APPROXIMATE METHODS FOR THE PREDICTION OF CREEP RUPTURE IN COMPONENTS

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SUMMARY

The design of engineering components and structures operating under creep conditions can now be made on a more rational basis than in the past. The development of phenominological theories for the prediction of the creep and creep rupture of structures combined with the increasing availability of computer-aided finite element methods of stress analysis for non-linear time dependent conditions have made this possible. The accuracy of such approaches, however, is vitally dependent on the comprehensiveness and validity of the constitutive equations used to describe the deformation behaviour of the elements. Additionally the cost of such analyses can be extremely high. Thus the development of approximate methods, which are capable of providing similar information, but for a fraction of the cost and effort is opportune.

The present paper considers the application of one such concept to the prediction of creep and creep rupture in thick-walled tubes and solid cylindrical bars under pure torque. Complicating factors such as anisotropy, inhomogeneity, and initial plastic loading strain which beset any method of analysis are discussed. In particular, the effect of pre-relaxation on the subsequent life of the component, and the prediction of those effects by reference stress methods are examined.

A spectrum of engineering-type metals have been included in the investigation; these are a 0.24 per cent carbon steel at 450 °C, a type 316 stainless steel at 600 °C, an aluminium alloy (RR58) at 180 °C, and a commercially pure copper at 250 °C. The components and testpieces were cut from a variety of initial forms, thus the type 316 stainless steel and the copper were in rolled bar form, while the aluminium alloy was in rolled plate condition. The 0.24 per cent carbon steel was initially in the form of a block from an ingot. The successful application of the predictive method, including coverage of such a diverse variety of metals and forms would encourage expectations of the general applicability of the technique.

While creep deformation paths, of up to 1 or 2 per cent proved generally predictable by the reference stress method, tertiary creep strain and rupture time predictions proved less satisfactory. Creep rupture time predictions could, however, be made by methods previously developed by the authors, though these required tensile creep rupture data.

Use of constant stress, as distinct from constant load, reference stress tests improved tertiary creep strain and rupture time predictions. For low deformation creep predictions, as might have been expected, no great advantage was obtained by using constant stress tests.

The effect of pre-relaxation on subsequent creep and creep rupture was found to be considerable for some metals and less so for others. Qualitatively the effect for components was successfully predicted from the corresponding reference stress tests.

The technique is a potentially rapid and inexpensive method of initial assessment of elevated temperature designs.

INTRODUCTION

The potential benefit of the availability of more-rational methods of high temperature design of engineering components in the form of non-linear finite-element techniques is tempered by the high cost that such analyses entails. Limitation on computer storage capacity and the complexity of constitutive equations are among the impediments to universal employment of these techniques however, and any simple, inexpensive approximate means to the same end are welcome. Examples are the recently developed Reference Stress Methods of creep analysis, whereby a single tensile creep test may replicate the overall behaviour of the component under creep conditions.

The present paper presents the results of the application of the technique to the prediction of the creep behaviour of a relatively simple component in the form of either a thick-walled tube or a solid cylindrical bar under pure torsional stress, to determine where the method succeeds or fails and thereby to obtain insight into its likely limitations.

A particularly attractive feature of the Reference Stress Method of Creep Analysis is its ready and simple extension to creep under changing load conditions - an extremely complicated problem for analysis. Indeed, no completely acceptable mathematical representation has yet been proposed for analytical methods. This is partly due to the lack of comprehensive constitutive equations, and the failure of metals to rigorously follow such behaviour simplifications as a Mechanical Equation of State. With changing conditions in mind, an introductory study has been made of the effects of relaxation on subsequent creep as an example of a mixed condition and to test whether Reference Stress methods are likely to be applicable to such systems.

THEORY

Finite element methods of non-linear, time-dependent stress analysis require appropriate constitutive equations which describe the creep behaviour of the individual geometrical elements. Reference Stress methods, on the other hand, require virtually only one tensile creep test performed at temperature and at the appropriate Reference Stress.

