A New Critical Damage Criterion for Creep

EXECUTIVE SUMMARY

Components used at elevated temperatures in nuclear, thermal power plants are designed for creep, and progressive deformation of a material either at constant load or stress is termed as creep. Creeping materials fail as a result of initiation and growth of damage. The design criterion for creep does not invoke creep ductility in arriving at the allowable stress. Therefore a 'critical damage criterion' is developed in terms of a new concept called 'time to reach Monkman–Grant ductility' (t_{MGD}) and is shown that damage attains a critical level at t_{MGD}. A critical damage criterion that depends only on the damage tolerance factor is deduced based on continuum creep damage mechanics (CDM) and MPC–Omega (materials property council) approaches and the validity of the criterion is demonstrated for a wide range of materials. It is also shown that it has useful implications to engineering creep design of high temperature components.

OUTLINE

Components used at elevated temperatures are designed for creep and the allowable stress for nuclear applications is based on the concept of lowest of the three; i.e., 100% of the average stress to produce 1% strain in a given time (say 105 h), 67% of the minimum stress to produce rupture in 105 h and 80% of the minimum stress to cause initiation of tertiary creep in 105 h. It may be noted that in design, creep ductility is not considered while arriving at the allowable stress. It is also important to understand when does creep damage becomes alarming so that a safe and un-safe regime concept can be defined for a creep curve. It is this intention that gave genesis for the original approach of critical damage criterion in terms of a new concept called time to reach Monkman–Grant ductility (MGD). MGD is the product of minimum creep rate and rupture life and is generally found to be a constant.

The new concept is developed in terms of time at which MGD is reached along a creep curve and is designated as t_{MGD}. Next it is addressed whether there is a relationship between t_{MGD} and tr and if so is it universal in nature. It is put forward that creep damage that grows along the creep curve attains a critical level at t_{MGD} and it is shown for a typical case of cavitation damage micro-mechanism in -iron that cavities attain a critical size at t_{MGD}. Based on CDM and MPC–Omega approaches, a critical damage criterion is deduced as universal relationship between t_{MGD} and t_r that depends only on the tolerance to resist creep damage (i.e., creep damage tolerance factor) .

Along the lines of CDM, the critical damage criterion is deduced as

$$t_{MGD}/t_r = 1\ \ [(\lambda-1)/\lambda]^{\lambda} = \text{constant} = f_{CDM}. \qquad \text{(Eq. 1)}$$

Similarly, based on MPC–Omega method, it is deduced as

$$t_{MGD}/t_r = 1 - \exp(-1) + \exp(-\lambda) = \text{constant} = f_{MPC}. \qquad \text{(Eq. 2)}$$

The key in the above Eq. (1) is that though t_{MGD} and t_r vary, f_{CDM} is a constant independent of stress and temperature, since is material constant in a given stress–temperature domain for a specific damage mechanism. The above physically based Eq. 1 (or Eq 2) is termed as critical damage criterion because damage attains critical level at t_{MGD}, when the criterion $t_{MGD} = f_{CDM}\ t_r$ is met. The validity of damage criterion is demonstrated in Figure 1 for various materials. The symbols correspond to experimentally obtained f_{EXP} values from t_{MGD} vs. t_r plots for the respective material. Figure 2 shows the plot of t_{MGD} vs. t_r with f_{CDM} calculated according to Eq. (1) knowing the constant value of λ for the respective material.

The important implication is that t_{MGD} can be viewed as the onset of true tertiary creep damage and stress to cause t_{MGD} in 10^5 h with proper safety factor can be suggested as a new creep design criterion. For creep curves at different stresses and temperatures (i.e., with constant λ), a contour that satisfies $t_{MGD} = f_{CDM}\ t_r$ can be drawn such that the region till t_{MGD} can be considered as a safe regime. Further, when Robinson life fraction damage rule is not applicable and it predicts non–conservative values of remnant life, a modified damage rule in terms of t_{MGD} has been proposed that is conservative.

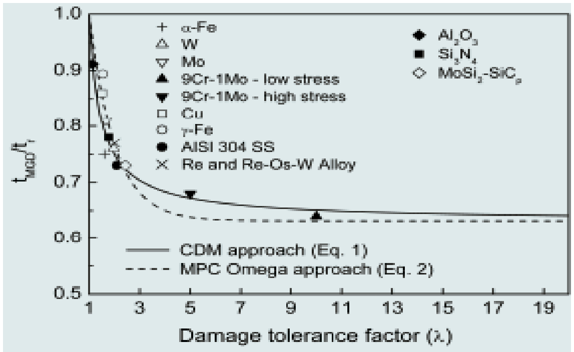

Fig. 1 : Validity of critical damage criterion for a wide range of materials. Solid symbols correspond to f_{EXP} values obtained from double logarithmic plots of t_{MGD} vs. t_r for different materials

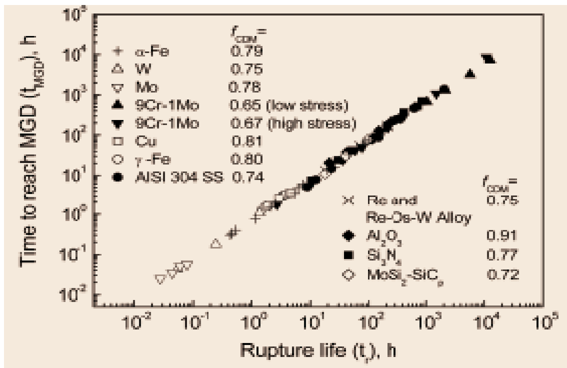

Fig. 2 : Plot of t_{MGD} vs. t_r demonstrating the validity of damage criterion with f_{CDM} values for various materials

