

## CREEP of MATERIALS

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### LIST OF SYMBOLS

<u>Symbol</u>		<u>Units</u>
A, B, C	Constants	-
E	Activation energy for creep	kJ/mol
k	Time exponent (polymers)	-
m	Stress exponent (polymers)	-
n	Stress exponent (metals)	-
R	Universal gas constant	J/mol K
t	Time	s
T	Absolute Temperature	K
$\alpha$	Constant	-
$\epsilon$	Strain	-
$\epsilon_0$	Initial (elastic) strain	-
$\dot{\epsilon}$	Creep rate (Strain rate)	S <sup>-1</sup>
$\sigma$	Stress	N/mm <sup>2</sup>

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## 1.0 INTRODUCTION

When a material like steel is plastically deformed at ambient temperatures, its strength is increased due to work hardening. This work hardening effectively prevents any further deformation from taking place if the stress remains approximately constant. Annealing the deformed steel at an elevated temperature removes the work and restores the steel to its original condition. However, if the steel is plastically deformed at an elevated temperature, then both work hardening and annealing take place simultaneously. A consequence of this is that steel under a constant stress at an elevated temperature will continuously deform with time, that is it is said to "creep".

Creep in steel is important only at elevated temperatures. In general creep becomes significant at temperatures above about  $0.4 T_m$  where  $T_m$  is the absolute melting temperature. However, materials having low melting temperatures will exhibit creep at ambient temperatures. Good examples are lead and various types of plastic. For example, lead has a melting temperature of  $326^\circ\text{C}$  ( $599\text{K}$ ), and at  $20^\circ\text{C}$  ( $293\text{K}$  or about  $0.5 T_m$ ), it exhibits similar creep characteristics to those of iron at  $650^\circ\text{C}$ .

The SM106 MkII Creep Measurement Apparatus is a simple unit designed for demonstrating and investigating the creep characteristics of lead and polypropylene specimens at room temperature. A temperature module is provided to enable investigation of the effects of temperature on creep rate.

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## 2.0 THEORY

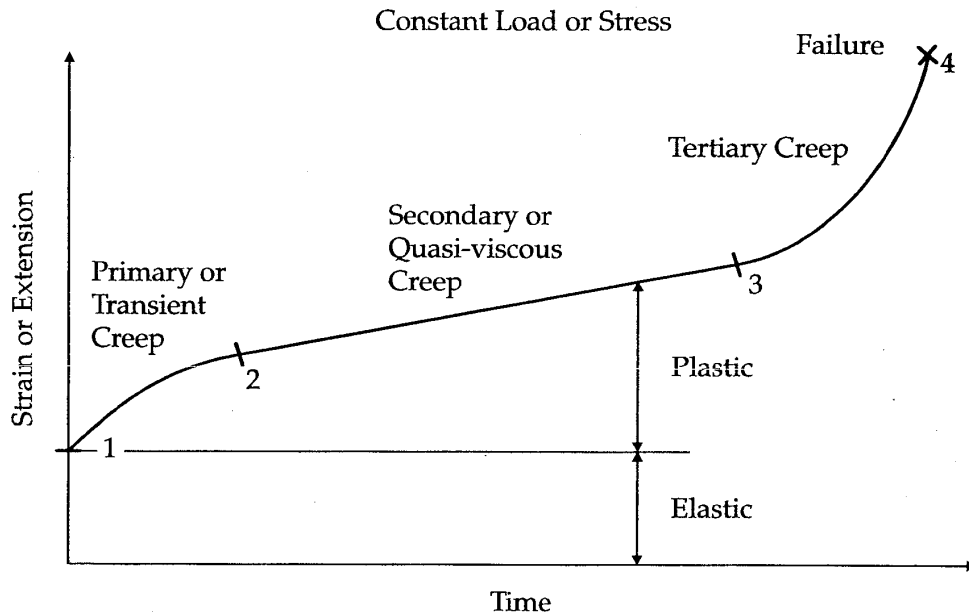


Figure 2.1 Typical Extension-Time Curve

### 2.1 Creep in Metals

A creep test is carried out by applying a constant load to a specimen and observing the increase in strain (or extension) with time. A typical extension-time curve is shown in Figure 2.1. Three regions can be readily identified on the curve:

- 1 to 2 **Primary Creep** - creep proceeds at a diminishing rate due to work hardening of the metal.
- 2 to 3 **Secondary Creep** - creep proceeds at a constant rate because a balance is achieved between the work hardening and annealing (thermal softening) processes.
- 3 to 4 **Tertiary Creep** - the creep rate increases due to necking of the specimen and the associated increase in local stress. Failure occurs at point 4.

