AN EXPERIMENTAL STUDY OF STRESS REDISTRIBUTION IN NIMONIC CYLINDERS

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SUMMARY

To predict the life of a component of an engineering system, it is essential to compute or otherwise estimate, the stresses and strains to which the material will be subjected. With this objective, many computer programmes have been written, which, it is claimed, compute the stress, strain and deformation histories of components subjected to any prescribed loading sequence. A common feature of many of these programmes is the computation of creep strains, under multiaxial stress, by use of the Mises yield criterion and flow rule, coupled with either a strain-hardening or a time-hardening hypothesis.

In the work described in the present paper, the authors' objectives were to test the validity of these methods under conditions in which the stress distribution in the component is changing with time. The experiment was simple in concept. A thick-walled cylindrical specimen of Nimonic 80A was placed in an evacuated furnace. An electric-resistance heater was mounted concentrically inside the specimen and the walls of the furnace were water-cooled to provide a heat sink. Insulating blocks were placed at the ends of the cylinder to minimise the axial temperature gradients in the specimen. The temperature distribution in the cylinder was in the range 700°C to 815°C, which is the temperature range over which the creep behaviour of this material is well documented.

The initial stress distribution, described by the Lamé equations, was modified by creep. The temperature distribution in the specimen was maintained for 500 hours, after which the specimen was cooled, in a controlled manner, to room temperature. The stress redistribution, due to creep during the prolonged heating, and the final residual stress distribution were computed, assuming various models of creep behaviour. The residual stresses were measured by a modified Sachs layer-removal procedure, in which the layers of material were removed by acid etching in order to avoid the development of additional machining stresses.

At the 2nd SMiRT Conference, the authors described preliminary results obtained from a single specimen. This paper includes results from several specimens subjected to identical load sequences. Repeatable results were obtained, indicating that the random errors are small. Attempts to predict the results by computer have been less encouraging: the authors conclude that neither strain-hardening nor time-hardening hypotheses predict the results well. The authors examine the reasons for the failure of these widely-used theories.

1. INTRODUCTION

In recent years, much effort has been devoted to the development of computer programmes which analyse the behaviour of complex structures, subjected to time-dependent loading, taking account of elastic, plastic and creep strains. However, the development of the numerical methods, on which these programmes are based, seems to have outstripped our understanding of the behaviour of the materials. Many materials are so complex that the physical and metallurgical processes involved are not fully understood: the mathematical models of the deformation processes are, at best, only approximations to the behaviour of the real materials. So, although many computer codes have been developed which manipulate and deliver numbers, the models on which they are based may differ in their behaviour from the real materials to such an extent that, for certain loading histories, the results may be erroneous and misleading.

The importance of the testing and further development of the mathematical models has been widely recognised. Most researchers, however, have chosen to work with specimens subjected to a homogeneous, albeit time-dependent, uniaxial stress, under isothermal conditions. The present authors chose to study a more realistic case, in which the material is subjected to non-homogeneous multi-axial stress, not necessarily under isothermal conditions.

The form of specimen selected for the work is a long, thick-walled cylinder, under axi-symmetric loading. This form of specimen has several advantages. The first advantage is that the material is subjected to non-homogeneous multi-axial stress, while the axial symmetry and the plane strain condition, which exists in all but the end regions of the specimen, simplify the analysis of the stress and strain history. This form of specimen therefore provides a searching test of the mathematical models and the algorithms on which the computer programme is based, but the cost of computing the stress and strain history is modest. In the work described in this paper, the authors assessed the stress redistribution in the specimen, due to creep, by measuring the resulting residual stresses in the specimen. A second reason for choosing this form of specimen, therefore, was the existence of established methods for measuring residual stresses in thick-walled cylinders. A third reason for choosing a thick-walled cylinder was that this is a geometric form which occurs frequently in power plant of all types.

The continuing long term objective of the work is to test the ability of different mathematical models to predict the stress and strain history in a component subjected to time-dependent loading. The computer programme used for the analysis, called PLAST, was developed at Imperial College by Mooiman [1] from an earlier programme written by Spoelstra [2]. The programme analyses the stress and strain history in a thick-walled cylinder subjected to time-dependent axi-symmetric loading, taking account of elastic, plastic and creep strains. This programme is economical and flexible, allowing different algorithms, based on different mathematical models, to be substituted.

