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Creep Behavior of Metallic Materials

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Abstract – This paper presents the theoretical aspect of the creep behavior in materials, particularly in metallic materials. Different creep mechanisms were displayed. The main models developed to determine or extrapolate the rupture time of materials were presented. Some real case studies of the creep phenomenon in metallic materials were presented. In addition, to give a more understanding of the creep behavior in metallic materials, the most important results of some selected and recent investigations were also discussed.

Keywords –Creep behavior; Metallic Materials; Mechanism; Rupture;

I. DEFINITION AND THREE STAGES OF THE CREEP BEHAVIOR IN MATERIALS

The creep behavior of a material takes place when a material is subjected to a constant load, even if it is less than the elastic limit of the material.The material deforms continuously with time indefinitely or until rupture. This phenomenon occurs in metals and certain nonmetallic materials, such as thermoplastics and rubbers [1]. The creep can take place over all temperatures above the absolute zero [2]. Generally, the temperature ranges for creep can be subdivided into three categories: first, high temperature creep ($T > 0.6\ T_m$), second intermediate temperature creep ($0.3\ Tm < T < 0.6\ T_m$) and third low temperature creep ($T < 0.3T_m$) where T_m is the absolute melting point of the alloy[3].The creep process is accelerated at high temperatures, because the additional thermal energy activates different mechanisms for creep [4, 5]. However, it is necessary to study the creep behavior of these materials under laboratory conditions. As shown in figure 1a, the creep test is to study the elongation changes of specimen with time at constant temperature and under applied load. The test can be performed using a vertical or a horizontal creep test machine. In both cases, the specimen is held in a constant tensile load and subjected to a constant temperature.Time and elongation (strain) changes are recorded and plotted to get a creep curve (Figure 1b).

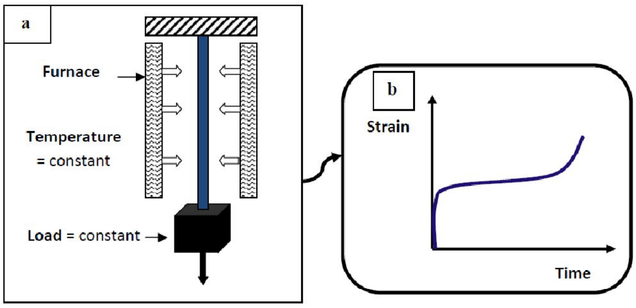

Fig. 1 (a) : Creep test and (b) : a typical recorded and plotted curve obtained from a creep test of material.

Figure 2 presents a typical curve obtained after a creep test of material with some details. There are generally three different stages of creep: primary creep stage, secondary creep stage, and tertiary creep stage. Primary creep stage is transient creep during which the creep rate decreases over time [6]. Then it reaches a secondary creep stage which is called the steady state stage followed by a rapid increase (tertiary stage) and fracture. During a steady-state: strain increases linearly with time, the creep rate is constant, and deformation may continue for a long time. This is the most important regime. In the steady-state stage of the creep, the creep rate $\dot{\varepsilon}$ is given by a simple power law [7]:

$$\dot{\varepsilon} = d\varepsilon/dt = A\,\sigma^{n}\, e^{-Q/RT} \qquad (1)$$

where $\dot{\varepsilon}$ is the steady-state creep rate, ***A*** is a constant for all stresses and temperatures, ***σ*** is the applied stress, *n* is the creep stress exponent, ***Q*** is the apparent activation energy for creep, ***R*** is the universal gas constant, and ***T*** is the absolute creep test temperature. After taking the partial derivative of both sides of equation (1) with respect to ***log σ***, the stress exponent n can be written as equation (2).

$$n = [\,\log\dot{\varepsilon}\ /\log\sigma] \qquad (2)$$

Based on the value of ***n***, the creep mechanism in the material can be defined. For engineering applications, materials subjected to creep process should limit its use in the secondary creep stage and should never reach the tertiary creep stage. Since the secondary creep gives the longest time without failure. The materials with small secondary creep rate as possible are appropriate for engineering applications . Tertiary creep is characterized by an increasing creep rate, and an effective reduction in area of specimen due to necking or void formation (Figure 3). This step of creep is the last stage of creep before rupture occurs [5, 8-11].This is an idealized curve because some materials do not have secondary stage, while tertiary creep only occurs at high stresses and for ductile materials.

