The ratchetting behaviour of stainless steel type 316 at ambient and elevated temperatures

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SUMMARY

This paper describes tests undertaken to determine the 1% strain accumulation boundary in stainless steel type 316 strip subjected to constant axial tension and a cyclic change of curvature. Boundaries are obtained for temperatures between 300°C and 500°C. These are compared with two design rules, both of which are shown to be conservative. Additionally, the temperature at which the transition from the characteristic room temperature behaviour of continued ratchetting to the "shakedown" observed at elevated temperatures is investigated. Preliminary results indicate such a transition at approximately 150°C.

1 INTRODUCTION

Over the past two decades numerous studies have been undertaken to estimate the strain behaviour of structures subjected to cyclic mechanical and thermal loads. For the design of liquid metal cooled fast reactors such strain behaviour is of particular significance since designs can permit cyclic thermal stresses in excess of twice yield together with significant primary stress levels. It is feasible to estimate the strain behaviour of structures subjected to this type of loading provided that the material characteristics are significantly simplified. Advances in formulating constitutive equations and improvements in computing power will permit such calculation to be undertaken for more complex material models. However, there is at present little reliable experimental data available to guide designers in what to expect of real materials under such loading. Notable exceptions to this statement have been collectively used by Clement et al. (1984) to formulate a design rule aimed specifically at stainless steel type 316 which is the material now specified for many fast reactor designs.

Design philosophy is now accepting that strain due to ratchetting should be limited over the life of the structure to a total accumulation of less than 1%. Thus, the so-called efficiency diagram of Clement et al. (1984), in common with other design rules (see e.g. ASME (1977)) depicts the 1% strain accumulation boundary as the design limit. With this in mind, it has been the authors' intentions to add to the available experimental data results of tests conducted on stainless steel type 316. The loading chosen was that thought to be representative of some circumstances encountered in LMFBR design and, the nature of these experiments permitted a range of operating temperatures to be investigated.

2 EXPERIMENTAL TECHNIQUE

The technique used was that which emulates Bree (1967) loading. That is, thin strips of the test material were subjected to a continuous axial load together with an alternating change of curvature. The temperature of the test environment could be controlled within the range RT-500°C to ±2°C. The strain accumulation in the axial direction of the strip is analogous to that produced in the hoop direction of a cylinder experiencing continuous internal pressure with alternating through wall thermal gradients.

The experimental procedure, equipment and techniques used are fully described in Ng et al. (1984). For the present series of tests it was intended to establish boundaries of ratchetting at 300, 400 and 500°C. That is, tests were to be conducted over a range of axial and bending stresses (analogous with pressure and thermal stresses) at each temperature. For each stress combination and temperature a fresh strip of S/S 316 (solution treated at 1050°C) was subjected to the loading described. The extension of the strip was monitored using LVDTs and not the strain gauge transducers as described in Ng et al. (1984). Testing was continued until either (a) further cyclic changes in curvature produced no increase in strain accumulation or (b) 500 cycles of curvature change had been completed.

3 MATERIAL PROPERTIES

Considerable difficulties were experienced in determining the tensile properties of the stainless steel strip used in this investigation. Since the strip was of such thin cross section, ceramic bonded or weldable strain gauges could not be used for strain measurement since any such device would be of greater stiffness than the section itself.

An arrangement in which a 250 mm gauge length of test material was contained within a temperature controlled furnace with extension arms to a room temperature zone was utilised. A strain gauged load cell was employed to monitor dead-weight loading of the test strip and LVDTs in the room temperature zone were used to measure extension. Tensile tests up to strains of 2.5% were undertaken using this equipment. The 0.2% proof stress values so obtained are listed below:

Temperature	Exp. $\sigma_{0.2}$	ASME S_m (S_{mt})
300°C	117 MN/m²	119 MN/m²
400°C	126 MN/m²	117 MN/m²
440°C	133 MN/m²	109 MN/m²

Since these experimental results differ significantly from the ASME data the latter values have been used to normalise results presented in Figures 1-4.