Clearly, one essential requirement of a computer code, if it is to predict accurately the stress and strain history of a component under time-dependent loading, is that it should correctly predict any redistribution, due to creep, of the stress in the component. The objective of the work described in this paper, therefore, was limited to testing the ability of the code, and the mathematical models and algorithms on which it is based, to predict stress redistribution due to creep.

In these experiments, thick-walled cylindrical specimens were subjected to a load sequence in which there was significant stress redistribution due to creep. The redistribution of stress manifested itself in a residual stress distribution after removal of the load. This residual stress distribution was measured and compared with the predictions of the code.

In the paper, the authors describe the experiment and present experimental results together with the computer predictions. Possible reasons are given for the discrepancies between the experimental results and the computer predictions.

2. EXPERIMENTAL DETAILS

The details of the experiment are reviewed only briefly, as a more complete description has already been given by the authors [3,4].

Bearing in mind the limited objective of this experiment, to test the ability of the computer programme adequately to predict stress redistribution due to creep, a simple form of loading was selected. The cylindrical specimen was mounted, with its axis aligned vertically, in a cylindrical vessel (see Fig.1 of reference [3]). An electric resistance heater was mounted concentrically in the bore. Insulating blocks were placed above and below the specimen, to minimise the axial heat flow, and the vessel was evacuated to eliminate the axial temperature gradients which otherwise would result from convection. The mechanism of heat transfer from the outer surface of the specimen was therefore radiation to the wall of the vessel, which was water-cooled. The radial temperature distribution in the specimen was monitored by five 1mm diameter Thermocoax chromel-alumel thermocouples located in axial holes in an upper guard ring which was lapped and dowelled to the specimen. The temperatures were recorded continuously on a Honeywell multi-point chart recorder. A prior investigation, in which thermocouples were placed at varying depths in holes which were extended into one specimen, confirmed that the axial temperature gradients were small.

In this simple rig, the specimen was subjected to a radial temperature distribution and therefore to stress, without the need to design and construct an apparatus suitable for high pressure operation. Furthermore, the temperature range in the specimen was such that stress redistribution would occur.

The material chosen for the experiment was Nimonic 80A, for several reasons. This material has physical and mechanical properties which combine to give reasonably high initial stresses with a modest radial heat flow. The experimental parameters were selected to ensure that the range of temperature in the specimen was within the normal operating range for the material, over which there are abundant creep data. Thus the need for an extensive programme of uniaxial creep testing was avoided: a few creep specimens were tested to check that the creep properties of this particular batch of material were within the normal range for the alloy. The cylinders were given the standard precipitation-hardening heat treatment, recommended by the manufacturers (Henry Wiggin Ltd.), after machining. Thus the surfaces were uniformly oxidised. This was important, as variations of surface emissivity, which would have resulted from variations of surface condition, would have led to variations of the temperature distribution between specimens. The extent to which the temperature distribution was replicated can be seen from the readings given in Table I.

In reference [3], the authors reported the difficulties encountered in the design and construction of a suitable heater element. The form of construction eventually adopted, and which was entirely satisfactory, was one in which platinum/20% rhodium wire, 1mm diameter, was wound onto a grooved, fused alumina core and covered with a thin uniform layer of Rockide "A" alumina, applied by flame-spraying. Additional strands of wire were added at the ends of the element and to the feeders, to increase the cross-sectional area of conductor and so reduce the heating in these regions, especially where the feeders were passed through metal/ceramic seals in the ends of the vessel.

A total number of eight cylinders have been processed. Results from the last five only are included in the paper, as the results from the first three cylinders were unreliable for various reasons. The cylinders had the following dimensions:

inside diameter	29mm
outside diameter	75mm
length	150mm.