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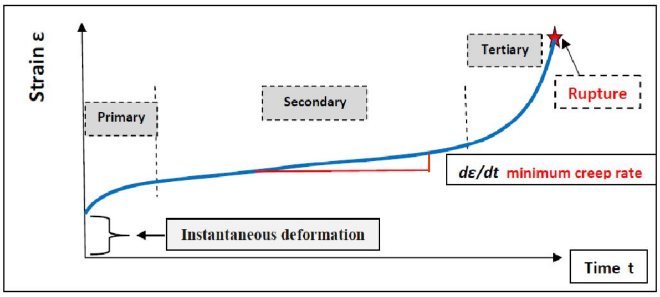

Fig. 2 Typical creep curve.

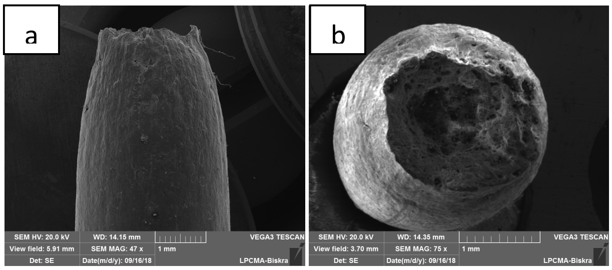

Fig. 3 Observation of specimen after rupture by creep test: (a) longitudinal view shows the necking zone and transverse view shows the voids formation.

II. CREEP MECHANISMS AND CREEP DEFORMATION MAPS

A. *Creep mechanisms*

The understanding of creep deformation mechanisms in materials is crucial in identifying solutions to increase the creep resistance of a material. There are three mechanisms for creep: dislocation creep, diffusion controlled creep, and grain boundary sliding [12].

A.1. Dislocation creep

In this mechanism, creep occurs by dislocation motion, i.e., glide and climb. For the climb-controlled process the simplified creep rate law can be expressed in equation (3) :

$$\dot{\varepsilon} = \Gamma \sigma^{n} \qquad (3)$$

where Γ: constant, and when $n > 1$ we refer to it as power law creep. For climb, n is in the range 4–5; for a glide-controlled process $n = 3$.

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A.2. Diffusion controlled creep

This kind of creep mechanism is due to atomic diffusion. There is no dislocation motion. For Nabarro–Herring creep the creep rate is given by equation (4) *:*

$$\dot{\varepsilon} = \alpha D_L \sigma \Omega / d^2 k T \qquad (4)$$

α a constant, D_L lattice diffusivity, k Boltzmann's constant, T absolute temperature, σ applied stress, Ω atomic volume, d grain size.

A.3. Grain boundary sliding

This mechanism is produced by shear process and promoted by increasing temperature or decreasing strain rate which induce a boundary migration. In this process, grain boundaries slide past one another to cause plastic deformation.

B. *Creep deformation maps*

For a given material, a specific creep mechanism may dominate at certain temperatures and stresses. As example, Figure 4 presents the creep deformation map of pure copper. Several deformation mechanism maps have been constructed for different engineering alloys in recent years.

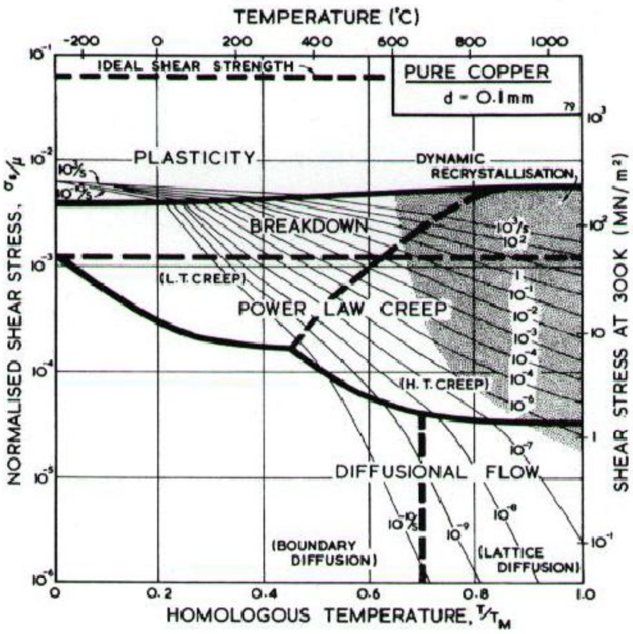

Fig. 4 Creep deformation map of pure copper [13].