An early form of Reference Stress was that suggested by Schulte(1) who pointed out that creep analysis of a rectangular beam under uniform bending moment revealed the existence of a position within the beam where the stress remained virtually constant during general creep/stress redistribution. Schulte then postulated that a uniaxial creep test performed at this stress would provide a creep curve representative of the creep strain developing at that point. Compatibility relations would enable the creep strain at all other parts of the beam to be evaluated. Johnson, Henderson and Khan(2) confirmed incidentally the existence of a position of approximately constant stress in an analysis of creep in thick-walled tubes under internal pressure. Subsequently Marriott and Leckie(3) considered several components for which creep analysis showed that a position of unchanging stress existed; this position they called the Skeletal Point. Later work by Mackenzie(4) Penny and Marriott(5) generalised the concept to components as a whole, and removed the restriction to structures possessing a position of constant stress; in their analysis the stress used to represent the stressing of the component was called the Reference Stress and directly related the creep deformation in the structure with the creep in the tensile creep test. However, in practice the evaluation of the Reference Stress for even relatively simple shapes was very difficult(5). Thus Sim's(6) work was particularly timely, where he proposed than an approximate estimate of the relevant reference stress σ^* could be derived from a simple plasticity/creep relationship

$$\sigma^*_u = (P/P_{ULT})\,\sigma_y \tag{1}$$

where P is the current load and P_{ULT} is the ultimate load in the component, assuming a rigid perfectly plastic material for which yield stress is σ_y at the temperature concerned.

The present work considers the cases of a thick-walled tube under torsion and a solid cylindrical bar similarly loaded, both being components in which a Skeletal Point calculation of the reference stress can be derived.

For the thick-walled tubes and solid cylindrical bars of the current investigation, the shear creep strain is given by

$$\phi = \frac{R\theta}{l} \tag{2}$$

and the axial strain ϵ^* of the corresponding Reference Stress test is

$$\epsilon^*_o = \frac{\phi}{\sqrt{3}} = \frac{R}{\sqrt{3}}\,\frac{2\pi}{360l}\,\theta(\theta \text{ in degrees}) \tag{3}$$

Thus for a thick-walled tube of external radius R_o and internal radius R_i under torque D, the Reference Stress is given by

$$\sigma^*_o = \frac{2R_oD}{\pi(R_o^4 - R_i^4)}\,\sqrt{3}\left(\frac{r^*}{R_o}\right) \tag{4}$$

where

$$\frac{r^*}{R_o} = \left(\frac{3n+1}{4n}\right)^{n/(n-1)} \left\{\frac{1-\left(\frac{R_i}{R_o}\right)^4}{1-\left(\frac{R_i}{R_o}\right)^{(3n+1)/n}}\right\}$$

and the Reference Stress is located at the intersection of the stress distribution for elastic conditions and the distribution of stress for creep stress index n.

For the Reference Stress at the more rational intersection of two creep/stress distributions of index n_1 and n_2,

$$\frac{r^*}{R_o} = \left[\left(\frac{3n_1n_2+n_1}{3n_1n_2+n_2}\right)\left\{\frac{1-\left(\frac{R_i}{R_o}\right)^{(3n_1+1)/n_1}}{1-\left(\frac{R_i}{R_o}\right)^{(3n_2+1)/n_2}}\right\}\right]^{(n_1n_2)/(n_2-n_1)}$$

The Skeletal radius thus determined proves, however, to be only marginally different from the radius at the intersection of the elastic and creep stress distributions for most metals.

Previous work at NEL(7) on creep rupture has revealed that for multiaxial conditions the controlling stress for rupture life could be either the Octahedral Shear Stress (von Mises) or the Maximum Principal Stress, depending on the metal. It would therefore be unlikely that a Reference Stress test, linked only to the von Mises criterion, would cover both rupture and creep strain for all metals. Thus, for metals controlled by the Maximum Principal Stress, rupture time predictions would require the constant $\sqrt{3}$ in equation (4) to be replaced by unity. For primary and secondary creep, however, the von Mises(8) criterion would represent all metals.

MATERIALS, SPECIMENS AND TEST MACHINES

Two steels, an aluminium alloy and a commercially pure copper were studied, details of which are given in Table I. The Type 316 austenitic steel was included as representative of steels currently under consideration for reactor applications. The 0.24% carbon steel, on the other hand, was a metal which, like the aluminium and copper, had been studied in previous multiaxial creep investigations(9).

