Interesting relationships for creep deformation and damage and their applicability for 9Cr1Mo ferritic steel

Article *in* Transactions- Indian Institute of Metals · April 2010

DOI: 10.1007/s12666-010-0103-0

B.K. Choudhary
Indira Gandhi Centre for Atomic Research, Kalpakkam - 603102, India

C. Phaniraj
Indira Gandhi Centre for Atomic Research (DAE), Kalpakkam-603102, India

Baldev Raj
Indira Gandhi Centre for Atomic Research

Transactions of The Indian Institute of Metals
Vol. 63, Issues 2-3, April-June 2010, pp. 675-680

Interesting relationships for creep deformation and damage and their applicability for 9Cr-1Mo ferritic steel

B. K. Choudhary, C. Phaniraj and Baldev Raj

Indira Gandhi Centre for Atomic Research, Kalpakkam - 603 102, Tamil Nadu, India

E-mail : bkc@igcar.gov.in

Received 10 February 2009
Revised 11 August 2009
Accepted 12 August 2009
Online at www.springerlink.com

***Keywords**:*
9Cr-1Mo steel; creep deformation; Monkman-Grant relation; transient creep; tertiary creep; creep damage; creep damage criterion

Abstract

The paper presents the validity of several interesting relationships examined for better understanding of creep behaviour of 9Cr-1Mo ferritic steel. Creep rate-rupture time relationships of Monkman-Grant type have been found to be valid. Like stress dependence of creep rate and rupture life, both Monkman-Grant and modified Monkman-Grant relations (MGR and MMGR) exhibited distinct constant values of C_{MG} and C_{MMG}, respectively for low and high stress regimes. The validity of MGR and MMGR is a consequence of the creep deformation behaviour of 9Cr-1Mo ferritic steel obeying first order kinetics. On the basis of creep rate-rupture time relationships of Monkman-Grant type, several other relationships involving transient and tertiary creep parameters have been evolved and their applicability have been examined for the steel. Analogous to MGR and MMGR, a relationship involving transient creep parameters and the other involving tertiary creep parameters were found to be valid. Further, 9Cr-1Mo steel obeyed a recently introduced critical damage criterion interrelating time to reach Monkman-Grant ductility with rupture life, and the criterion depends only on creep damage tolerance factor. This unique relationship is evolved based on the seminal concept of time to reach Monkman-Grant ductility as the time at which the useful safe creep life is exhausted and damage attains a critical level. The important implications of this concept have been discussed.

1. Introduction

Creep deformation and damage are important considerations for engineering creep design and in the development of new materials for high temperature applications. Creep deformation typically consists of three regions i.e., a decrease in creep rate in the transient creep region followed by a minimum or a steady state creep rate in secondary creep and an increase in creep rate during tertiary creep leading to failure. Creep damage is defined as the progressive reduction in the ability of a material to resist stress and the growth of damage is manifested as an increase in creep rate during tertiary creep eventually resulting in failure. Creep deformation and damage are interrelated is the essential message of the empirical relationship proposed by Monkman and Grant [1], where time to failure or rupture time t_r is inversely proportional to minimum or steady state creep rate $\dot{\varepsilon}_s$. Monkman-Grant relation (MGR) [1] in the generalised form is expressed as

$$\dot{\varepsilon}_s^m \cdot t_r = C, \tag{1}$$

where m is the slope of double logarithmic plot of t_r vs. $\dot{\varepsilon}_s$ and intercept C is a constant. It has been suggested that in the case of intergranular creep failure where most of rupture life is occupied by steady state creep stage, the product of creep rate and rupture life would be an appropriate measure of strain to failure, and m and C in eq. (1) will be independent of temperature, heat treatment and chemical composition of a particular alloy [1]. However, for materials which exhibit large tertiary creep and a decrease in creep strain to failure with increasing rupture life, a large scatter in the data in eq. (1) can be considerably reduced using the modified Monkman-Grant relation (MMGR) proposed by Dobes and Milicka [2] in the generalised form

$$\dot{\varepsilon}_s^{m'} \cdot \frac{t_r}{\varepsilon_f} = C', \tag{2}$$

where ε_f is the strain to failure and C' is a constant. The validity of MGR and MMGR are observed as slopes m and m' equal to unity in the plots of $\log t_r$ vs. $\log \dot{\varepsilon}_s$ and $\log(t_r/\varepsilon_f)$ vs. $\log \dot{\varepsilon}_s$ respectively. When $m = 1$, C becomes C_{MG}. Similarly, when $m' = 1$, C' becomes C_{MMG}. Then, eq. (1) and eq. (2) can be expressed as

$$\dot{\varepsilon}_s \cdot t_r = \text{constant} = C_{MG} \tag{3}$$

and

$$\dot{\varepsilon}_s \cdot \frac{t_r}{\varepsilon_f} = \text{constant} = C_{MMG}\ . \tag{4}$$

