



Basics of Material Creep

An Online Continuing Education Course for Engineers

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1 Preliminary Considerations

In the late 19th Century it has been observed, unexpectedly, that components subjected for long periods of time to elevated temperatures that are below the material's melting point and loaded at high stresses that are below the yield point, could continue to deform irreversibly. This phenomenon has been called "Material Creep." Incidences of material creep can change the geometry of the components so drastically that can lead to sub-standard machinery performance and can even cause component rupture and catastrophic machinery stoppage.

Material creep has been scientifically experimented and described by Andrade in the early 20th Century, with empirical tools, rather than based on a theoretical foundationⁱ. Further understanding has been achieved in the second half of the 20th Century, as engineers have been asked to design machinery for applications that required long life at elevated temperatures and stresses – turbines, turbochargers, steam generators, aerospace devices, internal combustion engines, chemical processing, foundries, and metallurgy, etc.

Having been studied for more than a century, the Materials Creep Theory is now based on a number of theoretical considerations that are supported and enhanced by physical experiments and further validated by numerous real-world applications. The Crystals Dislocation Theory has been shown to be able to quantitatively characterize Creep and has offered several equations that ease the ability to predict the components' life and performanceⁱⁱ. Moreover, the industry has begun to standardize creep methodologies since around the middle of the 20th Centuryⁱⁱⁱ.

This course presents the basics of performance degradation of materials due to creep, from the onset and up to rupture, inhomogeneous and isotropic ductile materials, under steady state loading conditions. Equipped with the knowledge presented in this material, the engineer can:

- design for creep resistance at an acceptable function / load and under a certain thermal regime
- understand a component's life under certain stress and thermal regimes
- design a component that is immune to a failure caused by creep

It is commonly accepted that metals do not "age"... however, under certain temperature and stress regimes that are significantly below any static failure conditions and acting for long periods of time, metal components can still suffer significant degradation of their mechanical and geometrical properties... in other words, metals can "age."

2 Definitions and Assumptions

The "component" represents the part of a machine that helps it provide a useful service. It can be a single part (a continuous piece of material of a tightly controlled shape), an un-separable assembly (such as several parts held together via welding) or an assembly of multiple parts.

The "machinery" represents the set of components assembled together in such a way that it provides one or more useful functions.

The "material" represents the substance that the component under analysis is manufactured. For the purposes of this course, the material is homogeneous, incompressible, and isotropic.

The "M-K-S" designation represents the meter / kilogram / second system of units.

3 The Creep Phenomenon

3.1 Definition of Materials Creep

The Creep Phenomenon in materials has been defined in various ways since its discovery. The original finding in the late 19th Century was that, over time, some structures stressed below their yield point and subjected to elevated temperatures below their melting point developed plastic strain. Later, this understanding has been augmented by the realization that other factors are also affecting this phenomenon: the time of exposure to those conditions, the material properties, and the initial elastic strain. Taking all those into consideration, a general definition of this phenomenon is:

Material creep represents the development of the inelastic strain variation in Components subjected to elevated stresses and temperatures, where the stresses are below the yield point, the temperature is less than the melting point, while those conditions are in effect over a long period of time.

The influence of all those factors to Creep can be mathematically compounded in the following equation:

$$\dot{\epsilon}_C = f_1(t) \cdot f_2(T) \cdot f_3(\sigma) \cdot f_4(\epsilon) \cdot k$$

where:

- $\dot{\epsilon}_C$ is the strain variation
- $f_i(p)$ is the i function ($i = 1 \dots 4$) describing the respective behavior of the parameter "p," as follows:
 - t is the time of exposure
 - T is the exposure temperature
 - σ is the stress developed in the material
 - ϵ is the initial Creep deformation (elastic strain)
- k is a material constant describing the Creep behavior

Particular forms of this equation will be presented in the following material, for each stage of the Creep Phenomenon and for various material responses.