III. FACTORS INFLUENCING THE CREEP BEHAVIOR

However, factors influencing the shape of the creep curve depend on the values of the applied stress and temperatures. As illustrated in Figure 5, for constant stress (Fig.5a), the creep curves will shift upward and to the left with increasing temperature. For applied constant temperature (Fig.5b), the creep curves will also shift upward and to the left with increasing the applied stress.

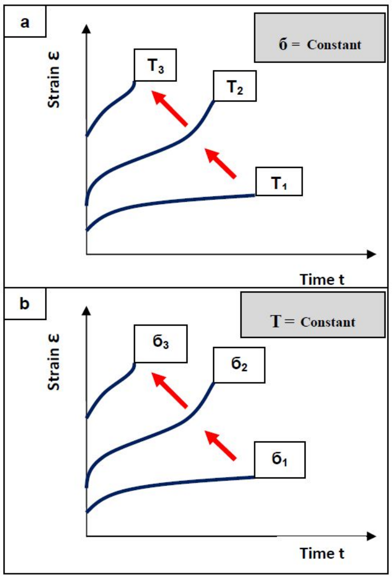

Fig. 5 Schematic representation of the effects of applied stress or temperature levels on the shape of creep curves at a constant temperature or stress respectively.

In addition, to the previous curve, a creep rate and strain curve can be plotted. Figure 6 shows a typical curve of creep rate and strain in a log-log scale. This curve which can be also divided into three stages, where the second stage exhibits a linear relationship of creep rate and strain while the first and third stages shows decreasing and increasing creep rates with strain respectively.

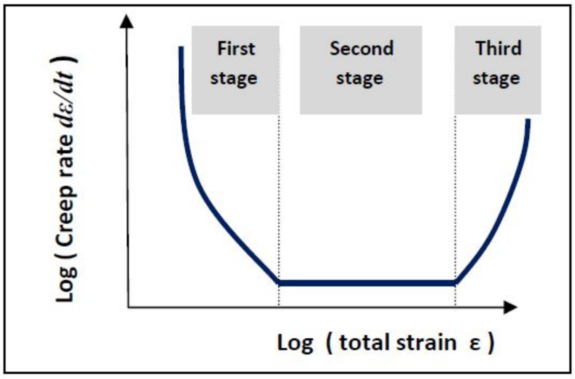

Fig. 6 Creep rate curve versus total strain in a log-log scale.

IV. THEORETICAL MODELS OF EXTRAPOLATION

It is unrealistic to perform creep tests for the exact service life of some engines and machines such as an aircraft which that would take seven to ten years of uninterrupted creep testing for a single test [6]. To gain a time, there is a great variability of models developed for design purposes to determine or extrapolate the rupture time of materials [14]. The most important models are :

A. Larson-Miller Model, MLM

Larson and Miller developed this time-temperature relationship for prediction rupture and creep stresses [14]:

$$T\,(C + \log t_r) = Q/2.3R \qquad (5)$$

This equation (5) can be written:

$$T\,(C + \log t) = P_{L\text{-}M} \qquad (6)$$

Where, **PL-M** is the Larson-Miller parameter, **T** is the absolute creep test temperature, **C** is the Larson-Miller constant, and **t** is time to either creep rupture or to a given creep strain level.

B. Manson-Haferd Model, MMH

However, the Manson-Haferd parameter determines two constants in lieu of the one proposed by Larson and Miller [15]. The Manson-Haferd parameter is:

$$MMH = cte = (\log t_r - \log t_a)/(T - T_a^{*}) \qquad (7)$$

This equation (7) can be written:

$$(T - T_a)/(\log t - \log t_a) = P_{M\text{-}H} \qquad (8)$$

Where, **PM-H** is the Manson-Haferd parameter, **T** is the absolute creep test temperature, T_a is the Manson-Haferd temperature constant, **t** is time, and t_a is the Manson-Haferd time constant. As with the Larson-Miller method, the time can either be the time to creep rupture or the time to a given creep strain level[15].

C. The Degui Model

J. Degui proposed the following model to determine rupture time [14]:

$$\log б = a + b\log t_r \qquad (9)$$

Where, **a** and **b** constants of the Degui model

D. Snedden Model

Snedden proposed the following simplest model to determine rupture time [14]:

$$t_r = A * 10^{bб}$$

V. INDUSTRIAL APPLICATIONS

Creep phenomenon in solids is one of the important topics in the scientific research. Therefore, investigation on the mechanism of the creep phenomena is essential and significant for engineering applications [16]. These two following examples give an idea about creep behavior investigations in two different metallic materials.

