INFLUENCE OF NECKING ON CREEP CURVE

M. Maldini and V. Lupinc*

The influence of necking development on the creep curve and time to rupture in tensile creep tests is analysed in single crystal nickel base superalloys.

The growth of necks in tension specimens is studied using numerical techniques. It is shown that the presence of a necking affects the average creep rate only at high strain. The conditions for necking are studied.

INTRODUCTION

In the study of constitutive equations, specially if physically based, the creep strain is generally considered to be homogeneous along the specimen. Actually in a measured creep curve, the contribution of necking could influence both the shape of the creep curve and the time to rupture.

In order to check physically based creep constitutive equations, it is important to know in which conditions and when the growth of necking begins to influence the measured creep strain rate so as to use the strain range where the necking contribution to the measured creep strain is negligible as data base.

In this work the necking development in a tensile creep test has been modelled and its influence on the creep curve has been analysed specially for nickel base superalloys, a particularly interesting class of materials for this purpose since they show increasing creep–strain induced softening

*CNR ITM Via Induno 10, 20092 Cinisello Balsamo (Mi), Italy

properties with the decreasing of the applied stress and hence the contribution of necking to the measured creep strain could strongly depend on the applied stress. In particular the analysis is performed on creep of single crystal superalloys where no grain boundaries cavitation damage mechanism is superimposed to the strain softening mechanism.

UNIAXIAL TENSION CREEP TEST

In general a creep test is performed at constant tensile load rather than at constant stress, hence the creep strain increases at an accelerating rate also because of the homogeneous decreasing in cross section. Usually other damage mechanisms, reviewed by Ashby and Dyson (1), intervene to anticipate the failure reducing the external (e.g. the environmental attack) or the internal (e.g. grain boundaries cavitation) resistance cross section, or increasing the creep strain rate (e.g. time or strain induced softening in the material).

The necking, i.e. the localised reduction of the cross section, is a further factor that increases the strain rate. Rather than to a physical damage mechanism, necking is due to intrinsic instability of tensile creep in realistic materials that are never perfectly homogeneous. If one part of the specimen has a slightly smaller cross section than the rest, then the stress there is higher, and the creep rate larger: as a consequence the inhomogeneity in the cross section is amplified.

It is important to know when the rate of amplification of a perturbation is large enough to significantly influence the creep rate, the life of the sample and the shape of the creep curve.

The necking development can be analysed studying the evolution of an initially imperfect bar subjected to constant load. Among the different perturbations that can originate the necking, i.e. geometrical, microstructural or thermal field inhomogeneities, a long wave geometrical deviation of specimen cross section from its average value has been considered here. Following Burke and Nix (2) the initial cross–section is supposed to vary as a cosine function along the axis of the specimen.

The evolution during creep of the shape of such a geometrically perturbed specimen is obtained representing the sample by a series of thin disks and considering each disk to be subjected to a homogeneous uniaxial stress. The strain of each disk follows the constitutive equation of the material and the elongation of the specimen is obtained adding the different elongation of each disk.

THE CONSTITUTIVE EQUATION

In the field of typical stresses and temperatures for single crystal superalloys as gas turbine blade material, the creep curve is characterised by a large tertiary creep that represents the majority of the curve. According to Dyson and McLean (3), this behaviour seems to be due to the increasing of the flux of free dislocations with the accumulated creep strain, and it has been successfully described by Maldini and Lupinc (4) utilzing the following relationship:

$$\dot{\epsilon}=\dot{\epsilon}_{o}(1 + C\epsilon) \tag{1}$$

for constant stress tests, or:

$$\dot{\epsilon}=\dot{\epsilon}_{o}(1 + C\epsilon)\exp(n\epsilon) \tag{2}$$

for constant load tests.

The strain induced weakening of the material is characterised by the parameter C that can typically assume values between 100 at high stress and 1000 or even more for the lowest applied stress that such materials can experience in service at high temperature. For single crystal superalloys, the values of the parameter C are always higher than 40 , the value chosen by Tvergaard (5) for the numerical analysis in a material subjected also to grain boundaries cavitation .

The parameter $\dot{\epsilon}_{o}(\sigma , T)$ represents steady state creep rate in the material if no damage mechanisms are active and generally is a power function of the stress, with n as exponent. Hence the expression $\exp(n\epsilon)$ in Eq. 2, takes into account the increasing of the applied stress with the increase of the strain due to the homogeneous reduction of the section of the specimen.

RESULTS AND DISCUSSION

In the simulations the influence of the parameter C in the interval C = 0 – 3000 has been studied, while the parameter n has been kept constant at a typical experimental value, n = 10. Fig. 1 shows, for different values of the parameter C, the R ratio of strain rate of a perturbed specimen having a deviation of $\pm 0.5\%$ of the initial cross section with the strain rate of a "perfect" specimen as a function of strain. The marked influence of the parameter C is apparent. In (2) it has been shown that the necking due to the parameter n influences the creep curve at strain < 20% only for n > 30.

