EXPERIMENTAL MEASUREMENT OF CREEP RELAXATION IN CYLINDRICAL METAL POWER PLANT COMPONENTS UNDER CYCLIC THERMAL LOADING

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SUMMARY

Several computer codes have been developed which predict the stress and strain history in a component subjected to any prescribed loading sequence, taking account of plastic and creep strains. One such code, PLAST, has been developed at Imperial College to perform a one-dimensional analysis of a thick-walled cylindrical component under axi-symmetric loading, in a state of generalised plane strain. This code has been checked against earlier experimental and analytical solutions only for certain loading cases, and it is important that the code should calculate transient creep strains correctly if the life of a component is to be predicted reliably.

The object of the work described is to test experimentally the code predictions of transient creep in a thick-walled cylinder. This is done by measuring experimentally the residual stress pattern in a cylinder which has been subjected to a load sequence during which transient creep is expected to occur, and compared with that predicted by the code.

For simplicity, the loading is obtained by inducing a radial heat flux in the wall of the cylinder by positioning an electrical resistance heater centrally in the bore of the cylinder within a specially built furnace. This is the only form of loading employed in the tests.

The selected test specimen is a cylinder of 75 mm outside diameter, 25 mm bore and 150 mm length and the material used in these tests is Nimonic 80A extruded bar.

Measurement of the residual stress distribution is by the well known method due to Sachs. To reduce induced stresses on layer removal, a method by chemical milling has been devised, in preference to lathe turning, and the resulting strain changes on the bore surface are measured by means of foil strain gauges.

It is intended to increase the scope of the investigation by building a second rig in which additional forms of loading may be applied to the component (e.g. pressure) to study further the cyclic accumulation of strain. It is probable that this will not be confined to thick cylinders and Nimonic material, with a view to Fast Reactor structures.

1. Introduction

Many power plant components are subject to the repeated application of some form of loading cycle, in the form of a thermal transient or a variation of imposed forces or displacements, or some combination of these. The material therefore experiences strain and stress cycles, introducing the possibility of fatigue failure or excessive deformation. In order to predict the life of a component, a reliable prediction of the amplitude of the strain and stress cycles is necessary, together with a detailed knowledge of the material fatigue properties.

For this purpose, several computer codes have been developed which predict the strain and stress history in a component subject to any prescribed loading sequence, taking account of plastic and creep strains. A good example is the code PITT, developed by the Central Electricity Generating Board [1], which deals with the complex behaviour of thick tubes. This code formed the basis of a similar programme PLAST developed at Imperial College, and performs a one-dimensional analysis of a thick-walled cylinder under axi-symmetric loading, in a state of generalised plane strain.

It has been possible to check these codes against earlier experimental and analytical solutions only for certain loading cases. For example, for a loading case in which the material remains elastic, the stress distributions predicted by the code may be compared with the Lamé solution. For a case of steady creep under constant load, the equilibrium stress distribution and the expansion rate of the cylinder have been compared with Bailey's analytical solution [2], which has been verified by a number of experiments [3].

However, there are no existing experimental results against which to test the code predictions for transient creep under either steady or varying load. It is important that these codes should correctly predict transient creep strains for accurate prediction of the component life.

The object of the programme of work described here is to compare the code predictions with experimental measurements when transient creep occurs in a thick-walled cylinder. To achieve this, a specimen cylinder is subject to a loading sequence, during which transient creep is expected to occur. On removal of the load after the loading sequence, the residual stress pattern present in the specimen is measured and compared with that predicted by the computer programme.

2. Description of Apparatus and Method

In order to fulfil the assumptions inherent in the computer code and in the method of residual stress measurement, an axi-symmetric form of loading is necessary. This is easily achieved by inducing a radial heat flux in the cylinder and for this purpose a special furnace has been built, as illustrated in Fig. 1. The cylinder is placed concentrically in the cylindrical furnace and an electric resistance heater positioned centrally within the bore of the specimen. A water jacket in the furnace wall provides a heat sink and insulating bricks at either end minimise the axial heat flow. The specimen is fitted with removable end-caps to further reduce axial temperature gradients in the test section. Preliminary tests showed that it was necessary for the furnace to be partially evacuated (~5mm Hg) to prevent axial temperature gradients due to convection currents. The radial temperature distribution in the specimen is monitored by five thermocouples placed in axial holes (1mm dia) drilled at different radii in the top end-cap, and a permanent continuous record of the loading sequence is kept via a temperature chart recorder. The mains voltage is controlled by a voltage stabilizer so that load variations are permitted only by means of the Variac variable transformer.

The test specimens have an outside diameter of 75mm and a wall thickness of 25 mm and are 150mm in length. These are machined from 75mm extruded bar of Nimonic 80A*, a creep resistant nickel-chromium alloy. The main reasons for choosing this particular material are that a great deal of creep data is available for it, and that a fairly high radial temperature gradient may be established, while maintaining the range of wall temperature within the range covered by the creep data. Thus a wall temperature difference of approximately 100°C is obtained with an inner surface temperature of 815°C, (the highest temperature for which creep data is available).