The validity of creep rate-rupture time relationships of Monkman-Grant type is shown to be the consequence of creep behaviour of material obeying first order kinetics [3-7]. The analysis of transient and tertiary creep of type 304 austenitic stainless steel [3,4] and 9Cr-1Mo ferritic steel [5-7] has shown that both these steels obeyed first order kinetics and its manifestation in terms of master creep curves (for a range of stress and temperature), one interrelating transient and secondary creep, and the other interrelating secondary creep and tertiary creep. Apart from master creep curves, the detailed analysis of strain (ε) - time (t) data in the framework of first order kinetic approach led to several interesting relationships between transient, steady state and tertiary creep [3-7]. The validity of these relationships has been examined for 9Cr-1Mo ferritic steel with an objective to gain insight into the creep deformation behaviour. The intention of the paper is not to predict ε-t creep curves, but to understand the interrelationship between the transient, steady state and tertiary creep parameters. 9Cr-1Mo steel is an important structural material for steam generator applications in thermal and nuclear power generating industries. Apart from these, the paper also discusses the applicability of recently proposed creep damage criterion [8,9], which is based on the seminal concept of time to reach Monkman-Grant ductility t_{MGD} (where Monkman-Grant ductility, "MGD" is the product of $\dot{\varepsilon}_s$ and t_r). t_{MGD} is the time at which the useful secondary creep ductility is exhausted and damage attains a critical level. The damage criterion has been obtained as a unique relationship between t_{MGD} and t_r that depends only on creep damage tolerance factor λ.

2. Experimental and analysis of creep data

The constant load creep test data obtained on 9Cr-1Mo ferritic steel are used for the analysis presented in this paper. Creep tests were performed on quenched and tempered (Q+T: 1223 K/5 h water quenched followed by 1023 K/8 h air cooled) and simulated post weld heat treated (SPWHT: 998 K/3 h with heating and cooling rates of 50 Kh^{-1} above 673 K) conditions, in the temperature range of 773-873 K and at a wide range of stresses. In this paper, the results obtained typically for 873 K are presented. The details regarding the chemical composition, heat treatments, microstructures and creep tests are described, elsewhere [5,10,11].

9Cr-1Mo steel showed small transient creep strain ε_T, well defined secondary creep stage characterised by a steady state creep rate $\dot{\varepsilon}_s$, and a large tertiary creep in terms of both time spent in tertiary creep t_t as well as limiting tertiary creep strain ε_t as shown in Fig. 1. The time spent in transient creep is defined as the time to onset of secondary creep t_{os}. Time spent in tertiary creep t_t is expressed as $t_t = t_r - t_{ot}$, where t_{ot} is time to onset of tertiary creep. The secondary creep contribution to overall creep strain i.e., the product of steady state creep rate and rupture time ($\dot{\varepsilon}_s \cdot t_r$) is called as Monkman-Grant ductility (MGD). Time to reach Monkman-Grant ductility t_{MGD} is determined as the time at which Monkman-Grant strain is exhausted along the creep curve as shown in Fig. 1. Limiting tertiary creep strain ε_t and strain to failure ε_f as expressed in terms of damage tolerance factor λ is given in Fig. 1 and the other terms used in various relationships presented in the paper are described in the following section.

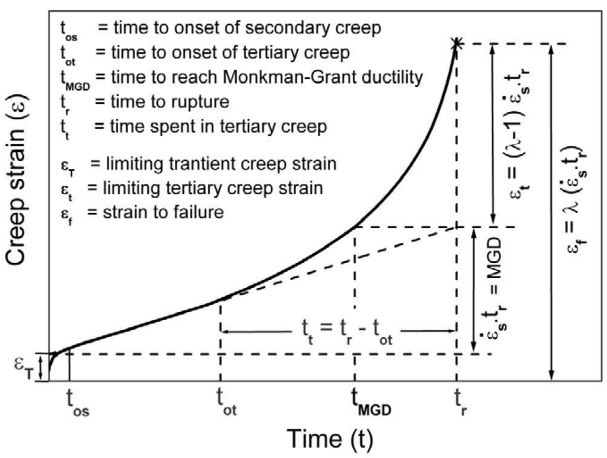

Fig. 1 : Typical creep curve for 9Cr-1Mo ferritic steel showing various parameters used for defining creep behaviour.

3. Interesting relationships and their applicability

3.1 Creep Rate-Time Relationships of Monkman-Grant Type

The variations in rupture time t_r as a function of steady state creep rate $\dot{\varepsilon}_s$ for 9Cr-1Mo steel in Q+T and SPWHT conditions at 873 K are shown as double logarithmic plot in Fig. 2. The validity of MGR is observed as the slope of logt_r vs. log $\dot{\varepsilon}_s$ plot is equal to unity. The value of Monkman-Grant constant C_{MG} (i.e., eq. 3) is obtained as 0.05 and 0.1 at low and high stress regimes, respectively. Figure 3 shows the variations in rupture time/strain to failure t_r/ε_f as a function of $\dot{\varepsilon}_s$ for the steel in both Q+T and SPWHT conditions at 873 K. Like MGR, the validity of MMGR is observed as the slope of log(t_r/ε_f) vs. log ($\dot{\varepsilon}_s$) plot is equal to unity. The value of modified Monkman-Grant constant C_{MMG} (i.e., eq. 4) is