■ ADDITIONAL INFORMATION ABOUT TIME TO REACH MONKMAN–GRANT DUCTILITY (TMGD)

Monkman–Grant in 1956 proposed that for different test conditions, the product of minimum creep rate $\dot{\varepsilon}_m$ and rupture life t_r generally is constant and this product is designated as MGD and is the minimum useful secondary ductility that is available in a creeping material. Therefore t_{MGD} is defined as the time at which this MGD is reached for a given creep curve when primary creep strain is negligible. Also t_{MGD} is the time at which the true tertiary creep damage sets in, since MGD is exhausted at t_{MGD}. Beyond t_{MGD} till failure corresponds to the accelerated growth of damage leading to linkage of cavities resulting in micro–cracks thus causing creep fracture.

■ CREEP DAMAGE CRITERION AND RELATIONSHIP BETWEEN t_{MGD} AND t_r

The concept of t_{MGD} is shown schematically along with time to onset of tertiary creep t_{ot}, limiting tertiary creep strain ε_t and damage tolerance factor for negligible primary creep strain ε_p. A large is desirable as the material can tolerate strain concentrations without local cracking and thus λ is a material performance characteristic.

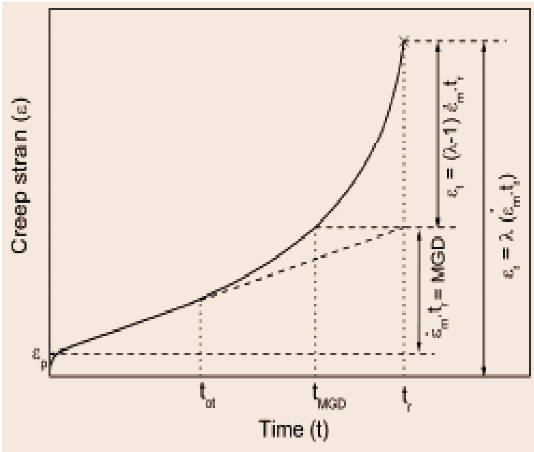

Fig. 3: Schematic creep curve with negligible primary strain ε_p illustrating t_{MGD}, t_{ot}, ε_t and damage tolerance factor λ

CDM and MPC–Omega Approach

Monkman–Grant relation does not describe the evolution of creep damage and its coupling to the deformation rate. The two approaches that describe this coupling are CDM and MPC–Omega approaches. According to CDM, damage is treated as an internal state variable and is expressed by the two coupled differential equations where first gives the deformation rate as a function of stress, temperature and scalar damage variable. The second equation describes the evolution of damage and the damage rate is expressed as a function of stress, temperature and damage variable. Defining these two coupled equations and after integrating them at constant stress, a relationship between strain fraction and time fraction can be obtained in terms of λ. Substituting the condition at $t = t_{MGD}$, $\varepsilon - \varepsilon_p$ = MGD, the damage criterion can be easily deduced. MPC–Omega approach gives the evolution of deformation rate as a function of strain with omega parameter which is reciprocal of MGD for negligible ε_p. On similar lines to CDM, damage criterion can be deduced following MPC method.

■ BRIEF DESCRIPTION OF THEORETICAL BACKGROUND

The essential message of Monkman–Grant relation is that creep deformation and damage are inter-related and creep fracture is strain controlled. This provided the genesis that at what time MGD is reached along a creep curve and is there any relation between t_{MGD} and t_r. If so, is it universal in nature and is it applicable to all creeping solids? Also, what is the physical meaning of t_{MGD} in terms of creep damage? Thus t_{MGD} is shown as the time at which damage attains a critical level and the critical damage criterion in terms of relationship between t_{MGD} and t_r has been deduced based on CDM and MPC approaches as these are apt to describe the coupling between the evolution of creep damage and deformation rate. The highlight of the study is that the proposed criterion depends only on that is related to damage mechanism and is constant in a given stress–temperature domain.

■ ACHIEVEMENT

The proposed new damage criterion has importance to basic understanding of creep damage and has useful implications to creep design. It is applicable even when Monkman–Grant ductility varies, since it depends only on damage tolerance factor. Further, this study has high relevance to our centre, since creep is of consideration in PFBR and also to elevated temperature applications in general.

■ PUBLICATIONS ARISING OUT OF THIS STUDY AND RELATED WORK

1. C. Phaniraj, B. K. Choudhary, Baldev Raj and K. Bhanu Sankara Rao, *J. Mater. Sci.* **40** (2005) 2561.
2. C. Phaniraj, B. K. Choudhary, Baldev Raj and T. Jayakumar, *Mater. Sci. Eng. A* **398** (2005) 373.
3. C. Phaniraj, B. K. Choudhary and Baldev Raj, Proc. "Inter. Conf. on Pressure Vessels and Piping, OPE–Chennai", Feb 2006, Chennai.

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