The method employed for measurement of the residual stress pattern is the well known Sachs technique [4] in which successive circumferential layers of the stressed material are removed and the resulting surface strain changes measured. Small T-rosette foil strain gauges are used and in order to obtain the largest strain change, they are bonded to the inner bore surface and the material removed from the outer surface. It has been found necessary to take strict precautions against temperature effects on the gauges.

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A method of layer removal by chemical milling has been employed as the stresses induced by machining were found to be large and variable, despite efforts at maintaining constant cutting conditions. However some difficulty has been encountered in maintaining dimensional symmetry during chemical milling and it has been necessary to 'true-up' the specimen at intervals by taking very light cuts in a lathe. The effect of this occasional machining on the gauge readings over most of the specimen wall thickness is only slight.

3. Results from the First Specimen

The loading cycle to which the first specimen was subjected is shown in Fig. 2. This is somewhat irregular due to difficulties encountered with the construction of a suitable heater element. These have since been eliminated and subsequent specimens have been subjected to a single steady cycle.

Polynomials have been fitted to the measured data by the "least squares" method and applied to the Sachs equations;

$$\sigma_A = - \frac{E}{1 - \mu^2} \left[(f - f_a) \frac{d\Lambda}{df} + \Lambda \right]$$

$$\sigma_T = - \frac{E}{1 - \mu^2} \left[(f - f_a) \frac{d\theta}{df} + \frac{(f - f_a)}{2f} \theta \right]$$

$$\sigma_R = - \frac{E}{1 - \mu^2} \left[\frac{(f - f_a)}{2f} \theta \right]$$

to calculate the principal residual stress values, presented in Table 1 and illustrated in Fig. 3. The residual stress values calculated by the code PLAST for this loading cycle, are also shown in Fig. 3.

4. Discussion and Conclusions

The results presented should be regarded as preliminary only. They were obtained from measurements on only one cylinder and the authors believe that the prior heat-treatment of this particular cylinder was not in accordance with the manufacturers' specifications for this material. The mechanical properties probably differed therefore from the published data. The authors are now repeating the experiment, using several identical cylinders heat-treated in accordance with the manufacturers' specification and subjected to identical temperature cycles. In parallel with these tests, conventional mechanical tests are being made on specimens from the same batch of material to check that the properties conform to published data.

The conclusion the authors draw from the results presented is that the experiment is feasible and can be extended to include other forms of load cycling, although other forms of loading will require a re-designed rig.

5. Notation

σ_A = axial stress

σ_T = tangential stress

σ_R = radial stress

$\Lambda = (\lambda + \mu\theta)$ where λ = measured axial strain
and θ = measured tangential strain

$\Theta = (\theta + \mu\lambda)$

μ = Poissons ratio

E = Youngs Modulus

f = cross sectional area of cylinder

f_a = cross sectional area of bore of cylinder

6. Acknowledgements

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7. References

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TABLE 1

MEASURED DATA FROM THE FIRST SPECIMEN

Diameter (mm)	Axial strain x 10^{-6}	Tangential strain x 10^{-6}	θ x 10^{-6}	Λ x 10^{-6}
76•28	0	0	0	0
75•57*	-20	-9	-15	-23
74•55*	-29	-16	-25	-34
74•35*	-39	-20	-32	-45
73•69*	-51	-29	-44	-60
73•10	-42	-39	-52	-54
72•29	-50	-48	-63	-64
70•94	-60	-61	-79	-78
69•72	-76	-78	-101	-99
69•11	-80	-82	-106	-105
68•02	-91	-99	-126	-121
67•13	-101	-110	-140	-134
66•29	-112	-121	-155	-148
65•48	-121	-133	-169	-161
64•67	-127	-141	-179	-169
64•44*	-136	-139	-180	-178
62•81	-142	-170	-213	-193
60•15	-160	-204	-252	-221
59•69*	-173	-205	-257	-235
58•40	-181	-234	-288	-251
56•57	-201	-263	-323	-280
55•07	-210	-284	-347	-295
53•59	-227	-309	-377	-320
52•40	-239	-328	-400	-337
51•79*	-253	-329	-405	-352
50•42	-262	-363	-442	-371
49•10	-280	-383	-467	-395
47•37	-298	-408	-497	-420
44•58	-310	-441	-534	-442
41•28	-360	-503	-611	-551
39•90*	-416	-518	-643	-571
37•39	-447	-592	-726	-625
33•78	-520	-676	-832	-723
32•92*	-582	-658	-833	-779