Either thick-walled tubes of outside diameter 15.9 mm (o.d./i.d. = 2) or solid cylindrical bars of 13 mm diameter were used in the torsional creep tests. Overall specimen lengths were 152.4 mm for the Type 316 steel tubes, 122 mm for the cylindrical bars of 0.24% C steel, and 305 mm for the aluminium and copper bars; the corresponding effective gauge lengths were 72, 58 and 224 mm. respectively. Solid cylindrical specimens of 9 mm diameter and 64 mm gauge length were used in the tensile Reference Stress tests.

The torsional creep tests were conducted in torsional creep testing machines described elsewhere(10), and the tensile reference stress creep tests were performed in conventional double-lever Denison 5 ton capacity creep machines.

TEST RESULTS

Table II gives details of the tests on tubular or cylindrical bars under torsion, together with the corresponding tensile Reference Stress tests. Examples are shown illustrating the effects of constant load rather than constant stress tensile creep tests. Tests to show the effects of anisotropy and pre-relaxation are also included. The rupture strains tabulated are the last readings of creep strain prior to fracture.

DISCUSSION OF RESULTS

Previous investigations at NEL(13), in the development of phenomenological relationships describing the creep behaviour of metals under multiaxial conditions of stress, have provided a large body of tensile creep data and multiaxial results which, together with certain additional tests, could be exploited to realise the objectives described at the beginning of this paper. The objectives were the examination of four metals for the degree to which primary creep, tertiary creep and creep rupture of a representative component might be predicted by a Reference Stress method. In addition, examination might be made of the effect of anisotropy, constant stress v constant load tensile creep data and, finally, the effects of plastic-prestrain, particularly resulting from prior-relaxation, preceding creep conditions. The latter effect could well be significant where stress relief processes were used or in assessing the effects of stress redistribution. It may be speculated how far unexpected failures, at positions in structures where triaxial stresses are believed to operate and low ductility failure occurs, are due to the creep damage developed at those positions because of severe stress redistribution and correspondingly high relaxation type damge accruing (ie, damage with littlle or no strain changes).

TYPE 316 AUSTENITIC STEEL AT 600°C

Type 316 steel is currently being considered internationally as a candidate metal for commercial fast reactors. Possessing what might be described as adequate ductility, the metal is capable of sustaining loads at temperatures well above that envisaged for such applications. As part of a more comprehensive programme of creep testing at various temperatures, a number of tensile creep tests at 600°C were used to predict creep strain and creep rupture of a corresponding series of torsional creep tests on tubes of OD/ID ratio 2 and OD = 15.9 mm. The tube tests have mainly involved either primary low-deformation creep or relatively short-term, tertiary-dominated creep; the torsional test times were 5000-16 000 hours.

Figs 1 and 2 show that, for creep strains up to 1 or 2 per cent, the Reference Stress test provides a reasonable prediction of the corresponding torsional tube test result. Further, despite an increasing amount of initial plastic strain before achieving full load, constant-stress as distinct from constant-load tensile tests do not greatly enhance the accuracy. For tertiary creep strain and rupture time predictions, however, the accuracy falls short of satisfactory, although some improvement is obtained by using constant-stress Reference Stress tests. In support of the present conclusions with respect to primary creep, it has been shown in a previous paper(11) by the authors that torsional creep relaxation (an effect dominated by the primary creep stage) could be excellently predicted by a corresponding Reference Stress relaxation test. Relaxation preceding creep proved to have little effect on either subsequent creep strain or creep life (Fig 3). Those differences that were noted were within the likely variation between specimens and differed in trend for the two types of test.

0.24%C Steel at 450°C

Previous studies had shown this steel to be relatively isotropic with respect to primary creep(8), and slightly anisotropic in tertiary creep and rupture lives. It is not surprising, therefore, that good correlation was obtained, for deformations up to about 5%, betwen the torsion tests on solid cylindrical bars and the corresponding Reference Stress tests (Fig 4). As for the Type 316 austenitic steel, improvements in tertiary predictions of creep and rupture times were obtained by using constant-stress rather than constant-load tests, although predicted rupture times were still considerably short of those in the actual torsion test. Tensile creep tests showed that previous relaxation led to a considerable increase in tertiary creep strain and early rupture. Little effect was produced, however, on primary creep (Fig 5).

