

ANELASTIC COMPONENT OF CREEP DEFORMATION

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ABSTRACT

There are several different sources of deformation at high temperature in response to an applied stress. Process of creep deformation involves three components of deformation. The first component is elastic deformation that is directly proportional to stress, and modulus that is temperature dependent can be determined. The second component is time-independent non-recoverable plastic deformation that is major source of creep deformation for all materials. The third component is time-dependent recoverable anelastic deformation that is not widely studied, but may become very important under non-steady conditions. Anelastic component of deformation is related with distribution of internal stresses that may relax resulting in the phenomenon of creep recovery. There are strong indications that anelastic phenomena should be included in design consideration.

Keywords: Creep, creep recovery, anelastic deformation

1. INTRODUCTION

The mechanism of plastic deformation is essentially different in crystalline materials and amorphous materials. Crystalline materials undergo plastic deformation as the result of slip along definite crystallographic planes whereas, in amorphous materials, plastic deformation occurs when individual molecules or group of molecules slide past one another.

Many materials, when stressed beyond a certain minimum stress, show a permanent, nonrecoverable deformation. This is called plastic deformation, and it is the result of permanent displacement of atoms or molecules or groups of atoms and molecules from their original positions in the lattice. The displaced atoms and molecules do not return to their original positions after the removal of stress. If the material subjected to a constant load of a sufficient magnitude shows a continuously increasing deformation, the phenomenon is called flow.

The flow is a characteristic phenomenon of liquids and gases that deform immediately when subjected to a shearing stress. But many solids, even those of crystalline nature, exhibit flow if they are subjected to high enough stress for a sufficiently long time.

2. CREEP AND CREEP RECOVERY

Creep can be defined as the slow and progressive deformation of a material with time under a constant stress. The phenomenon of creep is observed in metals, ionic and covalent crystals, and amorphous materials such as glasses and high polymers. Metals usually exhibit creep at temperature $T \geq 0.4 T_m$, where T_m is the melting point of the metal concerned in absolute temperature. Amorphous materials such as plastics and rubbers are very temperature-sensitive to creep, [1].

After the initial elastic deformation, there are three stages of creep deformation, Figure 1:

- The primary stage is characterized by a decreasing strain rate. The relatively rapid increase in deformation induced during this early time period is the direct result of enhanced deformation mechanisms. A common example for metal alloys is dislocation climb, and this enhanced deformation comes from thermally activated atom mobility, giving dislocations additional slip planes in which to move.
- The secondary stage of creep deformation is characterized by constant strain rate. In this stage, the increased ease of slip due to high-temperature mobility is balanced by increasing resistance to slip due to the buildup of dislocations and other microstructural barriers.
- In the final tertiary stage, strain rate increases due to an increase in true stress. This increase results from cross-sectional area reduction or internal cracking. In some cases, fracture occurs in the secondary stage, thus eliminating this final stage, [2].

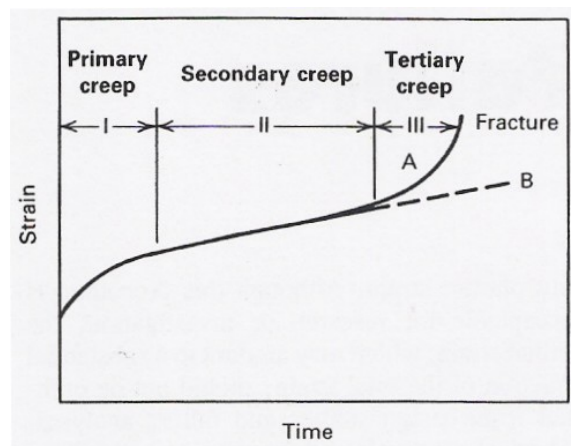


Figure 1. Schematic creep curves, [3]:
curve A constant-load test, curve B constant-stress test

At high temperatures, the application of a stress leads to creep deformation resulting from the motion of dislocations, mass transport by diffusion, or grain-boundary sliding. These processes in turn lead to a distribution of internal stresses that may relax on removal of the stress. This relaxation leads to a time-dependent contraction in addition to the elastic contraction and results in the phenomenon of creep recovery illustrated in Figure 2.

