

Behaviour of Metals
at Elevated Temperatures



BEHAVIOUR OF METALS AT ELEVATED TEMPERATURES

*LECTURES DELIVERED AT THE INSTITUTION
OF METALLURGISTS REFRESHER COURSE, 1956*

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FOREWORD

THE present volume contains the full text and illustrations of the lectures delivered at the tenth Refresher Course held in Llandudno in October, 1956. These Courses have now become a firmly established event in the Institution's year and are attracting an increasing number of members each year.

The selection of subjects for the Refresher Course is a matter to which Council gives most careful consideration and the interesting discussion that followed the present series of lectures indicated how wide was the interest they aroused. Council desires to record its appreciation to the lecturers for the not inconsiderable amount of work that was involved in the preparation of the papers. The book makes a valuable contribution to the subject which fully maintains the high reputation of the Institution's Refresher Courses.

G. L. BAILEY
President

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**THE ENGINEERING PROPERTIES OF
METALS AT HIGH TEMPERATURES**

DR. N. P. ALLEN, F.R.S.

THE ENGINEERING PROPERTIES OF METALS AT HIGH TEMPERATURES

FOR the purposes of this book, the engineering properties of metals are defined as those properties which must be taken into account by an engineer in designing a component to withstand the mechanical and thermal stresses to which it will be exposed and the chemical attack of its surroundings. Such properties as thermal conductivity which may be of great importance to the physical duty of the component, when, for example, it is used as a medium for the transfer of heat, are excluded except in so far as they are concerned in the mechanical behaviour of the component as part of a structure. Castability and forgeability are also excluded, for these only influence the way in which the component is made and not the way in which it behaves subsequently. For the same reason weldability and machinability are excluded, though no practical engineer is likely to forget that all components have to be machined and many have to be welded. The engineering properties of welds and of castings are, however, well within the scope of the book.

The properties for consideration include:

- (1) Stability of physical properties and dimensions.
- (2) Elastic constants and coefficients of expansion.
- (3) Resistance to plastic deformation and fracture under constant stress, and the effect of complex stresses.
- (4) Behaviour under fluctuating stresses.
- (5) Behaviour under fluctuating temperature.
- (6) Resistance to chemical attack, with or without simultaneously applied stress.

In this Paper, the effect of high temperature on these properties is discussed generally, in such a way as to prepare for the more detailed descriptions of the properties of individual materials in subsequent chapters.

Stability

Most metals and alloys are reasonably stable at room temperature although they may be very far from a condition of thermodynamic stability. When the temperature is raised they may return gradually to a condition of stability, or phase changes may occur in them as some boundary in their phase diagram is crossed. The changes are accompanied by changes of dimensions or of mechanical properties. Changes of dimensions are almost always undesirable as they lead to distortions. Changes of properties are not necessarily unfavourable but they generally lead either to weakening or to embrittlement, and it is best that materials for use at high temperature should undergo no extensive change either during prolonged heating at the service temperature, or during heating and cooling.

Two examples may be given of cases in which the lack of structural stability has been a cause of avoidable trouble. In the manufacture of ferritic steels, the too liberal addition of aluminium for deoxidation and grain refinement can produce a material in which the cementite decomposes during prolonged heating at 400-450°C. This results in loss of strength and failures at welds in steam power plant have been traced to this cause. High-chromium ferritic oxidation-resistant steels and some high-chromium austenitic steels may at temperatures of 600-700°C undergo a change whereby a hard and brittle phase, the sigma phase, is formed. The presence of a little of this phase is relatively harmless, but too much of it can make the material so brittle that it falls to pieces at the slightest shock.

An interesting case of lack of stability arises in uranium. The trouble is caused not by any structural change of the material but by the peculiar thermal expansion of the crystal. Alpha uranium has a layered lattice and the coefficient of expansion is quite normal in the two directions parallel to the layers. Across the layers the coefficient of expansion is negative. In a polycrystalline mass during heating and cooling, high stresses are set up between crystals in contact, some of which are trying to expand in a given direction, and others to contract. Plastic deformation occurs with every appreciable change of temperature and, as this is repeated, a bar may grow continuously in length and contract in diameter.

Another type of instability arises in metals subject to intense radiation. Nuclear reactions may result in the production of inert

gases or of new atomic species that have significant effects on the mechanical properties. The nuclear reactions are not themselves influenced by temperature but their effects may become apparent in certain temperature ranges. This is a subject of great importance to nuclear engineers but fortunately not to others. Radiation also affects the properties of metals by displacing a proportion of atoms from their mean positions but metals in general, and especially at high temperature, have a great capacity for recovering from this kind of damage, and its practical importance is quite limited and not so great as was feared at one time.