Aluminium Alloy (RR58 at 180°C

Because of the extremely low ductility manifested by this metal throughout the various stages of creep, there was no need to consider the effects of constant Reference Stress tests as distinct from conventional constant-load creep tests While excellent representation of the creep of solid bars in torsion (eg, Fig 6) was achieved by the Reference Stress test, where the specimen had been cut from the original plate so that maximum shear planes of both torsion and tension tests had a common orientation, tensile specimens from the long transverse direction of the plane could afford slightly optimistic predictions. Previous work(12) and Fig 7 showed that a considerable effect on creep rupture times was produced by pre-relaxation; primary creep, on the other hand, could be reduced by prior relaxation.

A test conducted on this metal at three stress levels (Fig 8) demonstrated the difficulties in making predictions for these conditions. The tensile creep test was performed on a specimen cut from the long transverse direction (due to shortage of material), although this direction had been shown earlier to provide a Reference Stress test of longer duration than was appropriate to the torsion test. However, making allowance for the anisotropy and calculating the Reference Stress creep test for the correctly oriented specimen led to improved but still optimistic predictions of the torsion test. The need for a more detailed investigation of this condition for all metals is clearly indicated.

Commercially pure copper at 250°C

Earlier work at NEL(7) on this metal at 250°C had revealed that, in contrast to the two steels and aluminium alloy considered in this paper, the multi-axial stress criterion governing creep fracture life was the Maximum Principal Tensile Stress, as distinct from the Octahedral Shear Stress (von Mises) which controlled the rupture times for the other metals. This was certain to necessitate a different approach to the evaluation of the appropriate Reference Stress with respect to tertiary creep and rupture times, if not for primary creep. Fig 9 shows that a Reference Stress test conducted at the von Mises type Reference Stress σ_o^* is extremely pessimistic. A Reference Stress test using the Maximum Principal Stress criterion σ_1^* , on the other hand, is optimistic for deformation, though providing a much improved prediction of rupture time.

During the examination of the copper for the effect of prior relaxation on subsequent creep, an extra test was performed, in which an attempt was made to replicate the creep strain developed in the relaxation test (ie, creep strain partially replacing elastic strain) by imposing the same plastic pre-strain under constant load conditions. The results are shown in Fig 10, from which it is clear that either form of pre-straining produce a considerable reduction in creep life. It is concluded that pre-conditioning of a component may invalidate the direct relevance of a representative tensile test or indeed the use of creep data for virgin material.

For low-deformation primary creep up to about 1 per cent, Reference Stress techniques lead to reasonable predictions of the creep paths of the component. Since this is the stage of creep most associated with creep relaxation, it is not surprising that earlier work(11) revealed this relationship for relaxation conditions. Creep fracture and preceding tertiary creep are, however, a different matter, and here the Reference Stress technique was less effective. Since the current Reference Stress technique which is reasonable for all primary creep used a von Mises multiaxial stress criterion for rupture, clearly as in the case of copper, materials controlled in this rupture behaviour by the alternative Maximum Principal Stress criterion could not be expected to be well represented. Nor, indeed, could a Reference Stress calculated according to a von Mises criterion for primary creep, be expected to relate equally well tertiary creep conditions when, although the representative stress (the octahedral shear stress) would be appropriate to both stages, the associated functional form in the total creep equation would be decidedly different. It is worth pointing out here that recent results at NEL have confirmed that many materials spend most of their lives in tertiary creep when operating at stress levels leading to lives of 100 000 hours or more. Reference stresses for these conditions must therefore be calculated in accordance with the foregoing findings and be appropriate to the creep stage. No universal form independent of material characteristics is likely to be available. Recent developments of Sim's(6) approaches, using a representative component to calculate upper and lower bounds on rupture times, depend for their usefulness on how disparate those bounds might be. Changing stress conditions in components are, by the above argument, equally likely to be representable by the Reference Stress technique, provided conditions are confined to low deformation problems.

Since constant stress, as distinct from constant load tests were shown to be only important at strains above a few per cent, and this area is not well represented by the present methods, no advantage is gained by conducting such tests. Anisotropy, on the other hand, when it occurs, is significant at both primary and tertiary stages of creep, and should be considered when conducting a Reference Stress test.

