CREEP AND SOME CREEP-RESISTING ALLOYS

by

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The projected use of gas turbines and of steam turbines operating at higher temperatures and stresses than have been employed hitherto brings the designer face to face with a property of materials known as creep, which it has not been necessary, in most cases, to consider in earlier designs.

In the ordinary course of events components are designed to work at stresses within a fairly well defined elastic limit ; when under stress they immediately take up a strain proportional to the stress and, on release of the stress, return to their original dimensions. Even in a case when the elastic limit is exceeded slightly and a small amount of plastic strain occurs, the rate of straining under steady load rapidly diminishes owing to stiffening of the material by plastic deformation (work hardening) until the strain reaches a maximum value, at which it remains stationary however long the load is maintained ; on release of the stress the elastic portion of the strain is recovered, but the component remains changed in dimensions by the amount of the plastic strain. On reloading to the same stress as was applied originally the strain returns to the same maximum figure as on the first occasion.

Above some temperature level, which is dependent on the material, a new mode of behaviour under stress becomes observable ; as the stress is applied, the material behaves at first in a manner generally similar to behaviour in the elastic range at normal temperatures but with a Young's Modulus lower than that found at atmospheric temperature, but when the full desired load is reached the strain does not quickly attain some maximum stationary value, it continues to increase at a greater or less rate over periods which may be very long and which probably always end in failure of the component. This continuing strain with constant load is the phenomenon generally known as creep which, obviously, places a limitation on the life at elevated temperatures of structures in which only limited changes of dimensions can be tolerated.

At one time it was thought that by studying creep behaviour of a material under various stresses at a given elevated temperature it would be possible to deduce a stress which would give zero creep at that temperature, but it was soon found that the stress for zero creep, if it existed at all, would be so low as not to be of any practical value, and the present outlook is to accept that some creep must occur and to stress components as highly as can be done while keeping the total strain within an acceptable limit over the required working life.

The general behaviour of material in which creep is occurring is shown in the strain/time curve in Fig. 1, and it will be observed that the curve is separable into three stages, generally referred to as the primary, secondary and tertiary stages of creep. During the primary stage, which is of fairly short duration, strain is rather rapid, but the rate of straining is diminishing ; in the secondary stage, which may be very long, the strain rate is approximately constant and relatively small. After the secondary stage has lasted for some time the creep rate accelerates increasingly and failure by rupture occurs in a fairly short time. It is not yet certain what mechanism is in operation during the various stages

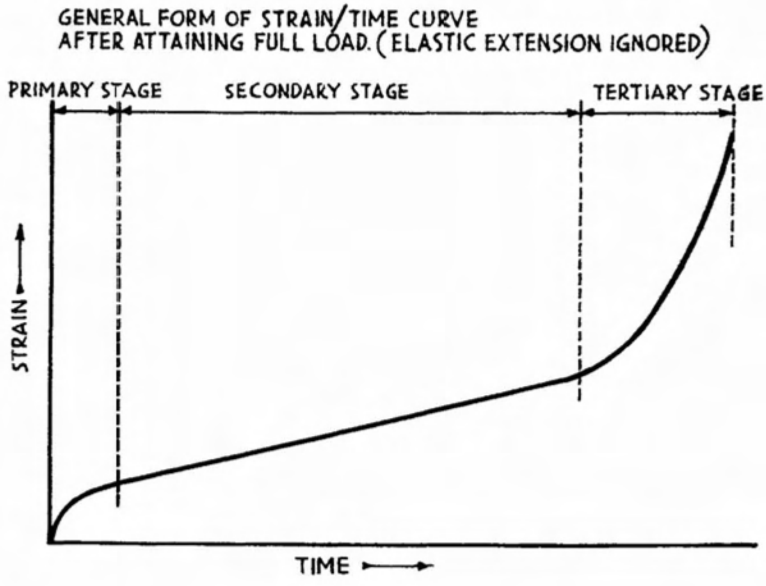

FIG. 1

of creep. One possible explanation in the case of materials which do not undergo precipitation hardening at the operating temperature is that the diminishing rate of straining in the primary stage is due, as in the plastic stage at room temperature, to stiffening of the material by work hardening, that the steady rate in the secondary stage represents a balance between the work hardening due to continuing plastic straining and the softening effect of exposure to the operating temperature, while the onset of the tertiary stage represents the exhaustion of capacity for further work hardening. In the case of alloys capable of precipitation hardening at the operating temperature it may be supposed that the work hardening effects mentioned above are supplemented by hardening due to the precipitation of a second phase; in these alloys also a time will come when all the precipitating phase is out of solution and softening of the alloy may be expected as a result of coagulation of the fine precipitate.