Elastic Constants and Coefficient of Expansion

The elastic constants and coefficient of expansion are important in calculating the changes of shape and dimensions arising from changes of temperature and stress. Both change continuously on heating, the elastic constants falling, and the coefficient of expansion rising, these two changes being fundamentally related to each other and both arising from the general loosening of the structure. The changes over the ranges of temperature experienced in practice are sufficiently large to make it necessary to take them into account, but not so great as to alter appreciably the characteristics of the metal. Departures from this behaviour are a sign of structural changes in the material. Sudden and marked alterations of elastic constants are not common, but peculiarities of coefficient of expansion are familiar and are generally due to structural changes giving rise to a change of density. They are as a rule temporary and disappear when the structural change is complete.

Plastic Deformation and Creep

More important than the effect of temperature upon the elastic constants is its effect upon the elastic limit and proof stress. As the temperature is raised, the elastic limit, proof stress and tensile strength of the typical metal fall progressively, rather slowly at first, and then more rapidly until a temperature range is reached at which the strength drops more or less suddenly to a low value, and the material becomes soft and plastic and capable of being shaped under moderate loads by the well known methods of hot working.

Below this temperature range, the elastic limit and yield point are almost independent of the rate at which strain is applied. Within

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and above this range, the metal becomes capable of yielding continuously under comparatively low stresses, and the resistance of the metal becomes highly dependent upon the rate of strain.

It is not quite correct to say that at low temperature the behaviour is independent of the rate of strain, for if the stresses are high enough, continuous yield will take place even at the lowest temperatures. The essential difference between the low temperature and the high temperature behaviour is well illustrated by two sets of curves shown in Figs. 1 (a) and 1 (b). These curves are due to Tapsell, but their fundamental importance is seldom recognized in theoretical treatments of creep. They relate to medium carbon steel, and contrast the behaviour at 300°C and 500°C. At 300°C the steel is effectively perfectly elastic at all stresses up to 12 tons/in.² At higher stresses up to 27 tons/in.² there is an immediate plastic strain, followed by a slow strain that continues for a while and then ceases. At stresses above 30 tons/in.² the slow strain is apparently continuous and after a while increases in rate until the specimen ultimately fractures. At 500°C there is apparently no stress so small that behaviour is perfectly elastic and stresses that lead to no very obvious immediate plastic deformation nevertheless produce a slow continuous strain that first decreases in rate, and then increases.

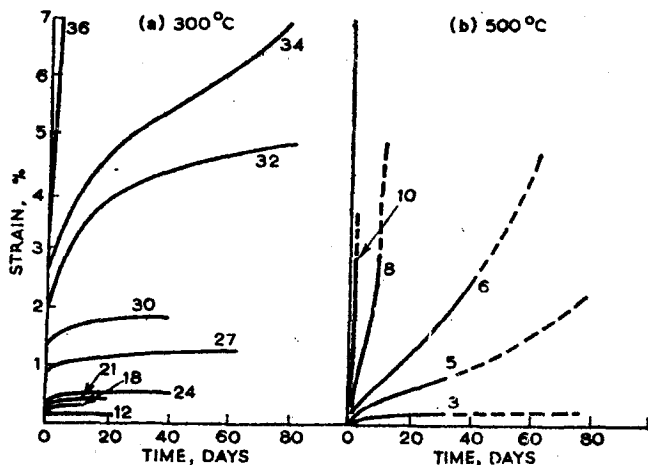


Fig. 1—Creep of medium-carbon steel (figures at curves in tons/in.²) (H. J. Tapsell: "Creep of Metals", Figs. 22 and 23. Oxford University Press, 1931)

