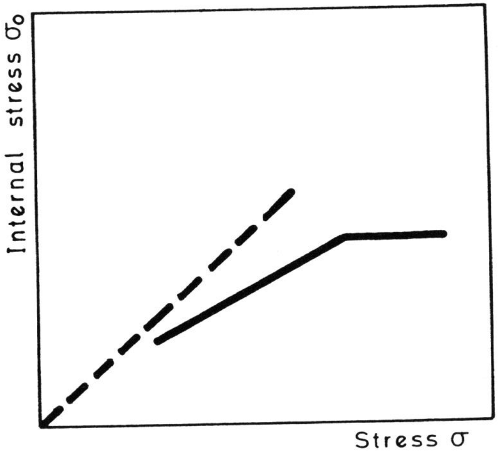
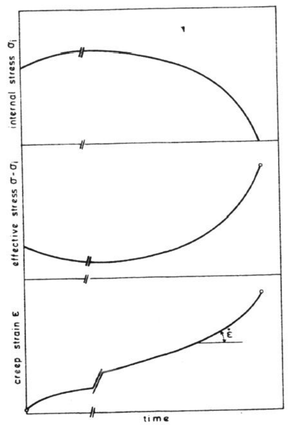


Fig. 1. Relationship between the applied stress and the internal stress in a creep test.

A method has been derived (Steen, 1983b) to obtain experimentally the $\sigma_i = \sigma_i(\sigma)$ relationship from low strainrate tensile tests at a given $t = t^*$. This relationship is of the form shown in Fig. 1. The value of σ_i corresponding to the service creep stress is obtained by linear extrapolation of this relationship. This yields the effective creep stress $\sigma - \sigma_i$ under service conditions. Substitution in (1) yields the corresponding creep rate. When at several time intervals samples are taken out of a component and subjected to low strainrate tensile tests, the internal stress corresponding to the creep stress at each of these moments can be determined. If the component is operating at a constant temperature and stress, these results can be displayed as in Fig. 2 and an "overall" creep curve of the component can be obtained by integration of the $\dot{\varepsilon}$ -values from (1). In this way the onset of the tertiary stage can be determined. Moreover a strain record of the component can be kept so that the achievement of a critical creep strain can be discerned.



When the component does not operate under steady state conditions of constant stress and temperature, the foregoing remains applicable. The strain record of the component will show approximately the same behaviour as in Fig. 2.
Another interesting application is the assessment of changed operating conditions, especially of a change in temperature. A method has been outlined by which this influence can also be taken into account (Steen, 1983b).

Fig. 2. Schematic evolution of internal and effective stresses and creep strain.

EXPERIMENTAL EVIDENCE

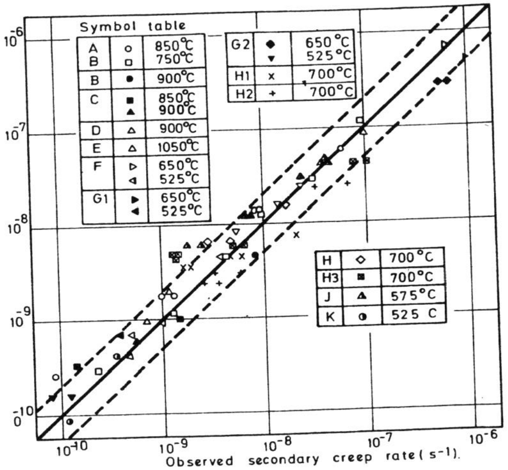
Up till now the results from low strainrate tests have not been applied as a surveillance procedure as shown above. However, tests have been performed on virgin and service aged material and the secondary creep rates predicted from low strainrate tests are compared to the ones obtained in creep tests at the same temperature in Fig. 3. The materials investigated range from low alloy ferritic to high austenitic. Their nominal composition and the test temperatures and material conditions are given in Tables 1 and 2.

TABLE 1 Nominal Composition of the Tested Materials (percent)

	C	Si	Mn	Cr	Ni	W	Nb	Mo	Fe
A-D	0,1	1	1	21	33	–	1,5	–	bal
E	0,5	1,5	1	25	35	1	1	–	bal
F-G, K	0,1– 0,18	0,1– 0,35	0,4– 0,7	0,7– 1,1	–	–	–	0,45– 0,65	bal
H	0,04– 0,01	1	2	18– 20	8– 10,5	–	–	–	bal
J	0,15	0,15– 0,50	0,40– 0,60	2– 2,5	– –	– –	– –	0,9– 1,1	bal