Pre-damage and pre-relaxation are well recognised in creep studies as impediments to the rigorous use of mechanical equation of state principles. The degree of those effects has not been fully investigated, but it is known that certain metals can be significantly affected in subsequent creep behaviour while others are very little affected. Only tests reveal into which category a metal falls. In general a Reference Stress test will manifest qualitatively at least the pre-damaging effects, usually a decrease in primary creep strain, an increase in tertiary, and earlier entry into tertiary creep and earlier fracture times.

Primary creep and low deformation in components have been shown to be reasonably predicted by a Reference Stress method. Tertiary creep and fracture time prediction will require the calculation of a different Reference Stress. This aspect is currently being studied at NEL. Anisotropy and pre-damage have been shown to be impediments to the accurate representation of creep in components by the Reference Stress methods discussed.

ACKNOWLEDGEMENTS

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NOTATION

D	Torque
l	Effective gauge length
n,n_1,n_2	Stress indices in minimum creep rate equations
R,R_o,R_i	Radius, outer radius, inner radius, respectively
r^*	Radius at which Reference Stress is calculated
ϵ^*_o	Reference creep strain at position of Reference Stress
θ	Angle of twist
$\sigma^*_u,\sigma^*_o,\sigma^*_1$	Reference Stress according to plastic strain/creep relationship, octahedral shear stress or maximum principal stress criterion, respectively.
ϕ	Shear creep strain.

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TABLE I

DETAILS OF PRODUCTION, HEAT TREATMENT, AND CHEMICAL COMPOSITION OF METALS TESTED

Metal	Production and dimensions	Heat treatment	Chemical composition (per cent)
Aluminium alloy RR58	Slab 915 x 851 x 76 mm; stretched 2¼ per cent, 5 h 20 min after quenching	530 ± 5°C and quenched in water not exceeding 40°C; aged for 30 h at 190°C	Cu 2.60, Fe 1.05, Si 0.07, Mn 0.06, Mg 1.50 Ni 1.18, Zn 0.04
0.24% C steel	Core from ingot; 406.4 mm dia. and 876.3 mm in length	3 h at 950°C followed by air cooling, then 15 min at 930°C followed by air cooling and finally a stress relieving treatment of 3 h at 575°C with furnace cooling	C 0.24, Si 0.32, S 0.036, P 0.033 Ni 0.27, Cr 0.09, Mo 0.03, Cu 0.16 Sn 0.005, Mn 0.69
Copper	Rolled bar; 38.1 mm dia.	400°C for 1 h and furnace cooled	Commercially pure
Type 316 steel	Rolled plate; 915 x 61 x 53 mm	1050°C and air cooled	C 0.04, Mn 1.67, Si 0.32, Ni 11.95, Cr 16.93 Mo 2.68, S 0.021, P 0.025

TABLE II

Material	Temp. (°C)	Form and dimensions, O.D., I.D. (mm)	Torque (N m)	Reference stress (MN/m²)	Rupture life (h)	Rupture creep strain (%)
Commercially Pure Copper	250	Cylindrical bar	24.7	83.5) 48.3)	5762	Shear 61
		12.7	31.0	104) 60)	1440	63
		Cylindrical (tensile)				Axial
		9.1		85 N	76	9.0
		"		57 A	1420	10.0
		"		48 A	3019	8.0
		"		46.3	3019	8.0
		"		46.3 FR	(C)	
		"		46.3 FPS	(C)	

N - Nominal
A - Average
FR - Following Relaxation

FPS - Following Plastic Straining
LTD - Long Transverse Direction
LD - Longitudinal Direction
C - Continuing

TABLE II (Contd)