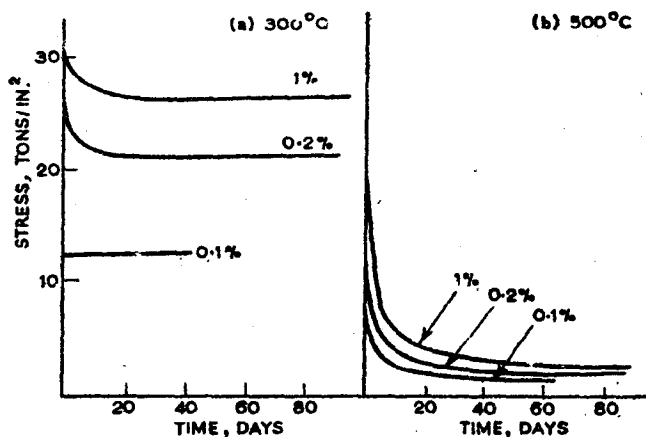


Fig. 2—Relaxation curves of medium carbon steel

If instead of a constant stress, a constant strain is applied to the metal, the subsequent changes of stress at 300°C and 500°C are as shown in Figs. 2 (a) and (b). At 300°C, no significant relaxation of stress takes place provided the strain is sufficiently small. If the strain is greater, the stress relaxes somewhat, but ultimately settles to a constant, high value. At 500°C the stresses due even to the smallest strains relax continuously and the stress that can be retained for long periods is very small indeed.

The creep curve for a metal extending at high temperature under constant load is conventionally considered to have three stages: the *primary* stage, in which as a rule strain hardening is taking place and the rate of strain decreases with time; the *secondary* stage, in which the rate of strain is approximately constant and has its lowest value; and a *tertiary* stage, in which the rate increases with time, until the test-piece breaks. The distinction between the three stages is not very real; there may or may not be a long period in which a constant rate of strain obtains and the secondary stage is probably best considered to be the result of a rather precarious balance between a hardening process and a softening process. Of these processes, the softening process prevails when the temperature is high, and when the total strain becomes high. The characteristic form of the families of curves obtained when the load is held constant and the

temperature is raised, and when the temperature is held constant and the load is raised, may be understood in this way (Fig. 3).

The fitting of mathematical expressions to these curves has been a popular but rather unprofitable enterprise, and the reason can be appreciated by considering the processes that are taking place. Creep at high temperature is undoubtedly a thermally activated process, for if we use the minimum creep rate as a measure of the speed of the process as a whole, and plot the logarithm of the minimum creep rate against the reciprocal of the absolute temperature for a series of experiments in which other conditions are held constant, straight lines are obtained. The process in question is the

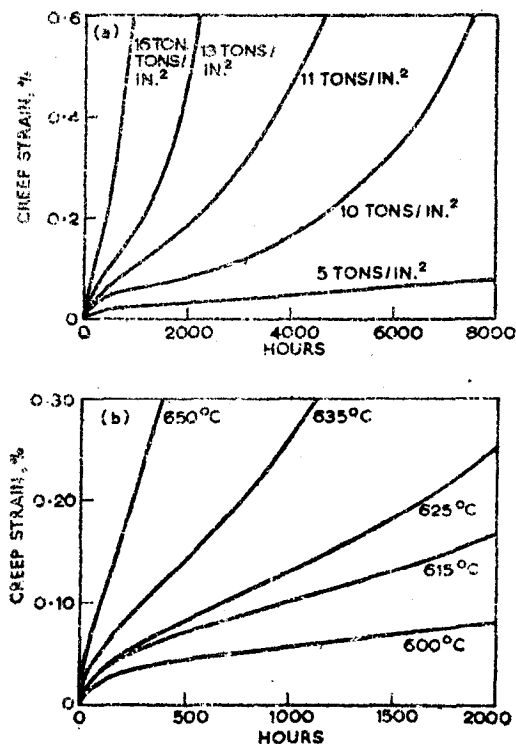


Fig. 3—Families of creep curves for constant temperature and for constant stress. (a) Nimonic 80 at 700° C. (b) Mo-V steel at 3 tons/in.²

movement of dislocations, for it is now abundantly proved that the majority of the strain is ordinary crystal slip and that movement at the boundary, which has figured largely in the literature, is a minor phenomenon when the material has enough strength to be of interest to the engineer. The movement of the dislocations is influenced by stress, and probably the adaptations of the rate process theory of Eyring contain the germ of the fundamental theory. These regard the dislocations at high temperature as not being entirely stationary but liable to be shifted in short lengths from side to side by the thermal fluctuations in the crystal. A shear stress favours the fluctuations in one direction and disfavours those in the opposite direction, so that on balance there is a tendency for the dislocations to move slowly in the direction of yield. Such theories lead to expressions for the variation of creep rate with stress and temperature of the type

$$\frac{d\epsilon}{dt} = A \exp \left(-\frac{E}{kT} \right) \sinh \left(\frac{aS}{kT} \right)$$

where E is the energy for a unit dislocation movement and a is a constant expressing the way in which this energy is influenced by the applied stress S .

These equations have a certain success, though their constants cannot be fundamentally evaluated.