A. Selecting appropriate materials for use on the Concorde

The creep properties of candidate aluminum alloys were examined in selecting appropriate materials for use on the Concorde. The alloy finally used, CM.001, was developed to meet the various material properties required, including creep resistance [17].

B. Phenomenology of the creep process of AlMgSi alloy wires for overhead power lines.

One of the aspects of operational behavior of overhead aerial power line conductors is permanent length increases leading to continuous lowering of tension force and as result the conductor being nearer the ground [18]. Generally, AlMgSi alloy is the appropriate candidate to use it as conductor (Fig. 7). Consequently, performing an investigation on the creep behavior of AlMgSi alloy is necessary.

Fig. 7 Creep behavior of overhead aerial power line conductors.

VI. RESEARCH QUESTIONS ON CREEP BEHAVIOR OF METALLIC MATERIALS

The most of the published work of creep phenomenon is devoted to the study of the creep behavior of metallic materials. Table 1 summarizes some selected and recent scientific research on creep behavior of some metallic materials with their research questions and their main findings.

Table 1. Research works on creep behavior of some metallic materials.

Research questions	**Findings**	**Ref.**
Degradation of creep properties at high-temperature of 9–12%Cr power plant steels.	The creep resistance be dramatically deteriorated by the formation of modified Z-phase after long-term creep exposure.	[19]
The creep behavior of 2124 aluminum reinforced with silicon carbide.	The creep stress exponents and activation energies for creep were determined from the experimental data.	[6]
Microstructure and tensile creep behavior of Mg–4Al based magnesium alloys with alkaline-earth elements.	-The improvements on creep resistance are attributed to the formation of interphases -Both grain boundary sliding and dislocation climb contribute to the creep deformation.	[20]
Understand the creep mechanisms in Cu-Al thin wires .	The lifetime depends on the existence of an initial heat treatment and on the applied stress.	[21]
Effect of Fe-rich particles and solutes on the creep behavior of 8xxx aluminum conductor alloys.	The threshold stress increased with increasing FeAl3 particle and Fe solute contents.	[22]
Low-temperature creep behavior and microstructural evolution in 8030 aluminum cables.	-The sizes of a small number of subgrains increase during the creep process - Suggesting that dislocation climb controlled by the grain boundary diffusion is the primary creep mechanism.	[23]
The creep behavior of pure aluminum .	- The creep behavior depends strongly on grain sizes and impurity concentrations -Microstructural observations revealed dislocations emitted from grain boundaries.	[24]
The effect of stress and temperature on the creep damage and ductility of prior plastic deformation of aluminum drawn wire.	- Increasing the stress or temperature shortens the transition creep stage and accelerates the steady creep rate, which was expressed by significant decrease of the lifetime - The damage was observed near the rupture surface by formation of cavities.	[25]
Effect of prior-heat treatments on the creep behavior of an industrial drawn copper.	- The difference of the creep behavior is attributed to the initial microstructure of drawn copper. - The non-heat treated drawn copper has the higher activation energy. - The origin of the fracture is the formation of micropores at the necking zone.	[26]

Based on these selected investigations, some comments can be deduced:

- Creep behavior is one of the mechanical behaviors of ferrous and non-ferrous metallic materials,
- Determination of the creep mechanism in any metallic materials is generally the main objective of any scientific investigation,
- Microstructural aspect of the creep behavior in metallic materials is the core of any investigation, because it confirms the creep mechanism.
- The mathematic aspect of the creep behavior is necessary in some investigation.

VII. CONSIDERATIONS TO AVOID CREEP

It has been reported that to avoid a creep phenomenon in some materials [27], some considerations must be taken into account , such as :

- Reduce the effect of grain boundaries, by :
  - The use of a material with large grains.
  - The addition of solid solutions to eliminate vacancies.
- Employ materials of high melting temperatures.
- Consult Creep Test Data during materials Selection.

VIII. CONCLUSION

Creep is a permanent deformation resulting from an applied stress in a material over a long duration of time. Creep phenomenon may be happened in many structures and materials which can limit the service life of the structures. Creep is normally an undesirable phenomenon and is often the limiting factor in the lifetime of a part. For engineering applications, materials subjected to creep process should limit its use in the secondary creep stage and should never reach the tertiary creep stage. Predicting the creep behavior is very important for designing the materials by applying some theoretical models. Understanding the creep behavior and its mechanisms for these materials is crucial. The microstructural aspect of the creep behavior in metallic materials is the core of any investigation, because it confirms the calculated parameters. To avoid a creep phenomenon or to increase the creep resistance of a material, some considerations must be taken into account.

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