In terms of dislocation theory, dislocations are being generated continuously in the primary stage of creep. With increasing time, more and more dislocations are present and they produce increasing interference with each

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others movement, thus causing the creep rate to decrease. In the secondary stage, a situation arises where the number of dislocations being generated is exactly equal to the number of dislocations being annealed out. This dynamic equilibrium causes the metal to creep at a constant rate. Eventually, however, the creep rate increases due to localising necking of the specimen (or component), void and microcrack formation at the grain boundaries, and various metallurgical effects such as coarsening of precipitates.

When in service, an engineering component should never enter the tertiary stage of creep. It is therefore the secondary creep stage which is of prime importance as a design criterion. Components which are subject to creep spend most of their lives in the secondary stage, so it follows that the metals or alloys chosen for such components should have as small a secondary creep rate as possible. In general it is the secondary creep rate which determines the life of a given component.

Secondary creep rate for a particular metal or alloy depends on several variables, the most important of which are stress and temperature. The most commonly used expression for relating secondary creep rate  $\dot{\epsilon}$  to stress  $\sigma$  and absolute temperature T has the form:

$$\dot{\epsilon} = A \sigma^n e^{-E/RT} \quad (2.1)$$

where:

A and n are constants

E is the activation energy for creep in the metal

and R is the universal gas constant (8.31 J/mol K)

The equation shows that the creep rate is increased by raising either the stress or the temperature. Taking natural logarithms gives:

$$\ln \dot{\epsilon} = \ln A + n \ln \sigma - \frac{E}{RT} \quad (2.2)$$

Thus for tests at constant temperature and varying stress, the stress exponent n can be found by plotting  $\ln \dot{\epsilon}$  against  $\ln \sigma$ . Alternatively, if the stress is kept constant and the temperature varied, E can be determined by plotting  $\ln \dot{\epsilon}$  against  $1/T$ . For the special case of lead, the stress exponent n has a value of about 10 for the relatively high levels of stress used in the SM106 MkII apparatus, and the activation energy E is approximately 120 kJ/mol.

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Most metals have a stress exponent of about 5 and this value is also applicable in the case of lead, but only when the stress is below about 5 N/mm<sup>2</sup>. At higher stress levels the exponent  $n$  increases to about 10, and eventually the simple power law of Equation 2.2 ceases to apply. Instead an exponential expression more adequately fits the experimental data:

$$\dot{\epsilon} = B e^{\alpha\sigma} e^{-E/RT} \quad (2.3)$$

where  $B$  and  $\alpha$  are constants.

A plot of  $\ln \dot{\epsilon}$  against  $\sigma$  will therefore yield a straight line of slope  $\alpha$ . If the stress is in units on N/mm<sup>2</sup> (or MN/m<sup>2</sup>) the value of  $\alpha$  is approximately 0.8 to 0.9 and also varies somewhat with stress level.

The fact that exponents  $n$  and  $\alpha$  vary with stress demonstrates the inadequacy of simple laws for correlation of data over a wide range of stress levels. In practice, more complicated equations are used to correlate experimental data. For our purposes however, it is sufficient to use either of the Equations 2.1 and 2.3 since the resulting plots are very nearly linear for the stress levels normally obtained with the SM106 Mk II apparatus. In this manual, the power law of Equation 2.1 is used in the analysis of results.

### 2.2 Creep in Plastics

Plastics also creep at ambient temperatures but, compared to lead, they are able to sustain much greater extensions before failure. The creep curves are similar in shape to those for metals, but the mechanism of deformation is quite different because of the difference in structure of the material. A polymer consists of long chain-like molecules in a tangled and coiled arrangement; creep occurs by chains untangling and slipping relative to one another. The creep rate is still dependent on stress and temperature but Equations 2.1 and 2.3 no longer apply.

The complex processes taking place during creep make it difficult to quote an equation that describes the creep behaviour of all polymers. Many empirical equations have been proposed and one which applies to some of the common engineering plastics has the form:

$$\epsilon = \epsilon_0 + B \sigma^m t^k \quad (2.4)$$

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where  $\epsilon$  is the tensile creep strain after a time  $t$ ,  $\sigma$  is the applied creep stress,  $\epsilon_0$  is the instantaneous or initial strain produced on loading, and  $B$ ,  $m$ ,  $k$  are constants for a given polymer. The elastic component of the initial strain can be calculated by dividing the creep stress by the tensile modulus of the polymer, which for polypropylene is 1250 N/mm<sup>2</sup>. In many polymers this initial strain is very small and can be ignored, so that in these cases:

$$\epsilon = B \sigma^m t^k \quad (2.5)$$

A plot of  $\log \epsilon$  against  $\log t$  will therefore be linear, and the slope will give the value of the exponent  $k$ . Values of  $k$  quoted in the literature range from 0.025 to 0.33. For polypropylene,  $k$  is in the range 0.1 to 0.2 and tends to increase with stress level.