Necessary design information

Evidently, one of the designer's first concerns is that at the stress and temperature to which a component is subjected the material shall not enter upon the tertiary stage of creep within the anticipated working life of the component since, once this stage is reached, failure is imminent. There is, at present, no method of estimating, from the form of the curve in the primary and secondary stages, when the tertiary stage of creep will commence; this factor has to be determined by direct experiment. However, when some amount of consistent data has been obtained for a given material and temperature it is possible to draw a curve relating stress to time for commencement of tertiary creep and to obtain from this curve the times at which the tertiary stage may be expected to set in under other stresses than those used experimentally; it is probable that the curve may be extrapolated to a small extent, but this should not be carried far outside the experimental conditions.

Being assured that there is no danger of entering the tertiary stage of creep during the anticipated working life of the component, the next point of interest to the designer is the amount of strain which may be expected in a given time under the designed conditions of stress and temperature, or, conversely, what conditions of stress and temperature may be imposed without exceeding some selected strain in a certain time. To obtain this information the first step is to obtain curves of the type shown in Fig. 1 for various stresses at each temperature. If the information required is the amount of strain to be expected in a given time for certain values of stress and temperature, it can be derived direct from the curve. If it is required to know the stress which will give a specified amount of strain in a certain time, then the method is to read off from each curve for the appropriate temperature the time for the specified amount of creep to occur and to plot a time/stress curve ; by interpolation, or by extrapolation provided that it is not carried too far, the stress which will give the specified strain in the required time can be read off.

Bearing in mind that curves of the type shown in Fig. 1 are the basis of practically all information about creep behaviour and noting that it is not possible at present to predict the course of the curve beyond the point to which it has actually been determined, it will be appreciated that, though reference has been made to the possibility of extrapolating various curves this cannot with any certainty be carried very far. If, from reasons of urgency, extensive extrapolation has to be made, the deductions made should be checked at the earliest possible moment by an ad hoc experiment. When carrying out extrapolation it is also desirable to consider the curve of stress against time for the onset of tertiary creep to see whether the failure conditions are being approached.

Presentation of data

It should be mentioned here that the strain/time curve as usually presented does not take any account of elastic strains, it being assumed that the designer will normally make allowance for elastic strains and only requires a knowledge of the permanent strains for which additional allowance must be made. Methods of reporting in figures the data obtained from a strain/time curve differ, some workers reporting total creep strain against time while others, and that the majority, more often report creep rate in the secondary stage. This latter method of reporting is unfortunate since it takes no account of the strain in the primary stage which may be a significant portion of the permissible strain. As an instance taken from actual test results may be quoted a material which under certain conditions of stress and temperature gave a steady creep rate in the secondary stage of 10^{-7} in./in./hr. equivalent to 0.1 per cent. strain in 10,000 hours ; on this basis the material might appear acceptable for an application involving 0.1 per cent. strain in this time, but on examining the full curve it appears that in the primary stage 0.03 per cent. strain occurred, one-third of the total strain considered permissible so that the total strain would actually be reached in about two-thirds of the required life. Even more striking instances than this could be cited and for this reason it is considered that the method of reporting total strain against time is much to be preferred.

Another convenient method of presenting the data, when sufficient results have been collected, is in the form of curves giving stress and temperature conditions appropriate to certain rates of creep strain, say, 0.1 per cent. in 1,000 hours or 1 per cent. in 1,000 hours. When making use of data presented in this form it is very necessary to know the duration of the tests on which the results are based ; so far as creep rate is concerned 0.1 per cent. in 1,000 hours is the same as 1 per cent. in 10,000 hours, but it would not be sound practice to take stresses appropriate to 0.1 per cent. in 1,000 hours, based on tests of 1,000 hours duration, and apply them to a case where 10,000 hours life is required and 1 per cent. strain is admissible ; the stress which gives 0.1 per cent. strain in 1,000 hours might cause failure in a shorter period than 10,000 hours.

Future requirements

Turning now to Admiralty requirements in materials for advanced steam conditions and for gas turbines, temperatures of immediate interest are 500°C. and 650°C., the required life is of the order of 10,000 hours and the total strain regarded as admissible in this period is 0.1 per cent. Considering these requirements it at once becomes evident that there is extremely little data available directly applicable to an estimate of materials suitable for these applications, and not very much more data which can be reasonably extrapolated to these conditions.