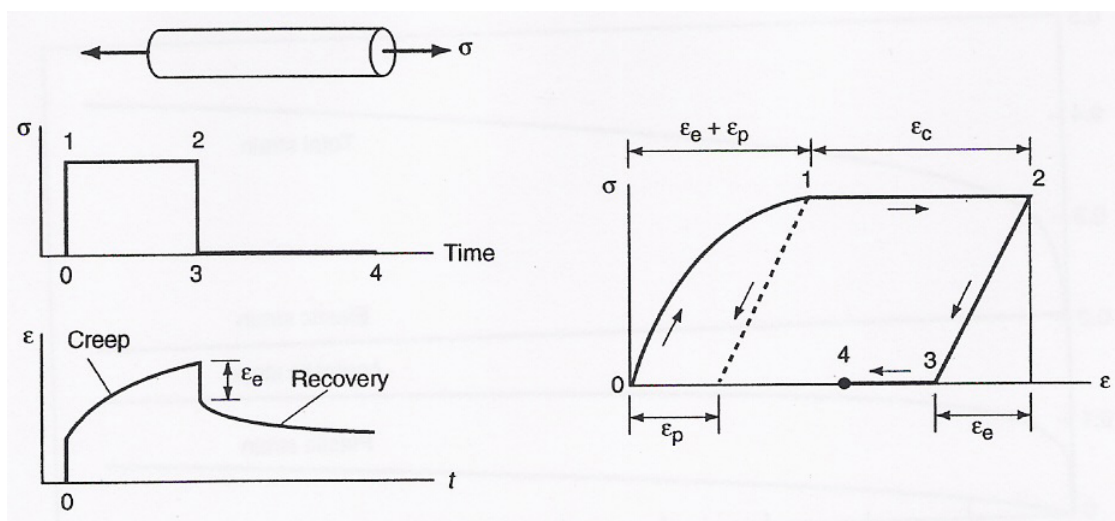


Figure 2. Stress-time step applied to a material exhibiting strain response that includes time-independent elastic, time-independent plastic, time dependent creep, and time-dependent anelastic (creep recovery) components, [4]

In polymers this phenomenon is termed viscoelastic recovery and is associated with the viscous sliding and unknicking of long molecular chains. In metals it is associated with the unbowing of pinned dislocations, rearrangement of dislocation networks, and local grain-boundary motion. In ceramics it appears to be primarily a grain-boundary phenomenon.

Whereas the importance of creep recovery is well recognized in polymer design, it has often been ignored in design of metallic and ceramic materials. A few extensive studies have been reported on metals that have led to several broad conclusions, [4]:

- Creep recovery strain increases linearly with stress for a fixed time at a given temperature, but is dependent on prestrain.
- The rate of creep recovery increases with increasing temperature.
- When the stress is low enough, essentially all transient creep is linear with stress and recoverable.
- Mathematically, the recovery may be described by a spectrum of spring dashpot combinations with a wide range of relaxation times.

3. COMPONENTS OF CREEP DEFORMATION

There are several different sources of strain at high temperature in response to an applied stress. The elastic strain is directly proportional to stress, and a modulus that is temperature dependent can be determined. For metallic materials and ceramics, although there is a strain-rate dependence of elastic modulus, it is small and often ignored. For polymers, by contrast, the elastic modulus is ill defined because of viscoelasticity.

Plastic strain for all materials may be treated as three separate constituents:

- Time-independent nonrecoverable, which may be thought of as an instantaneous deformation that is unlikely to be significant in practical applications except in the region of stress concentrations since loading is normally well below the macroscopic yield stress.
- Time-dependent nonrecoverable, that is the major source of creep deformation.
- Time-dependent recoverable, that is not widely studied or analyzed, but may become very important at low stresses and under nonsteady conditions, that is, high-temperature service. It leads to what has been termed recovery and anelasticity.