COMPONENT AND REFERENCE STRESS TESTS

Material	Temp. (°C)	Form and dimensions, O.D., I.D. (mm)	Torque (N m)	Reference stress (MN/m²)	Rupture life (h)	Rupture creep strain (%)
Type 316 Austenitic steel	600	Tubular				Shear
		15.8 7.9	102	200	16 000 + (C)	-
		15.8 7.9	128	250	5 318	100
		15.8 7.9		250 FR	5 906	
		Cylindrical (tensile)				Axial
		9.1		200 N	7 620	19.0
		9.1		200 A	16 000 + (C)	
		9.1		250 N	474	19.0
		9.1		250 A	1 807	29.0
		9.1		250 N,FR	360	19.0
0.24% C steel	450	Cylindrical bar				Shear
		12.7	74.5	247	4 486	188
		12.7	80.5	260	643	76
		12.7	86.1	278	989	168
		Cylindrical (tensile)				Axial
		9.1		247 N	1 119	18
		9.1		247 A	2 050	30
		9.1		260 N	608	16
		9.1		268 A	1 119	18
		9.1		278 N	387	18
		9.1		278 A	689 + (C)	
		9.1		247 N,FR	927	19
		9.1		278 N,FR	270	17
Aluminium alloy RR58	180	Cylindrical bar	61.1	200	675	Shear 4.0
		12.7		233,213,198	502	1.6
		Cylindrical (tensile)				Axial
		9.1		200 LTD	740	1.05
		"		200 LD	551	1.00
		"		200 FR,LTD	612	1.00
		"		(233,213,198) (LTD,LD Est)	909(718)	1.00

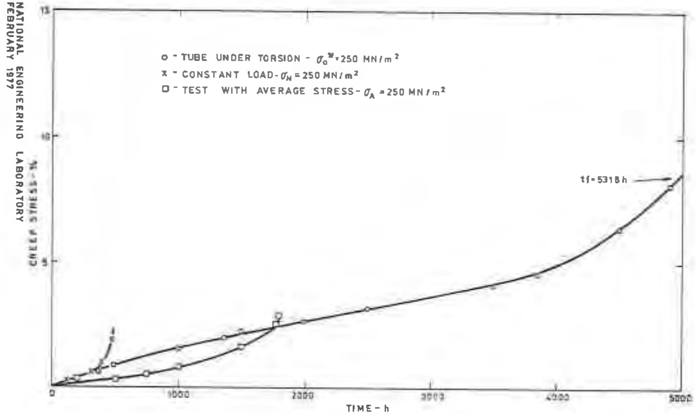

FIG 1 Creep of Thick Walled Tube Under Torsion Type 316 Stainless Steel at 600°C.

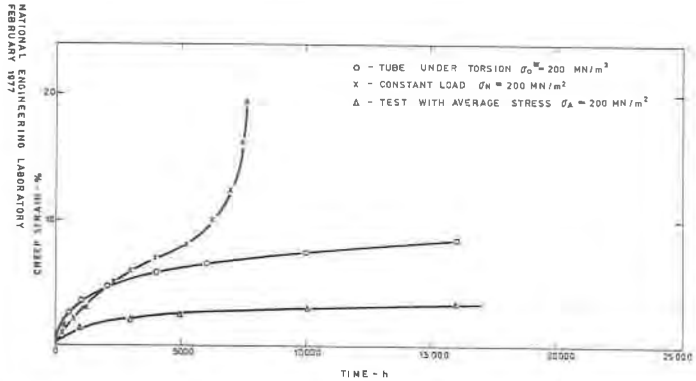

FIG 2 Creep of Thick-Walled Tube Under Torsion-Type 316 Stainless Steel at 600°C.

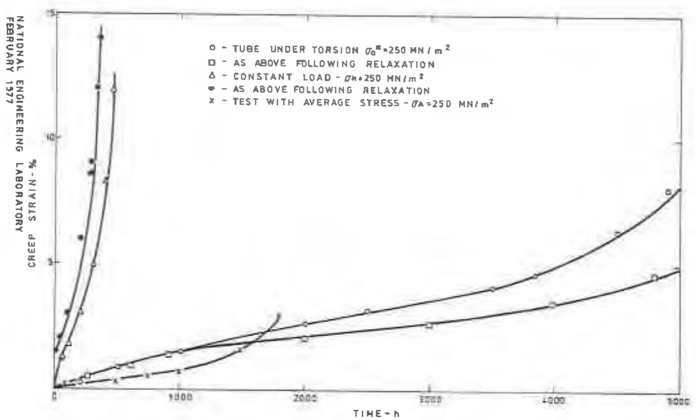

FIG 3 Effect of Prior Relaxation on Subsequent Creep Type 316 Stainless Steel at 600°C.

