in a series of empirical generalisations, then I am not sure if it has more than a descriptive interest.

As far as the strain-ageing comments of Graham are concerned, it is, of course, true that his fig. 2 (taken from H. S. Rance’s paper) shows a feature which is similar in some ways to that exhibited by strain-aged materials. A certain caution is required here, however, because strain-ageing is not a form of hardening due to cyclic straining (as might be assumed from Graham’s comments), but a return of the yield point characteristics with annealing time after a previous plastic straining beyond this yield point. A higher stress is thus required to initiate plastic deformation, after such an anneal, than would have been the case had the material been immediately reloaded without the intermediate anneal which results in the strain-ageing effect. I am not sure that the interpretation made by Graham is wholly valid.

Dr. Jobling makes an interesting comparison between the behaviour of metals and that of dilatant pastes. Has any explanation been advanced for the ductility increase of the pastes under a superimposed oscillatory stress? As far as the hardness changes under fatigue stressing are concerned, the reference he gives has been quoted by me elsewhere (J. Inst. Metals 87, 145, 1959), but does not fulfil the point I was trying to make, which was that hardness measurements made under dynamic stressing conditions (with the fatigue stress superimposed) may show differences from measurements made under normal conditions. In other words, I was suggesting an extension of my own experience with microcreep (where microcreep under a superimposed fatigue stress appeared to be the sensitive index) to other types of measurement. This has not, as far as I know, been tried with hardness as yet.

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Fracture as the Limit of Flow*)

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With 5 figures in 6 details

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1. Introduction

Because fracture appears always to be preceded by flow, a comparison between the trend of observed flow near fracture with that to be expected by an extension of well-established laws of flow into the range of fracture may indicate the circumstances of fracture. The simplest physical situation to consider is probably that in which fracture, or rupture, occurs after creep at constant stress and temperature.

The latter problem has been the subject of a rather detailed study by the writer and his colleagues as part of a fundamental investigation of the mechanical behaviour of commercial heat-resistant alloys. These appear to be as regular in behaviour and as amenable to precise study as metals and alloys of high purity. One of the recent objectives has been to provide a decisive assessment for Ni-Cr alloys of Nimonic type of a descriptive theory that had previously been shown to agree quantitatively with the creep of a variety of commercial alloys. The present paper is concerned with one aspect of this work, namely the detailed shape of the creep curve in the near neighbourhood of rupture in comparison with its regular shape until that time. Other aspects, together with experimental details will be treated elsewhere.

In order to establish the shape of the creep curve from the termination of loading until rupture, high-sensitivity creep testing equipment was used with calibrated extensometers that remained in position until rupture occurred. The effects of experimental errors in stress, strain, and temperature, were quantitatively assessed and kept to insignificant amounts. Curves from replicate tests were compared between themselves and with results from other sources in order to establish quantitatively both the errors of reduction of readings and the inherent scatter of the material.

The material was a Nimonic 90 type alloy from experimental casts and was chosen for its reproducibility in comparison with many other alloys. The nominal composition is:

- Ni Bal.
- Cr 18-21, Co 15-21, Ti 1.8-3.0, Al 0.8-2.0, C 0.1 maximum, Si 1.5 maximum, Mn 1.0 maximum, Fe 5.0 maximum.

The tests ranged in duration from 1.4 to 230 hours.

2. Shape of Flow Curve Away from Point of Rupture

Measurement of the shape of a creep curve is subject to a number of errors of which probably the largest, when present highly-developed creep testing techniques are used, arises from the fact that a creep test is essentially a two-part test: magnitudes assigned to the creep that occurs while the stress is constant are dependent upon an assessment of the flow while the state of constant stress is being attained. During the

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loading period, elastic straining and anelastic effects occur together with a certain amount of creep of the kind to which the subsequent constant-stress part of experiment is intended to refer. The various effects may completely obscure the basic shape of the creep curve.

Fig. 1 is a typical creep curve from the experiments of G. J. Bates. It is plotted as log strain versus log time. The corresponding dots in fig. 4 show the measured extension versus load during the period of loading. The full line in the latter figure represents a first estimate of the elastic component of the loading strain as made by drawing a straight line through the lower points. The progressive trend of the points away from the line in the range of the larger extensions may be attributed to creeping, but owing to scatter in the points, the progressive nature of creeping, and doubt whether anelastic effects are present, the exact position of the supposed elastic line is uncertain. Since the final point falls on a straight line through the lower points, it would appear that the amount of creep during loading is small, and in fig. 1, the dots show the form of creep curve that results from the assumption that the creep is zero. The zero of creep strain is then taken at the final ringed dot in fig. 4. If, however, as would be equally reasonable, the elastic line had been judged to pass through the cross in fig. 4, so that the ordinate distance between the cross and ringed dot represents the estimated creep during loading, then the creep curve predicted by the same data would be that shown by the crosses in fig. 1. In the later part of the curve, where the crosses are hardly to be distinguished from the dots, the crosses have been omitted.

Although the differences of strain involved are extremely small, of the order of 0.003 per cent, and are not of immediate practical significance, they are associated with a profound uncertainty of theoretical shape that extends over a considerable portion of the curve. Figs. 2 and 3 with the associated loading graphs in fig. 4 are similar examples from tests of specimens from cast RJ 63, all being primarily chosen for the purpose of the later discussion. In fig. 2, the first estimate of the elastic component proved to be acceptable.

The curves in the figures are typical of the many that have been obtained which are considered to justify, to a limited extent, the Andrade formula for creep, namely

\[ e = e_0 (1 + \beta t^n) e^{\frac{t}{h}}. \]  \[1\]

This may be written

\[ \log \frac{e}{e_0} = \log (1 + \beta t^n) + \frac{t}{h}, \]

or

\[ e = \beta t^n + \frac{t}{h}, \]  \[2\]

in which \( e \) is the natural strain, and the error in the approximation on the righthand side is negligible for the small measured strains involved in the present results. The first term of equation [2] has been rather fully substantiated by Andrade, A. J. Kennedy, and others, while the second is almost universally accepted. As fitted to the present results, the formula is shown by the full lines in the figures. Comparison with the crosses shows that it very satisfactorily fits the earlier part of what may well be the true shape of the creep curve.

The Andrade formula makes no claim to represent the accelerating creep often observed, as in the last cycles of log time in the figures, which increases more rapidly than with the first power of time.

The excess of the observed creep over that represented by the Andrade formula is shown plotted in the figures by the triangles. The lines drawn through the triangles are all of slope 3. The examples shown illustrate the result found for alloys of the present type that all triangles, with the possible exception of the one or two just prior to rupture, fit the line of slope 3 to the same rather satisfactory accuracy as the crosses of the remaining part of the curve fit the Andrade formula.

More precisely, a zero of creep strain may be chosen within the uncertainty of the creep that occurs during loading such that