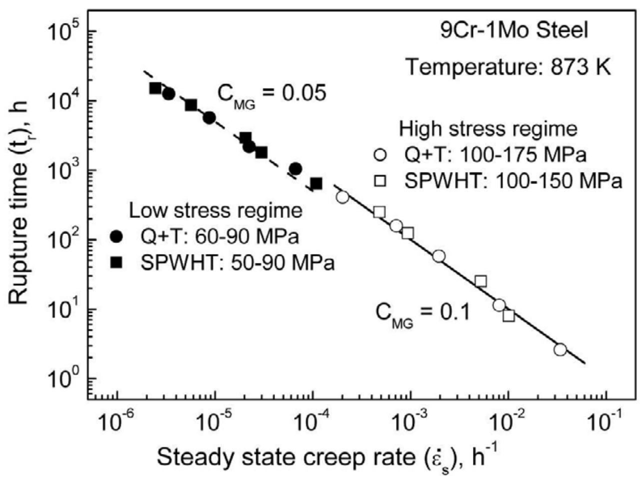

Fig. 2 : Rupture time vs. steady state creep rate plot showing validity of Monkman-Grant relation (eq. 3) with separate values of C_{MG} = 0.05 and 0.1 for low and high stress regimes, respectively.

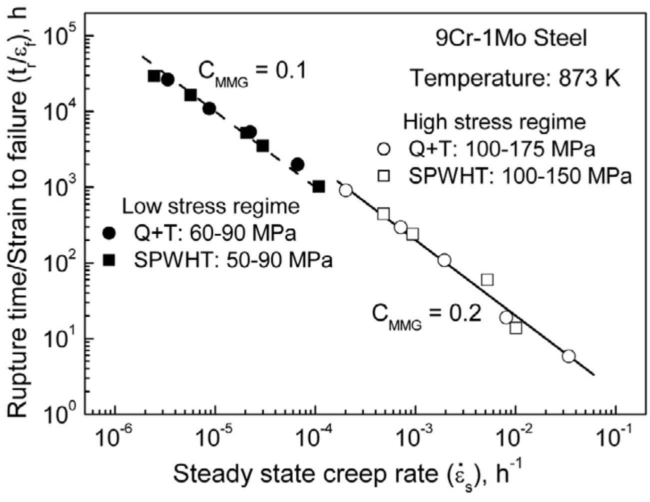

Fig. 3 : Rupture time/strain to failure vs. steady state creep rate plot showing validity of modified Monkman-Grant relation (eq. 4) with separate values of C_{MMG} = 0.1 and 0.2 for low and high stress regimes, respectively.

obtained as 0.1 and 0.2 at low and high stress regimes, respectively. Here, it is important to briefly summarise the results pertaining to the stress dependence of steady state creep rate and rupture time in 9Cr-1Mo steel. The steel exhibited separate values of stress exponents in the low and high stress regimes [5,10,11]. Also, distinct values of apparent activation energy were obtained in the two stress regimes. The rationalisation of stress and temperature dependence of creep rate invoking the concept of back/resisting stress suggested that the creep deformation in both the stress regimes occurs by dislocation climb controlled process [5,10]. Two stress regimes are reflected by the distinct values of C_{MG} and C_{MMG} in the low and high stress regimes as shown in Figs. 2 and 3, respectively. The validity of both MGR (eq. 3) and MMGR (eq. 4) also suggest that 9Cr-1Mo steel possesses constant creep ductility. 9Cr-1Mo steel displayed high creep ductility which remains nearly constant for the test durations examined in this investigation [5,11]. Low values of C_{MG} and C_{MMG} obtained for the steel suggest that the contribution of secondary creep strain to the overall creep strain in 9Cr-1Mo steel is relatively small. Further, the values of C_{MG} = 0.05 at low stresses and 0.1 at high stresses also indicate that the secondary creep strain contribution in low stress regime is half of that obtained in high stress regime.

Analogous to MMGR, a relationship involving steady state creep and transient creep parameters has been proposed in the generalised form as

$$\dot{\varepsilon}_s^{\alpha} \cdot \frac{t_{os}}{\varepsilon_T} = \text{constant}, \tag{5}$$

where t_{os} is time to onset of secondary creep i.e., time spent in transient creep and ε_T is the limiting transient creep strain as shown in Fig. 1. It has been shown that the value of a is equal to unity for conditions obeying first order kinetics [3,5] and accordingly eq. (5) takes the form

$$\dot{\varepsilon}_s \cdot \frac{t_{os}}{\varepsilon_T} = \text{constant} = C_{PC}\,. \tag{6}$$