In cases where the stress exponent  $m$  is close to unity we have the situation where  $\sigma/\epsilon$  is a constant as  $k \rightarrow 0$ , in other words the material is behaving in an elastic manner. Alternatively with high values of  $k$ , say  $k \rightarrow 1$ , then  $(\sigma/\epsilon)$  is a constant and the material is behaving as a viscous fluid. The value of  $k$  obtained from creep data is therefore a measure of the relative contribution of elastic and viscous deformation to the creep process.

Finally, it should be noted that with polymer materials the primary creep stage, where the creep is decreasing, is largely recovered when the creep load is removed. This behaviour is unlike that observed in most metallic systems, and the effect can be easily demonstrated using the SM106 MkII apparatus by removing the load after the polymer has been creeping for 7 to 15 minutes, and continuing to take strain readings. It will be found that the elastic strain is removed instantaneously, but that further recovery of strain takes place over a period of several minutes. This time dependent effect is due to recovery of the visco-elastic component of the creep strain. For the stress levels used in the SM106 MkII apparatus (typically 19 N/mm<sup>2</sup>), approximately 40% of the creep strain is recovered after 5 minutes.

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## 3.0 DESCRIPTION OF APPARATUS

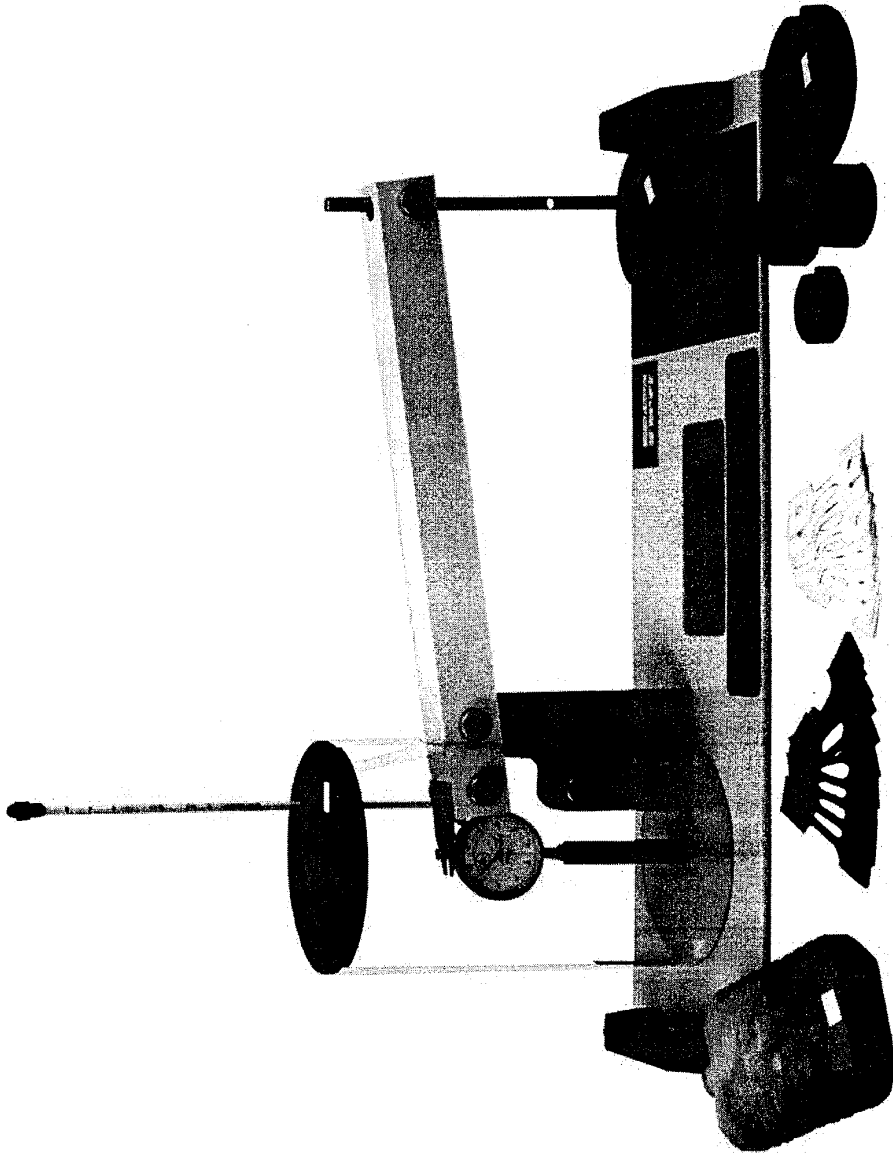
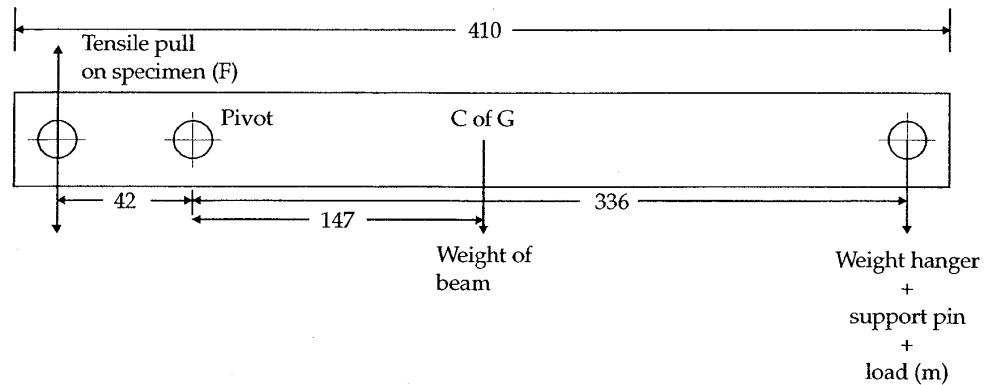