* Denotes layer removed by machining in lathe

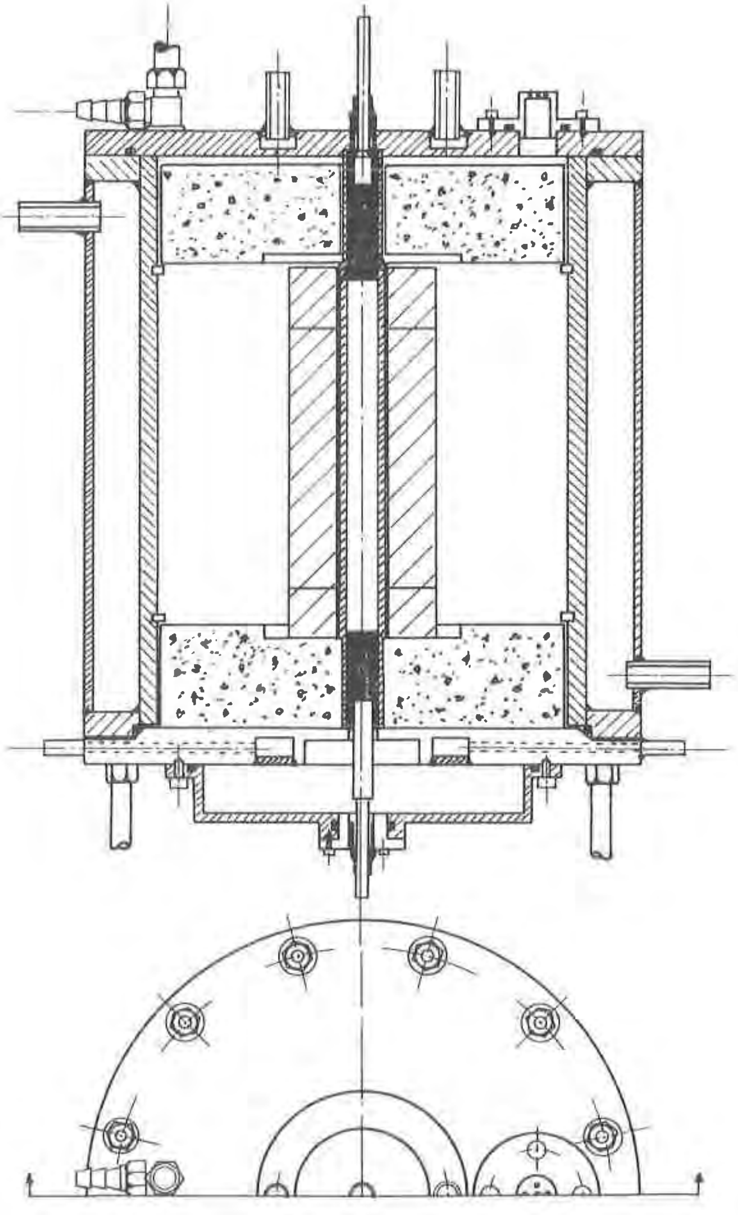

Fig. 1 Layout of Furnace

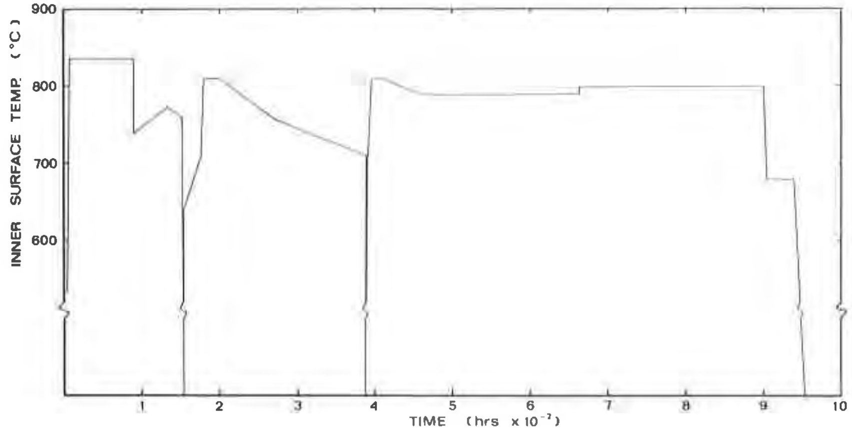

Fig. 2 Loading cycle of first Specimen

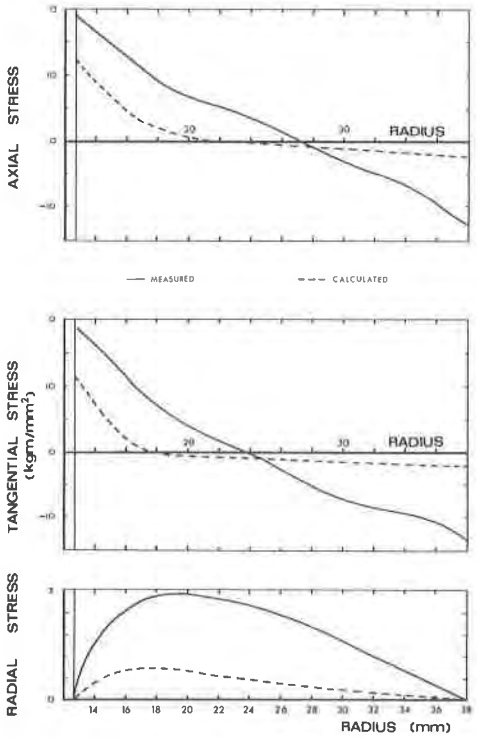

Fig. 3 Measured and Calculated Residual stresses in first Specimen