The variation of t_{os}/ε_T as a function of $\dot{\varepsilon}_s$ in Fig. 4 demonstrates the validity of eq. (6) for 9Cr-1Mo steel at 873 K. The variation of t_r/ε_f is also shown in the figure to demonstrate the analogy between MMGR and the proposed relationship involving transient creep parameters. Like MGR and MMGR, separate values of constant C_{PC} = 0.35 and 1.35 are obtained in the low and high stress regimes, respectively, for 9Cr-1Mo steel. On similar lines to eq. (5) and MMGR, another relation involving tertiary creep parameters has been proposed in the generalised form as

$$\dot{\varepsilon}_s^{\alpha'} \cdot \frac{t_t}{\varepsilon_t} = \text{constant}, \tag{7}$$

where t_t is the time spent in tertiary creep and ε_t is the limiting tertiary creep strain as shown in Fig. 1. For conditions obeying first order kinetics, α' is equal to unity [4,7] and eq. (7) takes the form

$$\dot{\varepsilon}_s \cdot \frac{t_t}{\varepsilon_t} = \text{constant} = C_{TC}\,. \tag{8}$$

Figure 5 demonstrates the validity of eq. (8) for 9Cr-1Mo steel at 873 K in addition to the analogy with MMGR. Like MGR, MMGR and the transient creep relation (eq. 6), distinct values of C_{TC} as 0.08 and 0.16 are obtained in low and high stress regimes, respectively.

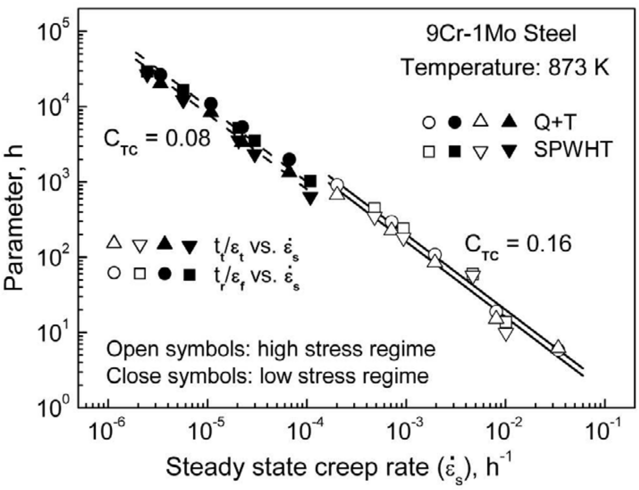

Fig. 5 : Analogy of eq. (8) with MMGR for tests at 873 K illustrating separate values of C_{TC} = 0.08 and 0.16 for low and high stress regimes, respectively

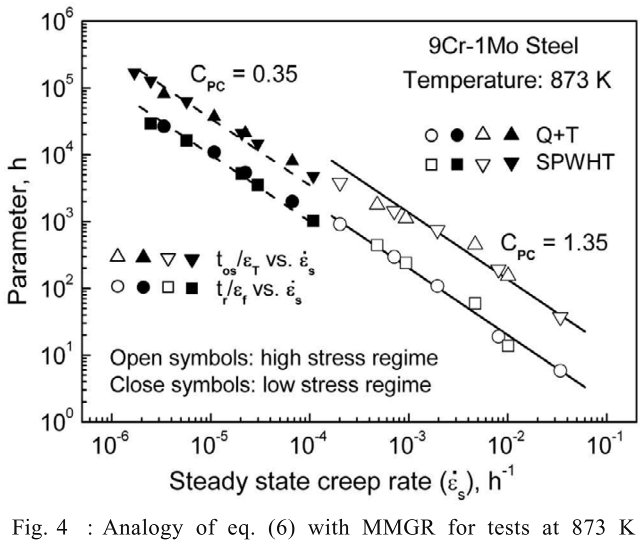

Fig. 4 : Analogy of eq. (6) with MMGR for tests at 873 K illustrating separate values of C_{PC} = 0.35 and 1.35 for low and high stress regimes, respectively

Another relation between rate of exhaustion of transient creep r and time to onset of secondary creep t_{os} is given as

$$r.t_{os} = \text{constant}. \tag{9}$$

The details pertaining to evaluation of r for each ε-t creep curves for different test conditions have been described, elsewhere [5-7] and is briefly given in the following. In the McVetty-Garofalo [12] equation $\varepsilon - \varepsilon_0 = \varepsilon_T [1 - exp(- r.t)] + \dot{\varepsilon}_s.t$, transient creep strain Δ at time t is given as $\Delta = \varepsilon_T [1 - exp(- r.t)]$. In this equation, ε_0 is the initial strain at t = 0 and other terms are already described. The parameter r is obtained as the slope of the straight line in the plot $ln(1 - \Delta/\varepsilon_T)$ vs. t. Further, r is the same as the rate constant in the formulation envisaged for climb controlled first order kinetic process interrelating transient creep and steady state creep proposed by Webster, Cox and Dorn [13]. 'r' is a measure of the rate at which the initial creep rate after loading i.e., at t = 0 decreases and approaches steady state creep rate $\dot{\varepsilon}_s$ at time $t = t_{os}$. r and t_{os} vary with stress and temperature.