Figure 3.1 Components of the SM106 Mk II Apparatus

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**Figure 3.2 Details of the Lever Arm**

The SM106 MkII Creep Measurement Apparatus, illustrated in Figure 3.1, uses a simple lever to apply a steady load to the specimen. The specimen is attached at one end to the lever mechanism by a steel pin and fixed at the other end to the bearing block by another steel pin. To prevent deformation of the specimen fixing holes, of the polymer specimens, during test, two 'U' brackets are provided.

Loads are applied to the lever arm by placing weights on the weight hanger, which is pinned to the lever arm. The weight hanger has two pinning positions: the uppermost is used to pin the hanger in the rest position whilst the lower hole is used to pin the hanger in the loaded position.

The lever arm has a mechanical advantage of 8. The mass of the arm is 0.367 kg, the weight hanger mass is 0.16 kg, and the pins used for pinning the weight hanger and specimen are 0.04 kg each. The load on the specimen can be found by taking moments about the pivot bearing as illustrated in Figure 3.2. If a mass  $m$  is added to the weight hanger then the tensile pull on the specimen ( $F$ ) is:

$$F = (2.84 + 8m) g \text{ Newtons} \quad (3.1)$$

where  $g$  = acceleration due to gravity

**Note: The mass  $m$  does not include the mass of the hanger: this is included in the constant 2.84.**

The specimen extension is measured by a dial test indicator (DTI). A tube fixed to the bearing block is the housing for the DTI and a nylon pinch screw is used to restrain the DTI under steady load conditions. The top of the DTI is attached to the lever mechanism by means of a grooved plate which is bolted



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to the lever arm. The arrangement is such that the groove in this plate is twice the distance from the pivot than that of the centre of the specimen. Therefore the extension given by the DTI is twice the extension of the specimen. It will undoubtedly have been noted that the geometry of the system, whilst permitting vertical movement of the DTI mechanism, constrains the extension of the specimen to follow a path which is the chord of a circle, whose centre is the pivot and whose radius is the distance between the pivot and the centre of the specimen pin on the beam. Hence the true extension of the specimen is not exactly half of the extension indicated by the DTI; however, as the maximum angle through which the beam pivots is only 20% the maximum error in extension should be less than 1.5%.

It should be noted that when zeroing the DTI, the nylon pinch screw should only be tightened finger tight, i.e. just sufficiently to prevent the DTI sliding upwards when under steady load. Over tightening could cause damage to the DTI when the specimen breaks.

Tests can be carried out above and below room temperature by using the perspex encapsulation, which houses a thermometer, and the cold pack. Low temperatures can be obtained by placing the cold pack in the freezer compartment until the pack is frozen (usually 2 hours). Higher temperatures are achieved by immersing the pack in hot water for 15 - 20 minutes. Note that the water temperature **MUST NOT EXCEED 70°C** to avoid damaging the pack. To conduct a test, above or below room temperature, the pack is placed to the rear of the bearing block close to the specimen. Once the DTI has been zeroed the perspex encapsulation can be fitted. Before starting the test allow 10 to 15 minutes for the temperature inside the encapsulation to stabilise. Once stabilised the temperature should remain relatively constant for at least 30 minutes when hot and considerably longer when cold.

The use of perspex encapsulation and cold pack is primarily designed for use in demonstrations; however, when used with care, quantitative tests can be carried out. When conducting a quantitative test, it is important to note that the thermometer does not indicate the true specimen temperature. The only sure way of obtaining the specimen temperature is to attach a temperature sensor to the specimen. A thermocouple attached to the bottom of the specimen with tape (to ensure a good thermal contact, a small quantity of heat sink compound should also be used) can be used successfully.