The loading sequence applied to each cylinder consisted of a period of about 1 hour during which the electrical input to the heater was slowly increased to a maximum of about 3kW. At the end of this period, a steady state temperature distribution was established. This temperature distribution was held for 500 hours, during which the maximum fluctuation of any thermocouple reading was $\pm 1^{\circ}$C. The final shut-down and cooling period was again about 1 hour. The rates of heating and cooling were chosen to avoid transient temperature and stress distributions that might cause yielding of the material. The steady-state temperature distribution for each cylinder is given in Table I.

After cooling, the residual stress distribution in each cylinder was measured by an inversion of the well-known Sachs [5] method. In principal, the method is simple. Strain gauges are attached to the inside surface, gauges being carefully aligned in the axial and circumferential directions respectively. Layers of material are removed from the outer surface and the changes of strain at the inner surface are measured. From the changes of strain, the residual stresses may be calculated.

In practice, the method presents several problems. Once layer removal has commenced, it is not possible to check for zero drift of the gauges. Great care was therefore taken to minimise all potential causes of zero drift. Two types of self-temperature-compensated foil gauge were used; Micro-Measurements 90° Tee Rosette, EA-06-125 TM-120, having a gauge length of 3.18mm, and Kyowa 90° Tee Rosette, KF-2-D1-11, having a gauge length of 2mm. The oxide layer, which formed on the surfaces of the cylinders during heat treatment, was removed by honing with a cast-iron plunger and grinding paste, which produced an even, but slightly roughened surface. The surface was then prepared according to the gauge manufacturers' instructions. The attachment of the gauges was facilitated by use of an expanding mandrel, which was constructed for this purpose. The adhesive was a room-temperature- curing epoxy resin cement, requiring only a low-temperature post-cure treatment. A special magnifying periscope was made, to enable the attached gauges to be examined. Any gauges found to be unsatisfactory, due, for example, to trapped air bubbles, were replaced. The performance of each gauge was checked, at the start and at the end of the layer removal process, by applying axial forces to the cylinder and to the residual thin-walled shell. In no case was any deterioration apparent. To minimise the errors due to temperature effects, the strain measurements were made with the specimen and the Wheatstone bridge placed inside a large box, which was insulated and heated. On-off control enabled the temperature to be held at 30 $\pm$ 0.1^{o}C. After each layer removal, the specimen was placed in the box for several hours, to reach a uniform temperature, before making any strain readings. A Tinsley slide-wire, null-balancing bridge was used, built into the side of the temperature-controlled box and operated from outside the box. The calibration was checked periodically, using precision resistors. The initial balance of each gauge circuit was attained with the aid of a Solartron balancing unit. The power supply was from a stabilised d.c. power pack, set to 2.000 volts and the voltage was constantly monitored by a Solartron digitial voltmeter. The a.c. ripple was less than 1 millivolt. Errors arising from gauge heating, earth leakage and impedence effects were thus kept to a minimum, without seriously reducing the sensitivity.

The first method used for layer removal was turning. This method proved to be unsatisfactory, as machining stresses introduced a large and variable error. Denton [6] has proposed a method of correcting for the error, but the method is based on the assumption that the machining stresses are the same after each cut. Despite taking every precaution, by maintaining a uniform cutting speed, depth of cut and tool profile, random variations of the strain gauge readings indicated that the machining stresses were not constant. Turning was therefore abandoned in favour of chemical milling (acid etching), using an etchant developed by Rolls Royce (Bristol).

To facilitate the repeated connection and disconnection of the gauges to and from the bridge circuit, multi-pin gold plated Lemo connectors were used. Checks indicated that the error due to variations of contact resistance were less than 5 microstrain. To protect the gauges, the inside surface and the ends of each specimen were coated with Turco rubber. In addition, double-taper bungs of rubber and polythene were used to prevent the ingress of the etchant to the bore. The bungs incorporated a sealed protective housing for the strain gauge connectors, to prevent damage in the event of the leakage of the etchant past the bungs.

In order to achieve near-uniform layer removal, the cylinder was mounted on two polypropylene rollers, arranged with their axis parallel to each other, below the free surface of the etchant in a polypropylene tank. The rollers were driven by electric motors, mounted outside the tank, through polypropylene gears. Thus the cylinder was slowly rotated and material removed fairly uniformly. It was necessary to take a very light cut by turning, once or twice during the entire process, to maintain a tolerance of $\pm$0.25mm on the diameter. The tank was mounted inside a water bath, which was kept at 60^{o}C, at which temperature a rate of removal of material of 0.025mm per minute could be achieved. The light machining produced a small step change of strain reading, due to machining stresses, but the effect was eliminated by subsequent etching of the stressed layer.