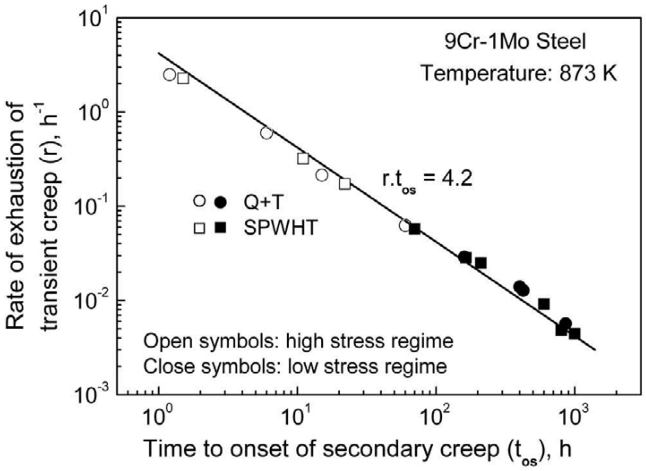

Fig. 6 : Variation of rate of exhaustion of transient creep r with time to onset of secondary creep t_{os} illustrating constancy of $r.t_{os}$ at 873 K.

Figure 6 demonstrates the applicability of eq. (9) with $r.t_{os}$ = 4.2 for 9Cr-1Mo steel in Q+T and SPWHT conditions at 873 K. It is necessary to mention that the analysis of MGR, MMGR, C_{PC} and C_{TC} revealed distinct values for the respective stress regimes. Whereas, it is important to note that the results obeyed eq. (9) as shown in Fig. 6 reveal a single constant value independent of the stress regimes.

A similar relation involving rate of acceleration of tertiary creep p and time spent in tertiary creep t_t is obtained as

$$p.t_t = \text{constant}. \tag{10}$$

Rate of acceleration of tertiary creep 'p' defines the rate at which creep rate increases from steady state value at time $t = t_{ot}$ to final creep rate at fracture i.e., at time $t = t_r$. The determination of p values for each ε-t creep curves has been described elsewhere [5,7] and is briefly given in the following. By treating tertiary creep as inverse of transient creep, remnant strain ε_R is given as $\varepsilon_R = \varepsilon_f - \varepsilon$ (where ε_f is strain to failure) and remnant time t_R as $t_R = t_r - t$. Then, on similar lines to the determination of r, tertiary creep parameter p can be evaluated from the equation $\varepsilon_R = \varepsilon_t\,[1 - exp(-\,p.t_R)] + \dot{\varepsilon}_s.t_R$ as the slope of the straight line in the plot $ln(1 - \Delta'/\varepsilon_t)$ vs. t_R, where $\Delta' = \varepsilon_t\,[1 - exp(-\,p.t_R)]$. The variation of the rate of acceleration of tertiary creep 'p' as a function of time spent in tertiary creep t_t is shown in Fig. 7 demonstrating the applicability of eq. (10) with $p.t_t$ = 6.6 for 9Cr-1Mo steel in Q+T and SPWHT conditions at 873 K. Similar to eq. (9), 9Cr-1Mo steel obeying eq. (10) exhibits a single constant value of $p.t_t$ for both the stress regimes. It may be emphasised that while r and t_{os} as well as p and t_t vary with stress; $r.t_{os}$ and $p.t_t$ are constants independent of stress regimes.

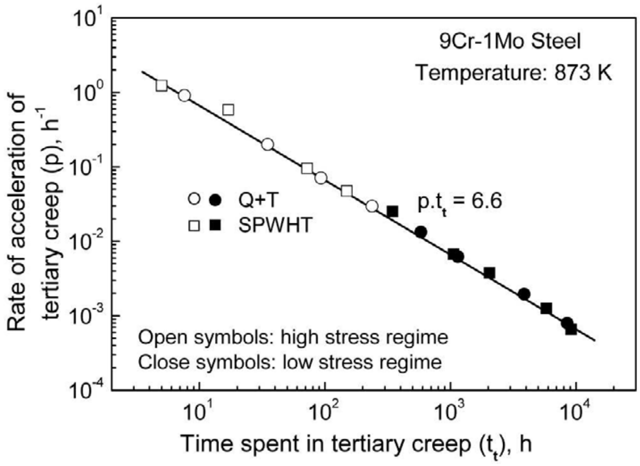

Fig. 7 : Variation of rate of acceleration of tertiary creep p with time spent in tertiary creep t_t illustrating constancy of $p.t_t$ at 873 K.

3.2 Relationship between time to reach Monkman-Grant ductility and rupture time

In the previous section, the similarities between creep rate-time relationships (of Monkman-Grant type) involving transient and tertiary creep parameters, with MGR and MMGR and their applicability have been demonstrated for 9Cr-1Mo ferritic steel. The product of secondary creep rate and time to rupture i.e., $\dot{\varepsilon}_s.t_r = C_{MG}$ is the total secondary creep strain contribution to creep ductility (referred to as Monkman-Grant Ductility or, MGD), and this is the minimum creep ductility that any creeping material possesses. A seminal concept of time to reach MGD i.e., t_{MGD} has been recently introduced (Fig. 1) as the time at which the useful secondary creep strain is exhausted along the creep curve. Further, t_{MGD} is the time at which true tertiary creep sets in and the creep damage attains a critical level [8,9]. Beyond t_{MGD}, accelerated growth of damage leads to failure. In other words, t_{MGD} conceptually divides the creep curve into safe-unsafe regions. Based on this concept and using the continuum creep damage mechanics (CDM) approach [14-18], a creep damage criterion [8,9] applicable for creeping solids has been recently proposed in the form of a relation between t_{MGD} and t_r that depends only on the creep damage tolerance factor λ. It is important to mention that λ is a significant parameter that assesses the susceptibility of a material to localised cracking at strain concentrations [18]. For engineering components, it is also suggested [16] to be a better measure of creep ductility as it is related to the ability of a material to redistribute stresses. The damage tolerance factor λ is defined [16,17] as the ratio of strain to failure ε_f to MGD (Fig. 1) and λ is expressed as