It is important to note that from the numerical simulation the parameter C of Eq. 2 starts to influence the strain rate at lower strain when increasing the value of the parameter C, as shown in Fig. 1, but always at quite high strains. Hence necking effect on time to rupture is negligible, as evident in Tab. 1 where simulated time to get different strains of a "perfect" and a "perturbed" specimen are compared for different values of the parameter C.

The influence of the parameter C in the development of necking is shown in Fig. 2 that compares the values of the strain far away and in the necking. The difference between these two strains sharply increases with the value of the parameter C. Without going into detail of the fracture mechanisms, studied for example by Ai et al.(6), and utilising the isostrain (the broken lines that join points of the same total strain value), it clearly appears that necking develops at a smaller total strain when the value of the parameter C increases.

These results of the model are supported by the experimental observations shown in Tab. 2 where fracture parameters of the single crystal nickel base superalloy CMSX–6 confirm the localization of the strain when, decreasing the applied load, the value of the parameter C increases.

CONCLUSION

The effect of the necking due to an initial geometrical inhomogeneity can be relevant to the shape of the creep curve and has to be examined and eventually considered when a physically based equation is adopted to describe creep behaviour. The time to rupture does not seem to be significantly influenced by the development of necking.

TABLE 1– Ratio of time to reach a strain in a perfectly cylindrical specimen and in a specimen with a perturbation of ∓.5% in the cross section, for different C values

ϵ (%)	C = 0	30	100	300	1000	3000
5	1.001	1.002	1.002	1.003	1.003	1.007
10	1.002	1.005	1.007	1.010	1.011	1.016
15	1.003	1.010	1.015	1.020	1.024	1.029
20	1.005	1.019	1.027	1.033	1.036	1.038

TABLE 2– Creep results of the single crystal superalloy CMSX–6

T (°C)	σ (MPa)	ϵ_r	Z_r	Z_r/ϵ_r
950	250	0.24	0.56	2.3
	200	0.25	0.56	2.2
	180	0.28	0.49	1.8
1000	180	0.20	0.58	2.9
	140	0.19	0.55	2.9
1050	120	0.12	0.50	4.2

SYMBOLS USED

ϵ = strain

ϵ_r = strain to rupture

$\dot{\epsilon}_\circ$ = initial tertiary creep rate (h^{-1})

C = strain softening parameter

n = Norton type stress sensitivity of $\dot{\epsilon}_\circ$

σ = tensile stress

t_r = time to rupture

Z_r = necking area reduction

R = ratio of strain rate of a perturbated specimen with a deviation of ±0.5% of the initial cross section from the average value with the strain rate of a "perfect" specimen

REFERENCES

(1) Ashby, M.F. and Dyson, B.F. "Creep Damage Mechanisms and Micromechanisms", Advances in Fracture Research, edited by D.M.R. Taplin et al., Pergamon Press, Oxford, England, 1984.

(2) Burke, M.A. and Nix, W.D., Acta Metall., Vol. 23, 1975, pp. 793–798.

(3) Dyson, B.F. and McLean, M., Acta Metall., Vol. 31, 1983, pp. 17–27.

(4) Maldini, M. and Lupinc, V., Scripta Metall., Vol. 22, 1988, pp.1737–1741.

(5) Tvergaard V., Acta Metall., Vol. 4, 1987, pp.923–933.

(6) Ai S.H. et al., Scripta Metall. et Materialia, Vol. 26, 1992, pp. 579–584.

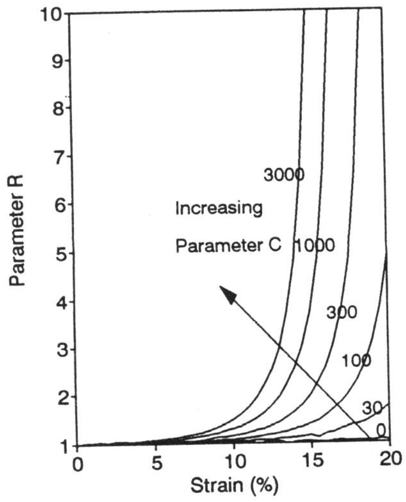

Figure 1 Relationship between R and ϵ at different C values.

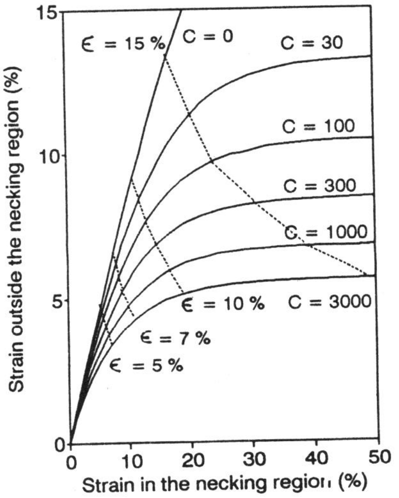

Figure 2 Relationship between the strain in and outside the necking for different C values.