3. RESULTS

Table I shows the steady-state temperature distribution in each of the last five specimens. Fig.1 shows the stress distributions computed for several time points during the 500 hours at the steady-state temperature distribution measured in specimen 8. The figure shows also the computed residual stress distributions. These results were obtained using a time-hardening creep theory. The results obtained using a strain-hardening theory were very similar and are therefore omitted. Fig. 2 shows the strain gauge readings from the five specimens and indicates the variance of the readings. It should be noted that on each cylinder at least four gauges were used in each direction. Thus the sample size is never less than 20. The error bars indicate two standard deviations either side of the mean strain.

Polynomials were fitted, using a least squares computer programme, to the strain gauge readings from each cylinder. The residual stress distribution in each cylinder was calculated using a form of the Sachs' equations proposed by Barker and Hardy [7]. The use of the equations in this form reduces the error involved in extrapolating to the inner radius of the cylinder: for practical reasons, the layer removal process was discontinued when the residual shell wall thickness was reduced to about 1mm, thus it was necessary to extrapolate to the inner radius. Fig.3 shows the average residual stresses derived from the strain gauge readings from the five cylinders. The error bars indicate the range of values of the stresses, between the five cylinders, at each radius. The figure also shows the computed residual stresses.

3. DISCUSSION AND CONCLUSIONS

Figs. 2 and 3 indicate that the random errors in the measurement of the residual stresses have been reduced to an acceptable level. The agreement between the measured residual stresses and the computer predictions is not good. The discrepancy could, of course, be due to systematic error in the method of measurement, the most probable source of systematic error being zero drift of the gauges. However, the extreme care taken to prevent zero drift, and the performance of the gauges before and after layer removal, lead the authors to the conclusion that zero drift was not significant.

It is the authors' opinion that the discrepancy is more likely to be due to inadequacies of the models on which the computer programme is based. One obvious inadequacy is the inability of the time-hardening and strain-hardening theories to take account of creep recovery, which might be expected to occur in regions where the stresses are relaxed during the 500 hours heating period. Another possible source of error in the computer prediction is the assumption that the material was isotropic. Metallographic examination, after heat treatment, failed to detect anisotropy of the microstructure. But, as the creep properties may be expected to be influenced by the smallest variations of microstructure, conventional creep tests are being made, on specimens cut from the axial and transverse directions of the bar stock.

Cox [8] and Myatt [9] have observed that, in Nimonic 80A, over-aging at a high temperature can result in changes of the Young's modulus measured at that temperature. For example, a reduction of modulus by up to 20% has been reported, after soaking at 800°C for 800 hours. No significant change has been detected in the modulus measured after cooling to room temperature. If this change of the elastic modulus with over-aging is characteristic of this material, and if the effect is temperature-dependent, the stress distribution during the heating cycle may be sufficiently modified to cause significant changes of creep strain and, therefore, of the residual stress distribution. The authors have some evidence that this effect may have influenced the residual stresses: hardness measurements, made at different radii across the end face of one cylinder, showed that after the prolonged heating there was a significant variation of hardness. While this does not provide positive evidence of a variation of Young's modulus, it does indicate that over-aging may have caused non-uniform changes of microstructure.

In conclusion, the authors have confidence in the experimental results, but cannot yet explain the discrepency between these results and the computer predictions. Additional work, not yet completed, may help to explain the discrepency. But it is clear that the computer programme, which is based on models which are very widely used, does not predict the stress history in the simple loading sequence used in these experiments. This result, therefore, casts doubt on the ability of the programme to compute the stress and strain history in more complex loading sequences.