The measurement of small strains occurring in very long times is, evidently, work requiring equipment of great sensitivity and precision quite apart from the time consuming aspect of long duration tests. The amount of equipment in existence of adequate sensitivity to measure strains of the order of 0.1 per cent. in 10,000 hours is small and, in view of the wide field of materials and temperature conditions to be explored when all high temperature applications are considered, it is not surprising that most of the testing carried out has been of relatively short duration, mostly of the order of 300 to 1,000 hours, and rarely exceeding 2,000 hours. Further, the amount of strain regarded as acceptable has generally been of the order of 1 per cent. rather than 0.1 per cent., so that more often than not stressing has been such that more than 0.1 per cent. strain has taken place in the primary stage. Any attempt to extrapolate results of tests which had in mind 1 per cent. strain in 1,000 hours to such widely different conditions as 0.1 per cent. strain in 10,000 hours, conditions which may be considered as 100 times different, must be regarded as completely unsafe. Some very long duration tests have been carried out at lower temperatures than 500°C., but these are not, of course, applicable to the present problem.

In order to indicate what data is known to exist which might be of use in assessing likely materials, though the use of this data involves an undesirable degree of extrapolation, it will be assumed that, apart from the condition of 0.1 per cent. strain in 10,000 hours there are four other strain/temperature/duration conditions of interest :—

1. 0.1 per cent. strain in 1,000 hours at 500°C.
2. 0.01 per cent. strain in 1,000 hours at 500°C.
3. 0.1 per cent. strain in 1,000 hours at 650°C.
4. 0.01 per cent. strain in 1,000 hours at 650°C.

In considering what materials may have good resistance to creep at 500°C. and 650°C. it may be mentioned that it is a matter of observation that there is some parallelism between the melting points of metals and their creep resistance. The metals of highest melting points which are available in sufficient quantity to be useful for structural purposes are iron, nickel, cobalt and chromium, and the majority of creep resistant materials in current use are based on iron, nickel and chromium, though there is a growing tendency to introduce cobalt to a greater extent than hitherto. All of these metals may be strengthened by alloying with other elements which go into solution in the basis metal, and also by addition of elements which form compounds and give either dispersed second phases or precipitation hardening effects.