$$\lambda = \frac{\varepsilon_f}{\dot{\varepsilon}_s \cdot t_r} \tag{11}$$

On rearranging, eq. (11) can be written as

$$\frac{\varepsilon_f}{t_r} = \lambda \cdot \dot{\varepsilon}_s \tag{12}$$

The ratio of strain to failure and rupture time (ε_f / t_r) can be defined as average creep rate, and the double logarithmic plot of average creep rate ε_f / t_r vs. steady state creep rate $\dot{\varepsilon}_s$ following eq. (12) gives the value of intercept as λ. On further rearrangement, strain to failure ε_f and tertiary creep strain ε_t is expressed in terms of λ as shown in Fig. 1. A comment on the value of λ indicating a dominant damage mechanism operating during creep is appropriate. Creep damage can occur by various mechanisms such as loss of external cross section (with or without necking), loss of internal cross section (formation, growth and linkage of cavities at grain boundaries), degradation of microstructure (thermal-coarsening of particles, substructure-induced acceleration of creep) and gaseous-environmental attack (internal oxidation, failure of external oxide) [17]. Each damage micromechanism, when acting alone, results in a characteristic shape of creep curve and a correspondingly characteristic value of λ [17]. For example, damage due to growth of cavities by coupled diffusion and power-law creep results in λ values between 1.5 and 2.5, whereas it can be as high as 5 or more when thermal-coarsening of particles causes damage. In the following, creep damage criterion in terms of the relationship between t_{MGD} and t_r is introduced briefly, and its applicability for 9Cr-1Mo steel is demonstrated.

In CDM approach, evolution of creep deformation and damage are expressed in terms of stress, temperature and internal state damage variable by the coupled differential equations [8,18]. Further, upon integrating these coupled equations at constant stress, the relation between strain fraction $\varepsilon/\varepsilon_f$ and time fraction t/t_r in terms of damage tolerance factor λ can be obtained as eq. (13).

$$\frac{\varepsilon}{\varepsilon_f} = 1 - \left(1 - \frac{t}{t_r}\right)^{\frac{1}{\lambda}} \tag{13}$$

Starting with eq. (13) and by substituting the condition that creep strain ε = MGD = $\dot{\varepsilon}_s.t_r$ at $t = t_{MGD}$ in eq. (13) and on rearrangement gives

$$\frac{\varepsilon_t}{\varepsilon_f} = \left(1 - \frac{\dot{\varepsilon}_s \cdot t_r}{\varepsilon_f}\right) = \left(1 - \frac{t_{MGD}}{t_r}\right)^{\frac{1}{\lambda}} \tag{14}$$

For negligible primary creep as shown in Fig. 1, $\varepsilon_t = (\lambda - 1)\dot{\varepsilon}_s.t_r$ and $\varepsilon_f = \lambda(.t_r)$. Substituting ε_t and ε_f in eq. (14) and on rearrangement *'critical damage criterion'* in terms of a universal relationship between t_{MGD} and t_r [8,9] can be deduced as

$$\frac{t_{MGD}}{t_r} = 1 - \left(\frac{\lambda - 1}{\lambda}\right)^{\lambda} = \text{constant} = f_{CDM}\ , \tag{15}$$

or,

$$t_{MGD} = f_{CDM}\ .t_r\ . \tag{16}$$

The detailed formulation of damage criterion is described, elsewhere [8]. The physically based eq. (15) has been called 'critical damage criterion' because damage attains critical value at t_{MGD} when the criterion $t_{MGD} = f_{CDM}.t_r$ is met, whereas t_{MGD} is the time at which damage attains a critical level. By knowing λ value, the theoretical value of f_{CDM} can be evaluated using eq. (15). The proposition that the damage attains a critical level at time $t = t_{MGD}$ is validated for cavitation micromechanism [9]. Based on detailed analysis using the published mechanistic creep data on α-Fe [19], it has been shown [9] that t_{MGD} matches well with time to reach critical cavity size. Beyond t_{MGD}, rapid growth of damage leads to failure [9]. The applicability of the damage criterion has been demonstrated for pure metals and alloys and variety of other materials such ceramics, intermetallics and silicides [9].