TABLE 2 Test Temperatures and Material Conditions

Material	Test temperature	Condition
A	750°C and 850°C	virgin
B	850°C and 900°C	service-aged for approximately 50.000 hrs at 750°C
C	850°C and 900°C	service-aged for approximately 50.000 hrs at 860–870°C
D	900°C	virgin
E	1050°C	virgin
F	525°C and 650°C	virgin
G	525°C and 650°C	service-aged for approximately 43000 hrs at 500–540°C
H	700°C	virgin
H1	700°C	shielded metal arc welded
H2	700°C	gas metal arc welded
H3	700°C	submerged arc welded
J	575°C	aged for 700 hrs at 575°C
K	525°C	service-aged for approximately 85.000 hrs at 535°C



Some tests on weldments are included too. In Fig. 3 the virgin materials are represented by open symbols, the aged materials by the solid and semi-solid ones, and the weldments by cross symbols. In total over sixty data points are included. The logarithmic standard deviation equals 0.08, which corresponds to a factor 1.2 in creep rate.

Fig. 3. Comparison of predicted and observed secondary creep rates.

APPLICATIONS

The results obtained from low strainrate tests can be used in several ways. First, a quick screening of the creep behaviour of a material (within one week) is possible. In this context, the method is currently being applied in the development of a modified 9-12 % Cr steel (COST 501, 1983).

In much the same way it can be used to assess the strengthening factors to be used for welds in welded joints. Therefore tests are carried out on specimens taken from base material and specimens containing a weld. The relative strength of both series of specimens gives a guideline to the strengthening factors to be used.

Another important application area is residual life assessment (Steen, 1983b). In this respect, the strain record of the component (Fig. 2) obtained by this method, yields useful information. Particularly, an easily discernable criterion for removal of the component from service can be established as the entering of the tertiary creep stage or the attainment of a critical creep rate acceleration. When a Monkman-Grant relation is available, the remanent life can be calculated from the creep rate predicted by the method. Also predicted strainrates at given times can be used in a tertiary creep model by Cane (1982) instead of strainrates measured on plant, thus yielding a remanent life estimation (Steen, 1984).

CREEP FATIGUE INTERACTION

As already mentioned a creep based approach should prove most useful in tackling this problem. On this ground, Franklin (1978) has proposed a phenomenological so-called 'cyclic-creep' model. In line with the foregoing, such an approach can also be established using the internal variable philosophy. In that case the evolution of the internal variable (internal stress) within a stable hysteresis loop has to be determined. Several attempts thereof have been made (e.g. Tsou and Quesnel, 1982). In Fig. 4 the periodic evolution of σ, σ_i and $\sigma - \sigma_i$ in a symmetrical stress-controlled LCF test on a superalloy at 850°C is shown. This evolution is obtained by fitting the measured inelastic strainrates to (1). As can be observed, the internal stress σ_i lags behind the applied stress. This is mainly due to the much slower change of direction of the internal stress at the points of stress reversal, which can be ascribed to time-dependent recovery phenomena that also occur in creep.

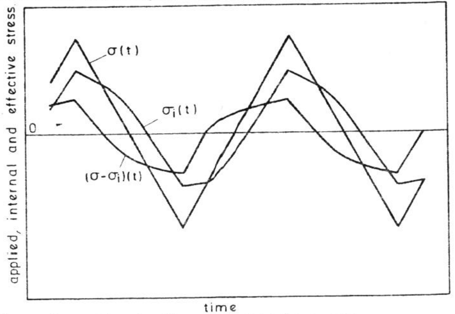


Fig. 4. Periodic variation of applied, internal and effective stress in a stable hysteresis loop.

After the stress reversal, the effective stress $\sigma - \sigma_i$ is positive, which reflects the fact that forward creep is still observed with decreasing external stress. Also the direction of creep is reversed before the applied stress reaches zero. The time lag between applied and internal stress has been invoked by Harrison (1977) to explain the increased number of cycles to failure with increasing frequency in zero to tension stress controlled LCF-tests.

Application of the internal stress concept to LCF for prediction purposes should follow the opposite direction. The evolution of the internal stress as a function of the applied stress should be known first in order for the strainrates occurring in the hysteresisloop to be determined from it. Moreover the number of cycles prior to the attainment of the stabilized hysteresisloop should be accounted for. In order to represent this behaviour, the internal stress in LCF has been considered to be composed of at least two components : one that changes from cycle to cycle and eventually reaches saturation, and another that changes continuously within a cycle and should be a periodic function of the applied stress in the stabilized cycle. For the identification of these internal stress components and for their experimental determination, further research is warranted. Finally, for life prediction purposes a damage rule should be available by which conversion to a number of cycles to failure could be achieved.

SUMMARY

The use of a single internal variable constitutive equation in predicting the creep behaviour from short term low strainrate tensile tests is described. Several possible applications of the extrapolation procedure are discussed. Finally, the extension to low cycle fatigue is briefly touched upon.

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