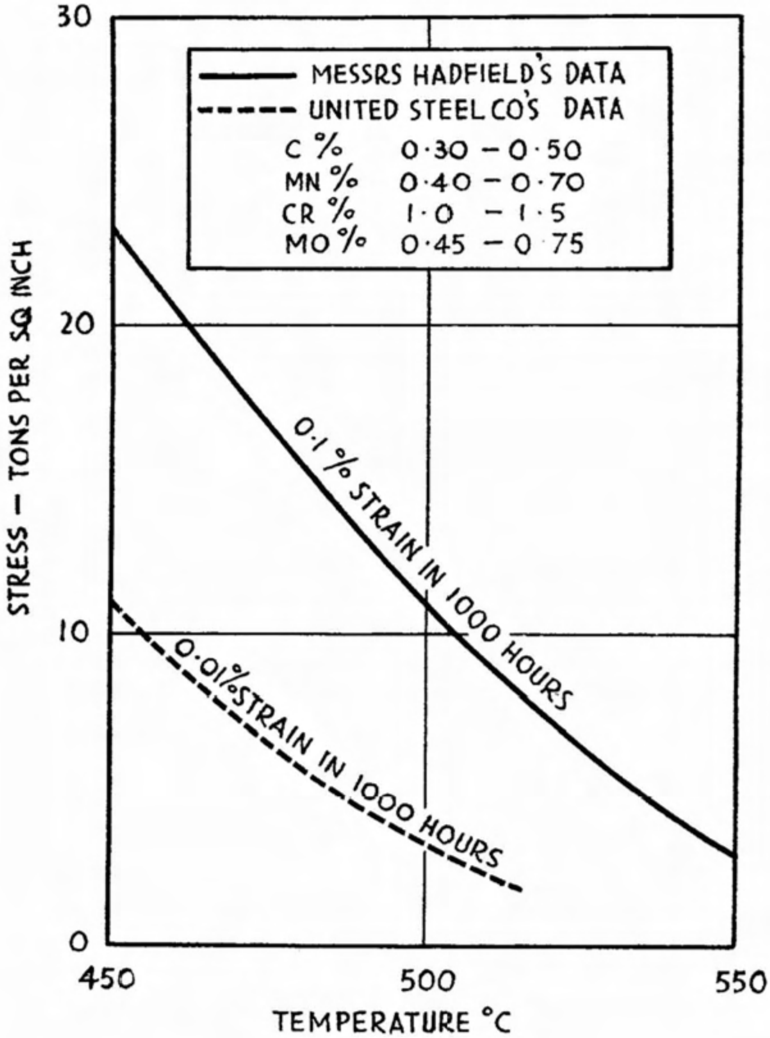

FIG. 2

Low alloy steels

Up to about 550°C. low alloy steels of the ferritic type exhibit a fair degree of resistance to stress and are generally used ; the alloy elements most favoured for increasing the creep resistance of the basis plain carbon steel being chromium and molybdenum, sometimes with the addition of vanadium. Above 600°C. it is necessary to go to highly alloyed steels of the austenitic type or to non-ferrous alloys, usually based on nickel and chromium, and, generally, it has been found desirable to add small percentages of other elements which confer precipitation hardening effects on the basis alloy.

Although it is known in a general way what alloy elements are most effective in promoting resistance to creep and there is increasing knowledge of an empirical kind as to the relationship between microstructure of a given alloy and its creep resistance, it cannot be said at present that all the factors affecting creep resistance are fully understood or fully under control and there is not, as yet, any certainty that one batch of a given material will behave in a precisely similar manner to another batch nominally identical with it ; such discrepancies as exist from batch to batch, while they may not be of great importance in fairly short life components may produce marked differences in the final result over a long life. It is, therefore, necessary to allow some margin of safety when considering results obtained from one batch of material, since other batches may behave slightly differently.

Materials which may be of use for high duty steam turbines or for gas turbines and which are in regular production, as distinct from experimental alloys not yet produced in volume on a commercial scale, are :—

I. *Ferritic Steels*

(*a*) 1 per cent. chromium, 0.5 per cent. molybdenum

(*b*) 3 per cent. chromium, 0.5 per cent. molybdenum

(*c*) 3 per cent. chromium, 1.0 per cent. molybdenum

NOTE.—Any of the above steels may be further improved by a small addition of vanadium, but this is not very general practice as yet.

II. *Austenitic Steels*

(*a*) 20 per cent. chromium, 8 per cent. nickel with additions (Stayblade, etc.)

(*b*) 15 per cent. chromium, 15 per cent. nickel with additions (Rex 78, Jessops G18B, etc.)

(*c*) 11 per cent. chromium, 35 per cent. nickel (A.T.V., etc.)

III. *Non-ferrous Alloys*

(*a*) 80 per cent. nickel, 20 per cent. chromium with additions (Nimonics)

It must be appreciated that the compositions given above, particularly for the austenitic steels, are very approximate, and that the amount of alloy elements present in individual alloys of a type may vary appreciably from the figures given above as indicative of the type.

Fig. 2 shows the stresses producing 0.1 per cent. and 0.01 per cent. strain in 1,000 hours in steel of the 1 per cent. chromium, 0.5 per cent. molybdenum type at temperatures in the range 450–550°C. It is believed that these figures have been derived from a consideration of creep rates in the secondary stage and do not take account of strain in the primary stage ; the stresses for 0.1 per cent. and 0.01 per cent. total strain in 1,000 hours would, therefore, be somewhat lower than those given in Fig. 2.

The only data known to exist for the 3 per cent. chromium molybdenum steels relate to conditions which cannot reasonably be extrapolated to give figures for 0.1 per cent. in 1,000 hours, but it is believed that some tests are in progress which may be more useful.

Material of the type mentioned under II (*b*) above is represented by Stayblade, for which there is data relating to rather high creep rates at low durations, data which cannot be extrapolated to meet the conditions set out above.

Material of type II (*b*) is represented by Rex 78 (Brown-Firth) and also by G.18B (Jessop). So far as can be inferred from extrapolation of the known data on Rex 78 it might be expected to give 0.1 per cent. strain in 1,000 hours at 650°C. under a stress of 10 tons/sq. in. G.18B tested at 650°C. gives a creep rate in the secondary stage of 10^{-6} (0.1 per cent. strain in 1,000 hours) under a stress of about 12 tons/sq. in. ; the stress for 0.1 per cent. total strain in 1,000 hours would be somewhat lower than this.