4. ACKNOWLEDGEMENTS

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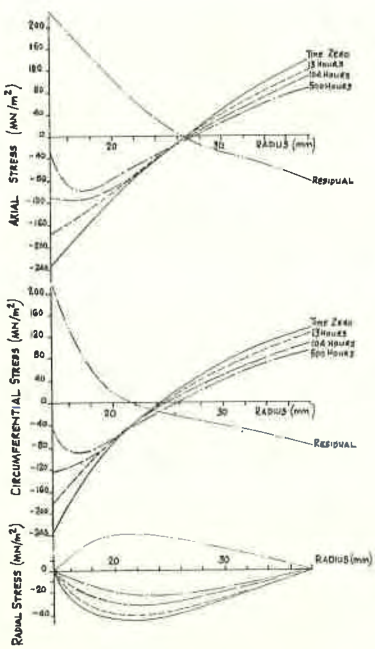
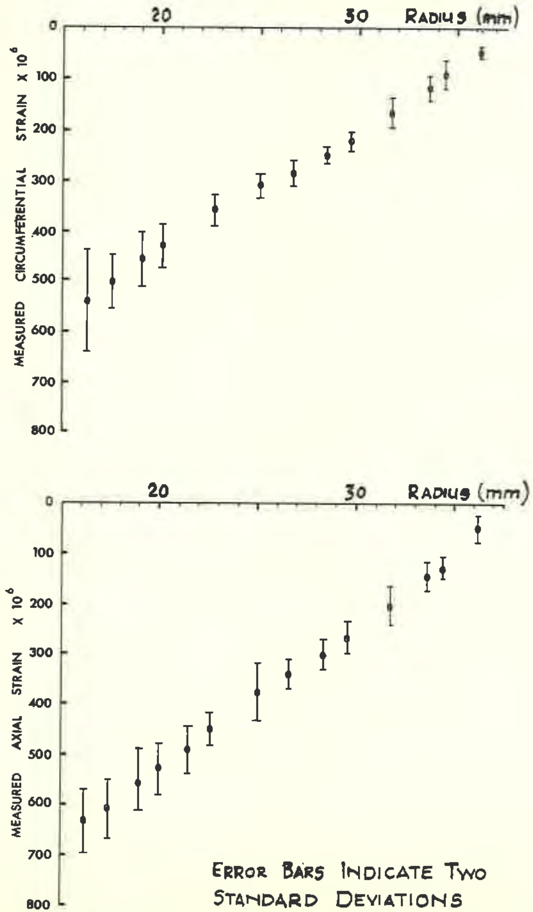
Table I

Measured Steady-state Temperature Distributions

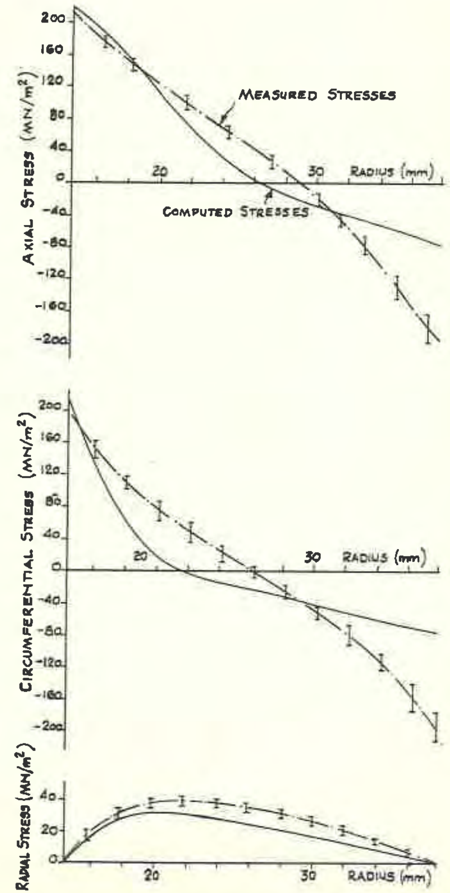
Radius (cm)	1.42	1.67	2.09	2.56	3.55
Specimen	Temperature (^{o}C)				
4	810	807	788	774	752
5	810	782	768	770	728
6	808	788	775	772	732
7	813	792	780	770	728
8	813	798	782	774	737



Computed Stress Distributions



Strain Gauge Readings



Measured and Computed Residual Stress Distributions