Assuming that the measured recovery strain after unloading had made an equivalent contribution to forward creep, it was possible to separate the anelastic and plastic creep components as shown in Figure 3.

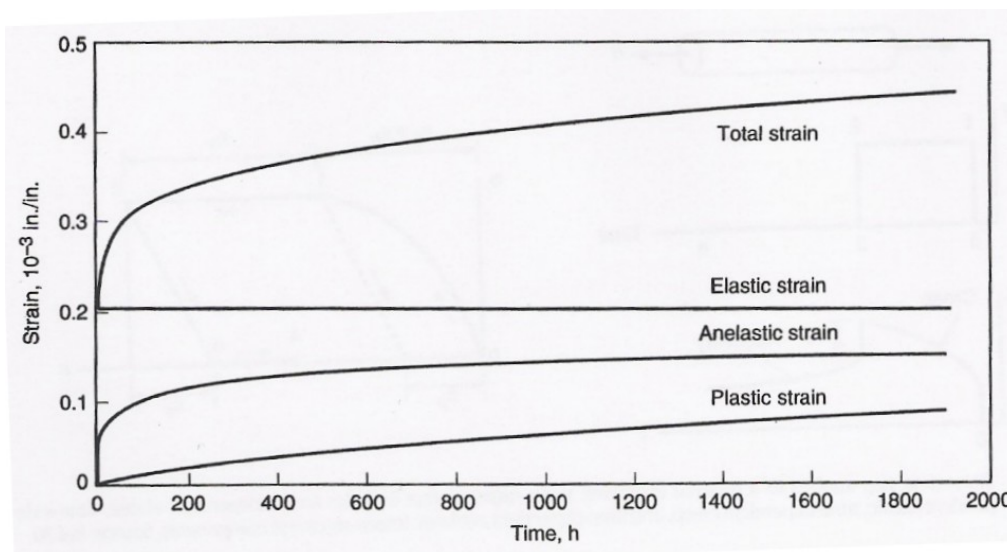


Figure 3. The separation of strain components for a creep test on Cr-Mo-V steel at 538 °C and 35 MPa, [4]

Because the anelastic component is linear with stress and the plastic component is a power function of stress (for the same time), at very low stresses the strain is entirely anelastic. This observation led to the definition of a plastic creep limit that was time dependent. For times up to 100 h in low-alloy steel tested at 425 °C it was found this limit to be 140 MPa; all creep below this stress was fully recoverable. In tests on a similar alloy at 538 °C it was found that the creep limit ranged from 150 MPa for 1 h to zero at 5000 h, [4].

Anelasticity may arise because of the diffusion of thermal energy or interstitial atoms or substitutional solute atoms, or because of grain boundary effects, dislocations, and thermal currents within crystal. This effect is also a result of retarded elasticity and is called the elastic aftereffect or anelastic effect, [1].

4. FINAL REMARKS

Time-dependent deformation and fracture of structural materials at elevated temperatures are among the most challenging engineering problems faced by materials engineers. In order to develop an improved design methodology for machines and equipment operating at high temperatures, several key concepts and their synergism must be understood. These include:

- Plastic instability at elevated temperatures,
- Deformation mechanisms and strain components associated with creep processes,
- Stress and temperatures dependence,
- Fracture at elevated temperatures, and
- Environmental effects.

There are strong indications that anelastic phenomena should be included in design considerations. Anelastic contraction as well as extension can occur depending on whether the stress is decreased or increased, whereas plastic shortening never occurs. Although several authors have pointed out that, because of the linear stress dependence the analysis should be much simpler than for plastic creep analysis, accurate measurements at the low stresses of interest for service applications are difficult. The possible link with fracture processes is also of great interest, but neither consideration has influenced design practice

5. REFERENCES

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