Figure 8 shows the variation of average creep rate ε_f/t_r as a function of steady state creep rate $\dot{\varepsilon}_s$ for 9Cr-1Mo steel in Q+T and SPWHT conditions at 873 K. The two stress regimes observed for creep deformation and rupture behaviour [10,11] is also reflected as distinct and constant values of λ = 5 and 10 for high and low stress regimes, respectively. Further, the high values of λ indicate microstructural degradation as the dominant creep damage mechanism operating in the steel. This is in agreement with the observed high creep ductility, absence of typical intergranular creep damage, prolonged tertiary creep in terms of both time and strain fractions, decrease in dislocation density, and coarsening of precipitates and dislocation substructure [11]. Also, high λ value obtained at low stresses compared to that at high stresses suggests higher dominance

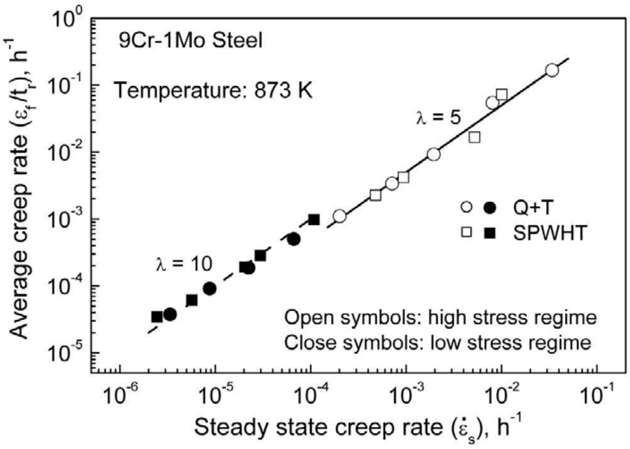

Fig. 8 : Variation of average creep rate with steady state creep rate illustrating constancy of λ at 873 K. Separate values of λ = 10 and 5 are obtained in the low and high stress regimes, respectively.

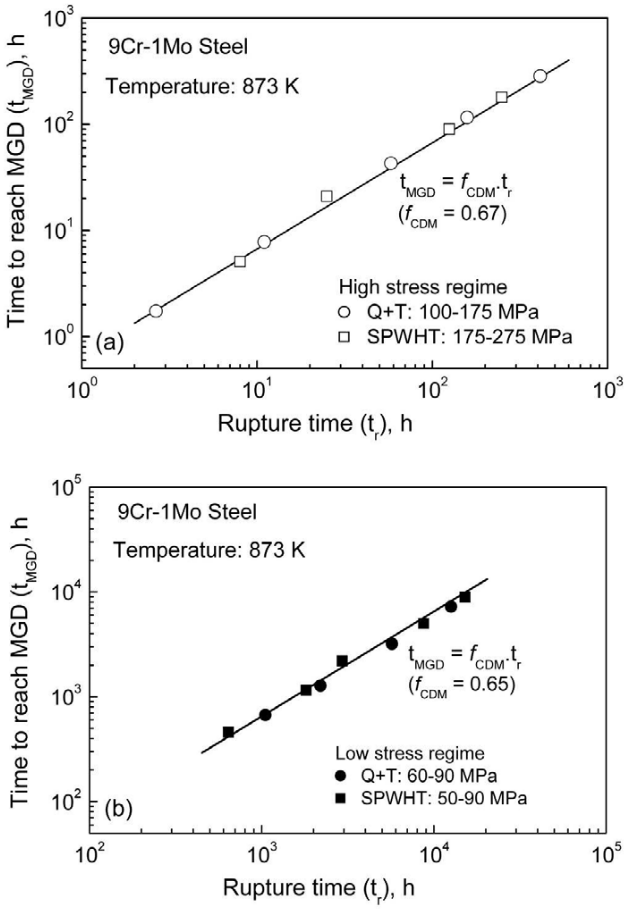

Fig. 9 : Variation of time to reach MGD with rupture time illustrating the validity of eq. (15) for 9Cr-1Mo steel for (a) high and (b) low stress regimes. Solid line is according to eq. (15) with f_{CDM} values calculated using λ = 5 and 10 for high and low stress regimes, respectively. Symbols correspond to experimental data.

of microstructural degradation in the low stress regime than in the high stress regime [11]. The validity of critical damage criterion for 9Cr-1Mo steel in Q+T and SPWHT conditions at 873 K is shown as the variation of t_{MGD} as a function of t_r in Fig. 9a and Fig. 9b for high and low stress regimes, respectively. In Fig. 9, the symbols correspond to the experimental data points and the solid lines are the theoretical lines according to eq. (15) for the respective value of λ i.e., $\lambda = 5$ at high stresses (Fig. 9a) and $\lambda = 10$ at low stresses (Fig. 9b). The calculated values of f_{CDM} determined from $f_{CDM} = 1 - [(\lambda - 1)/\lambda]^{\lambda}$ as $f_{CDM} = 0.67$ at high stresses for $\lambda = 5$ and 0.65 at low stresses for $\lambda = 10$ are given in Fig. 9a and Fig. 9b, respectively.