The dislocations are not, however, all equally well placed for movement in the first place nor does the resistance to their movement remain unchanged with time. When the load is first applied, some favourably placed dislocations move almost at once and continue until they encounter some obstacle which temporarily brings them to a stop. Less favourably placed dislocations move more slowly and at a later stage, so that the rate of deformation, fairly rapid at first, tends to decline as the mobile dislocations become exhausted. The groups of dislocations arrested at obstacles are the cause of work hardening, which in some cases may be sufficient to bring the creep to a stop. In other cases, the groups are unstable and tend to disperse themselves in such a way as to permit further movement. The rate of creep is then dominated by the rate of dispersal of the dislocation groups, that is, by the rate of removal of work hardening. Thus the details of the initial distribution of the dislocations in the material and the laws governing the rate of removal of work hardening play a great part in the form of the creep curve, and it is well

known that the form of the initial part of the curve in particular can be varied considerably by slight modifications of the material.

The rate of removal of work hardening increases as the strain increases and this is largely the cause of the increase in rate of strain characteristic of the third stage of creep. The increase of stress consequent upon the decrease of cross-section is also concerned. Sometimes the crystals draw down considerably and break with a transcrystalline fracture. When this occurs a definite recrystallization may take place, and the third stage of creep is protracted and leads to a considerable general extension. Sometimes intercrystalline cracks form at an earlier or later stage. The rate of strain then rises rapidly and rupture takes place rather quickly with a fairly low total extension.

In either case rupture occurs in a time which increases rapidly as the stress decreases. The total extension at fracture generally falls as the stress is decreased and the time to rupture is increased. Fractures are more likely to be intercrystalline when the time to rupture is long. There are, however, exceptions to this rule. Some materials apparently go through a stage in which the tendency to intercrystalline fracture with low elongation is a maximum and, if tested under conditions which lead to fractures in extremely long times, will undergo changes that lead to an increase of the elongation at rupture and decreased susceptibility to the intercrystalline type of fracture. Similarly, although it is the general rule that fractures are more likely to be intercrystalline when the temperature is high, there are several materials that have a maximum sensitivity to intercrystalline fracture in a fairly closely defined temperature range.

When a material is behaving in the way that has been described, it is unreasonable to expect it to last for ever. The engineer must decide how long he wishes his component to last and adjust his stresses and temperatures so that the component does not either break nor deform unduly within that time. There are very few components in which an appreciable risk of fracture can be allowed, though there are some. As a rule the permissible strain is small: it is rarely above 1 or 2% and in components like the rotors and casings of turbines is of the order of a few thousandths of an inch in 30 or 40 in., that is, about 0.02%.

It is very important not to exaggerate the accuracy with which the dimensions must be held. In Fig. 4(a) are shown the permissible stresses that are arrived at for typical creep-resisting alloys when the

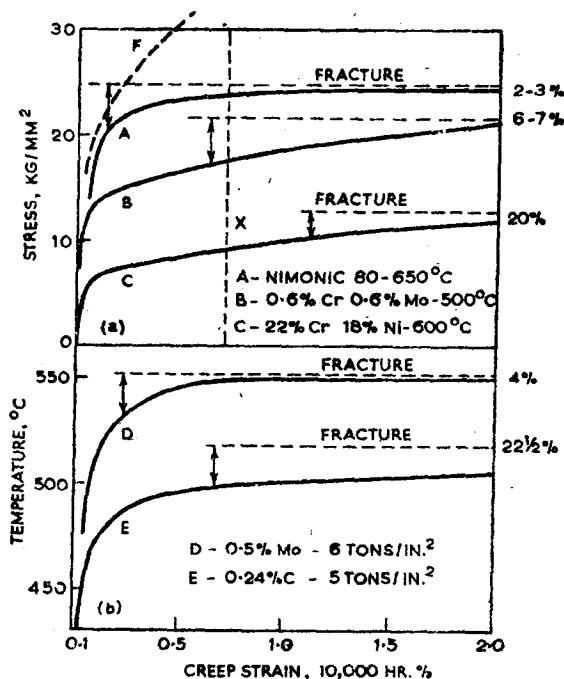


Fig. 4—Permissible stresses and temperatures for permissible strains

component is to serve at 500–650°C for 10,000 hr. and the permissible strain is varied from 0 to 2%. It is seen how steeply the permissible stress falls as the permissible strain is reduced below 0.1%. On the other hand, the difference between the stress which produces 2% strain in 10,000 hr. and that which produces fracture in 10,000 hr. is comparatively small. Bearing in mind that the stress on a component is rarely known with complete certainty, it may be concluded that the stresses that can usefully be applied are generally those which produce between 0.1 and 1% strain in the expected lifetime.