In addition to the above mathematical dependencies, the Creep Phenomenon is exhibiting several characteristics that affect the performance of machinery:

- overall non-linearity: throughout the creep regime, the strain increase is usually non-linear with time
- irreversibility: this phenomenon is irreversible^{iv}
- dynamic effects: dynamic loads amplify the creep effects^v
- variation in utility: while generally unwanted, moderate creep is beneficial in some situations (such as for some concrete structures), as it relieves tensile stresses that would otherwise lead to breakage^{vi}

3.2 Homologous Temperature

Engineers have adopted the Homologous Temperature concept to describe the point at which materials become susceptible to creep. The Homologous Temperature is the temperature at which creep begins to occur, represented as a fraction of the material's melting point, in Kelvin. Note that while this quantity is often referred to as a decimal number (such as 0.4), it is in actuality, and implicitly a temperature, (such as $0.4 T_{mp}$).

$$T_H = \frac{T_c}{T_{mp}} (\%), \text{ or: } T_H = \frac{T_c}{T_{mp}} (\%) \cdot T_{mp}, \text{ where:}$$

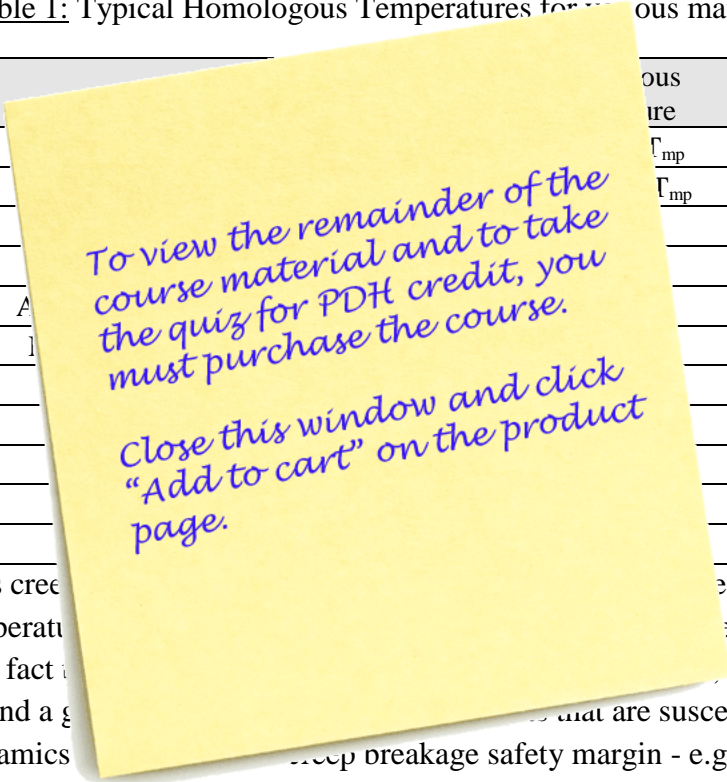
- T_H is the Homologous Temperature
- T_c is the temperature where Creep begins to occur, in Kelvin
- T_{mp} is the melting point of the material, in Kelvin

While creep typically occurs at elevated absolute temperatures, this is not always the case. Some metals (such as Solder), asphalt, concrete, and some plastics exhibit creep at room temperatures, as they have low melting temperatures, while others exhibit creep at even lower temperature – ice for example.

The following table shows typical Homologous Temperatures for various materials used by engineers^{vii}:

Table 1: Typical Homologous Temperatures for various materials

Material	Homologous Temperature
Aluminum	0.3
Steel	0.4
Concrete	0.5
Asphalt	0.6
Plastic	0.7
Solder	0.8
Ice	0.9



Note that in metals creep occurs at high temperatures because they show low Homologous Temperature relative to their melting point... this, combined with the fact that metals are ductile makes them highly resistant to creep and a good choice for structural applications that are susceptible to creep. The flip side is that ceramics are brittle and have a low creep breakage safety margin - e.g., once in creep