The creep damage criterion in terms of the relationship between t_{MGD} and t_r has important implications. As mentioned earlier, t_{MGD} conceptually divides the creep curve into safe and unsafe regions and this is something similar to the tensile stress-strain curve, where the plastic instability divides the stress-strain curve into uniform and non-uniform deformation regimes. In other words, it is presumed that the development of damage (irrespective of the type of dominating damage mechanism) is more or less homogeneous till t_{MGD}, and beyond t_{MGD} till failure is the region of localised creep damage. Another important implication is for engineering creep design criterion. Stress to cause rupture in 10^5 h with a factor of safety of 67% is used as one of the criterion to arrive at the design allowable stress intensity limits [20,21]. This factor of safety is employed as a rule of thumb by the material engineers based on the experience. It has been shown [8,9] that t_{MGD}/t_r following eq. (15) decreases with increase in λ and saturates approximately to a value of 2/3 at high λ values. This possibly may provide the physical basis for what is practiced as a rule of thumb. Further, since true tertiary creep damage sets in at t_{MGD} and minimum ductility is assured up to this time, it has been suggested [8,9] that stress to cause t_{MGD} in 10^5 h with proper safety factor can be considered as a useful design criterion for creep of elevated temperature components.

4. Conclusions

Creep rate-rupture time relationships of Monkman-Grant type have been found to be valid for 9Cr-1Mo steel. Like stress dependence of creep rate and rupture life, both Monkman-Grant and modified Monkman-Grant relations (MGR and MMGR) exhibited distinct values of C_{MG} and C_{MMG}, respectively for low and high stress regimes. The validity of MGR and MMGR is a consequence of creep deformation obeying first order kinetics for 9Cr-1Mo steel. On the basis of creep rate-rupture time relationships of Monkman-Grant type, several other creep rate-time relationships involving transient and tertiary creep parameters have been evolved and their validity have been demonstrated. These relationships along with MGR and MMGR not only provide a better understanding of creep behaviour, but also they are useful for reliable extrapolation of creep data. Based on the concept of time to reach Monkman-Grant ductility i.e., t_{MGD} as the time at which damage attains a critical level, a recently introduced creep damage criterion in terms of the relationship between t_{MGD} and t_r is found valid for 9Cr-1Mo steel. The useful implications of this relationship in terms of safe and unsafe regimes and further engineering creep design have been described.

References

1. Monkman F C and Grant N J, *Proc. Am. Soc. Testing Mater.*, **56** (1956) 593.
2. Dobes F and Milicka K, *Metal Sci.*, **10** (1976) 382.
3. Phaniraj C, Nandagopal M, Mannan S L and Rodriguez P, *Acta Metall. Mater.*, **39** (1991) 1651.
4. Phaniraj C, Nandagopal M, Mannan S L, Rodriguez P and Kashyap B P, *Acta Mater.*, **44** (1996) 4059.
5. Choudhary B K, *Tensile, Creep and Low Cycle Fatigue Behaviour of 9Cr-1Mo Ferritic Steel*, Ph. D. Thesis, I. I. T. Bombay, Bombay (1997).
6. Choudhary B K, Phaniraj C, Bhanu Sankara Rao K and Mannan S L, *Key Engineering Materials*, **171-174** (2000) 437.
7. Choudhary B K, Phaniraj C, Bhanu Sankara Rao K and Mannan S L, *ISIJ Inter. Supplement.*, **41** (2001) S73.
8. Phaniraj C, Choudhary B K, Bhanu Sankara Rao K and Baldev Raj, *Scripta Metall.*, **28** (2003) 1313.
9. Phaniraj C, Choudhary B K, Baldev Raj and Bhanu Sankara Rao K, *J. Mater. Sci.*, **40** (2005) 2561.
10. Choudhary B K, Bhanu Sankara Rao K and Mannan S L, *Trans. Indian Inst. Met.*, **52** (1999) 327.
11. Choudhary B K, Saroja S, Bhanu Sankara Rao K and Mannan S L, *Metall. Mater. Trans.* A, **30** (1999) 2825.
12. Garofalo F, *Fundamentals of Creep and Creep-Rupture in Metals*, McMillan, New York (1965).
13. Webster G A, Cox A P D and Dorn J E, *Metal Sci. J.*, **3** (1969) 221.
14. Kachanov L M, *Izv. Akad. Nauk.*, USSR, Otd Tekd Nauk., **8** (1958) 26.
15. Robotnov Y N, *Creep Problems in Structural Members*, North Holland Publ. Co., Amsterdam (1969).
16. Leckie F A and Hayhurst D R, *Acta Metall.*, **25** (1977) 1059.
17. Ashby M F and Dyson B F, in *Advances in Fracture Research*. Eds. S. R. Valluri et al., Vol. 1, pp. 3-30, Pergamon Press, Oxford (1984).
18. Dyson B F and Gibbons T B, *Acta Metall.*, **35** (1987) 2355.
19. Davis P W and Williams K R, *Acta Metall.*, **17** (1969) 897.
20. ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 and Section III, Division 1, Subsection NH (Class I Components in Elevated Temperatures Service), 2001.
21. Woodford D A, in *Materials Selection and Design*, ASM Handbook, ASM Inter., **20** (1977) 573.