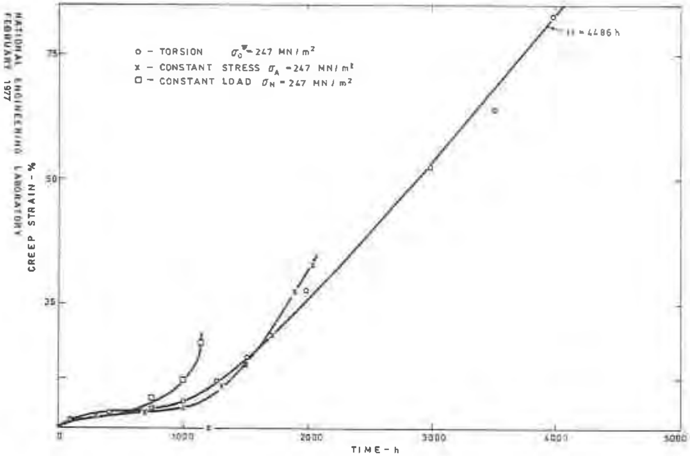

FIG 4 Creep of Solid Cylindrical Bar Under Torsion - 0.24%C Steel at 450°C.

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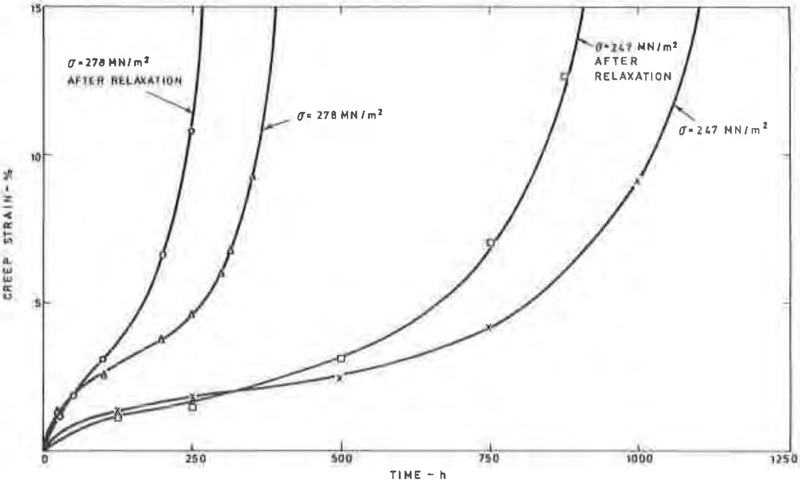

FIG 5 Effect of Prior Relaxation on Subsequent Creep - 0.24%C Steel at 450°C.

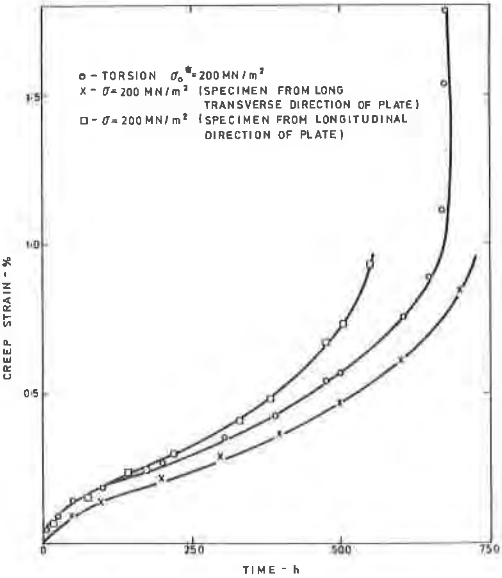

FIG 6 Creep of Solid Cylindrical Bar Under Torsion Aluminium Alloy at 180°C.