The same general conclusion is reached if one considers the temperatures at which the material could be used under a given stress (Fig. 4[b]). The temperature at which fracture would occur in 10,000 hr. is very little higher than that at which 2% strain would be

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produced, whereas the temperature for 0.05% strain is very much lower than the temperature for 0.2% strain.

Working stresses at high temperature are determined by making creep tests on the material either at constant temperature and at successively altered stresses, or at constant stress and at successively altered temperature. The logarithm of the time to produce specified strains or rupture are plotted against the stress (or log stress) in one case, or against the temperature in the other. In either case, families of approximately parallel curves are obtained. The curvature is generally small so that interpolations are easy and reliable (Figs. 5[a] and [b]). No difficulty arises if the expected life is less than 1,000 hr., for creep tests can readily be continued for such times. If, however, a life of several years is required, creep testing for the

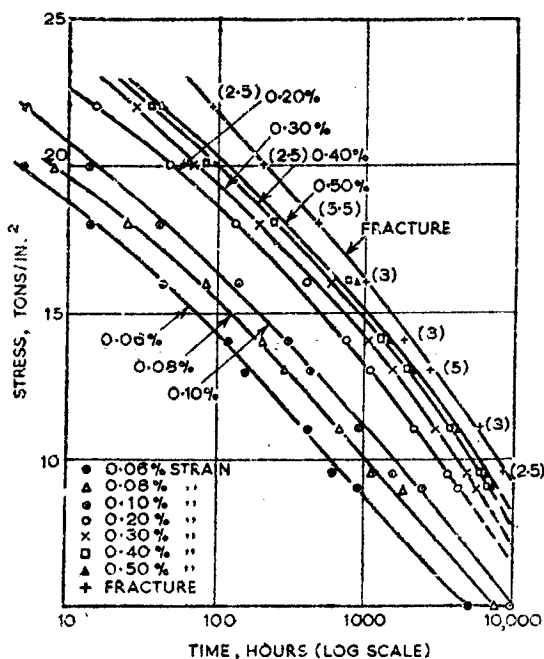


Fig. 5a—Family of stress/log-time curves at 700° C for Nimonic 80. Figures in brackets are elongations at fracture ($4\sqrt{A}$) (N.P.L. unpublished data)

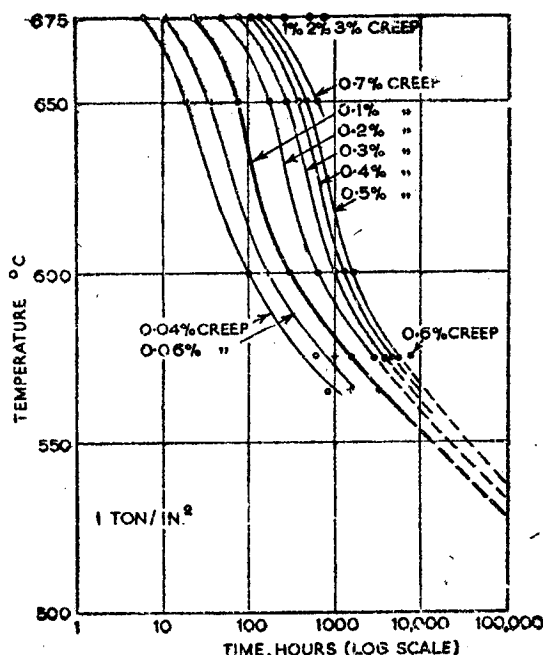


Fig. 5b---Family of temperature/log-time curves at 1 ton/in.² for 0.6% molybdenum steel (H. J. Tapsell and R. W. Ridley: *Proc. Inst. Mech. Eng.* 1945, 153, 181)

whole of this time is impracticable and the problem of extrapolation arises. There is no agreed solution to this problem, for many materials are liable to undergo structural changes that are difficult to predict and may have good or bad effects on the creep resistance. Those who are most experienced are most firm in their conclusion that extrapolations should be as short as possible, very cautious and confirmed by experiment as soon as possible.

Temperature-log time curves are often very good straight lines, and when this occurs, it means that the activation energies of the governing processes are varying very slowly over the range of temperature studied, and it may reasonably be hoped that they will continue to do so over the range of the extrapolation. It was for a long time claimed that log stress-log time curves were straight lines. It was