Material of type II (*c*) is represented by A.T.V., which has been in use for many years for turbine blading, but for which no creep data applicable to the conditions under consideration is known.

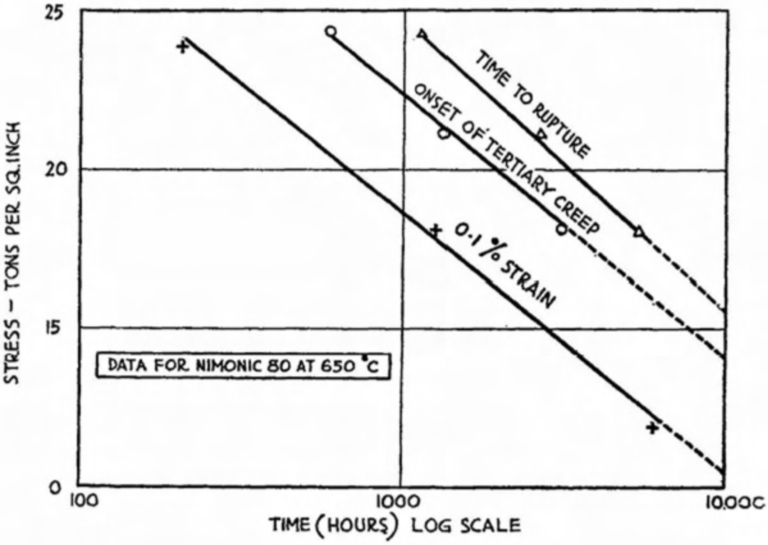

Fig. 3.

The non-ferrous nickel-chromium alloys are represented by Nimonic and, so far as is known, Nimonic 80 is the only material for which data applicable to the requirement of 0.1 per cent. strain in 10,000 hours at 650°C. is available. This data is given in Fig. 3 and shows, not only the stress to produce 0.1 per cent. creep in any period up to 10,000 hours, but also indicates the margin of safety existing at each stress before the onset of tertiary creep. It is thought likely that it is in this form that the designer will find the information about a material most useful.

During the past few years a considerable amount of data has been collected in U.S. about high temperature behaviour of materials, but this again has been concerned mainly with appreciably shorter durations and greater strains than are necessary for the Admiralty requirement. Further, much of the published data relates either to alloys which are in the experimental stage or to specially produced heats which cannot yet be said to be regularly available ; it may be this experimental nature of some of the more promising alloys which has resulted in batches of material obtained for test in this country failing, in some instances, to confirm the results reported from U.S. on the original batch of material. However, there is no doubt that in due course some of the best materials will be brought into regular and consistent production.

One general point which may require consideration is the grounds on which requirements are to be based ; at present it appears possible that the maximum temperature and maximum stress which may be anticipated, and the maximum strain which is considered acceptable are the criteria. In components such as turbine rotors and blades the maximum conditions of stress and temperature do not occur at the same position and it is very likely that the most severe combination of temperature and stress occurring in the component is appreciably less exacting than would be suggested by considering the maximum conditions of both factors. Further, the most arduous conditions probably only operate in a restricted region, conditions on either side of this region being less severe, and the strain occurring in these regions being less than the strain in the portion subjected to the most severe conditions ; this would indicate that a strain rate might be accepted for the region of most severe conditions appreciably higher than is considered acceptable for the component as a whole.

GAS TURBINE BLADING FOR AERONAUTICAL PURPOSES

The development of the appropriate high-temperature steel of turbine blading at the Firth laboratories under Dr. Hatfield was one of the major factors which made the gas turbine possible, and the development of the engine has been accompanied by developments in the materials of construction. At one time turbine blade failures were unfortunately common. To-day they are a rarity. Accuracy in manufacture, avoidance of small radii at root junctions, sound stressing methods, understanding of turbine vibration problems, as well as improvements in material, have all played their parts in the elimination of failures.

The outstanding blading material developed for the British engines is Nimonic 80 : this material was discovered by the Mond Nickel Company in 1940, soon after they had discovered Nimonic 75, which is particularly suitable for combustion parts., Nimonic 80, with its excellent creep and fatigue properties at the working temperature, is sufficiently easily forged at about 1,100 deg. Cent. to permit blade blanks to be stamped practically to finished size. It is now the standard material for turbine blading.—*H. Roxbee Cox. From the Wright Brothers' Lecture, delivered before the Institute of Aeronautical Services.*