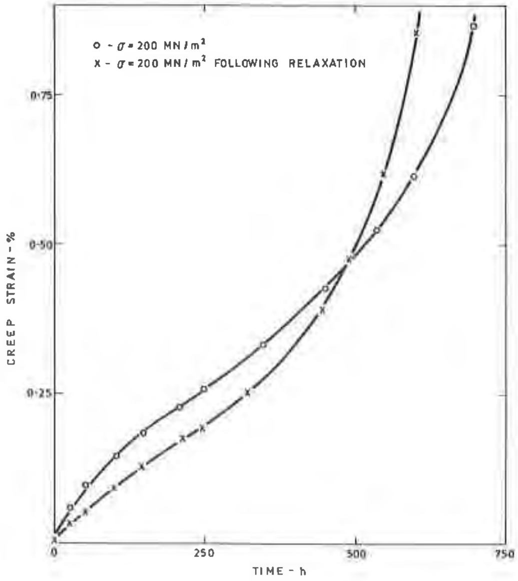

FIG 7 Effect of Prior Relaxation on Subsequent Creep Aluminium Alloy at 180°C.

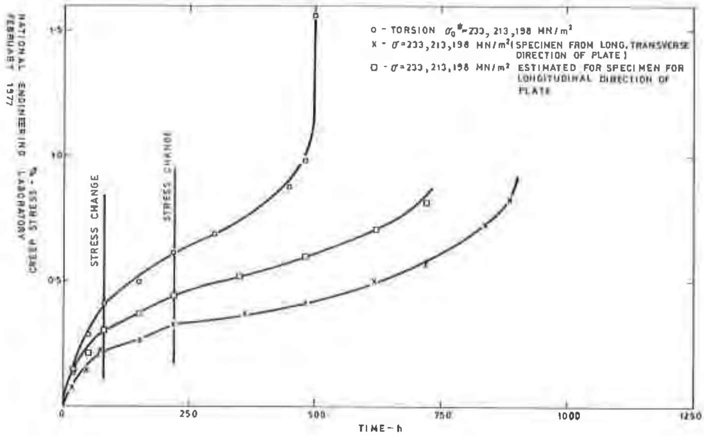

FIG 8 Creep of Solid Cylindrical Bar Under Changing Torsional Stress Aluminium Alloy at 180°C.

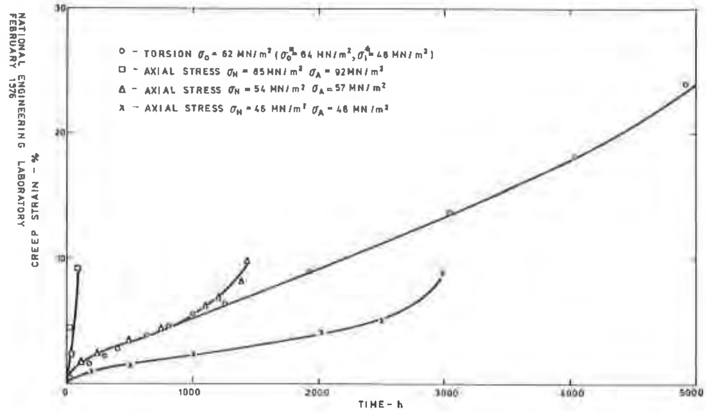

FIG 9 Creep of Solid Cylindrical Bar Under Torsion - Commercially Pure Copper at 250°C.

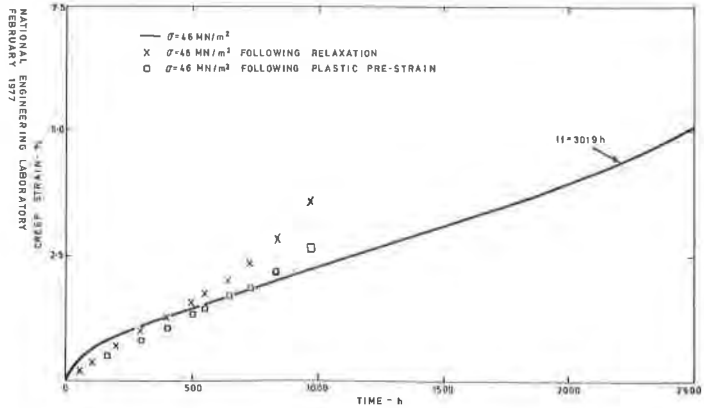

FIG 10 Effect of Prior Relaxation or Plastic Pre-Strain on Subsequent Creep - Commercially Pure Copper at 250°C.