4 1% STRAIN ACCUMULATION BOUNDARIES

At the outset of this work the testing procedure planned was to specify an operating temperature and cyclic curvature change so that tests could be conducted to study the effect of increasing the axial stress. It was anticipated that such tests would show a transition from "shakedown" to ratchetting behaviour - when moving from left to right on the so-called Bree Diagram. Within the temperature range 300-500℃ no such transition was found since for all bending stress and direct stress combinations the material appeared to "shakedown" (i.e. cease ratchetting) within 100 curvature change cycles. However, the strain accumulated in attaining this "shakedown" state was very large and thus the investigators chose to identify the loading states which gave rise to a 1% strain accumulation. Figs. 1, 2 and 3 show these data plotted on Bree type diagrams at the test temperatures of 300, 400 and 500℃. Also depicted on these diagrams are the ASME Design Code Section III (1977) recommendations. In all cases these design curves are conservative. It should be noted that in preparing these curves the authors have used the material properties quoted by ASME (1977) for the relevant temperatures. In a similar manner the test results have also been plotted on the Efficiency Diagram and presented here as Fig. 4.

5 SHAKEDOWN/RATCHETTING BEHAVIOUR WITH CHANGING TEMPERATURES

Earlier work in this area e.g. Ng and Moreton (1982) had shown that a distinct "shakedown"/ ratchetting boundary existed for stainless steel type 316 at room temperature. It is reported above that no such boundary was detected within the temperature range 300-500℃. Thus it was felt important to identify at what temperature the transition in behaviour occurred.

Tests were conducted in the manner detailed previously. A bending stress ratio σ_B/σ_y = 3.90 and an axial stress ratio σ_D/σ_y = 1.67 were initially used, where σ_y was the measured room temperature yield stress. The furnace temperature was raised to a chosen level before curvature cycles were commenced. Tests were undertaken at temperatures between room temperature and 400℃. Curvature change cycles were continued until either "shakedown" was established or 500 cycles had been completed. With a cycle time of 42s this corresponded to about one working day (including heat-up time). The test programme was repeated for a bending stress ratio of 2.89. The strain accumulated in reaching a "shakedown" state or the total strain accumulated (within 500 cycles) was recorded and has been plotted as Fig. 5. This figure also indicates if "shakedown" was achieved within the 500 cycle limit or if ratchetting persisted.

6 DISCUSSION OF RESULTS

The technique used to establish the mechanical properties of the test steel at elevated temperatures was not considered to be entirely satisfactory. Various methods had been attempted but because of the very thin section of the test strips no totally reliable technique could be found. The results obtained by the technique described previously were found to differ significantly from those quoted by

ASME Design Code Section III and Code Case N47 (1977) and thus the figures from those publications have been employed in normalising the stress values.

The plots of 1% strain accumulation detailed by Figs. 1, 2 and 3 show a trend, which would be expected, of following the Bree ratchetting boundary. Reference to Moreton and Ng (1981), for example, indicates lines of constant strain accumulation to be parallel with such a ratchetting boundary. These illustrations also serve to indicate the conservative nature of the ASME Design publications. Similarly the Efficiency Diagram of Clement et al. (1984) provides a design curve which is conservative for designing to 1% strain accumulation.

The work aimed at identifying the temperature at which ratchetting behaviour ceases has proved to be successful although limited in scope. It is apparent, from the results available that ratchetting ceases at about 150°C and that this is associated with a peak value of strain accumulation. The data presented is for one wheel size and two values of axial load only. Early results indicate that the peak strain accumulation does not occur at the same temperature for tests conducted with different bending stress ratios. However, this data is as yet incomplete and will be discussed further in the presentation of this paper.

7 CONCLUSIONS

Ratchetting tests have been conducted at temperatures between 300°C and 500°C by imposing constant axial stress together with alternating changes of curvature on thin strips of stainless steel 316.

It was found that within the temperature range investigated "shakedown" was always achieved within a relatively small number of curvature change cycles. However, the strains accumulated in reaching this state were large. Lines indicating 1% strain accumulation have been plotted together with ASME design curves. The latter have been shown to be conservative.

In similar tests, conducted between room temperature and 400°C a transition between ratchetting and "shakedown" behaviour has been identified at 150°C.

ACKNOWLEDGEMENTS

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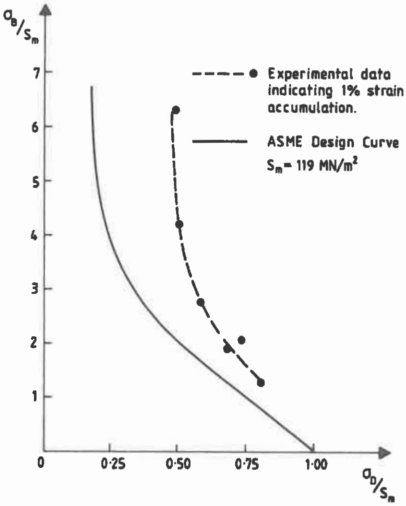

Fig. 1 Data for 300°C

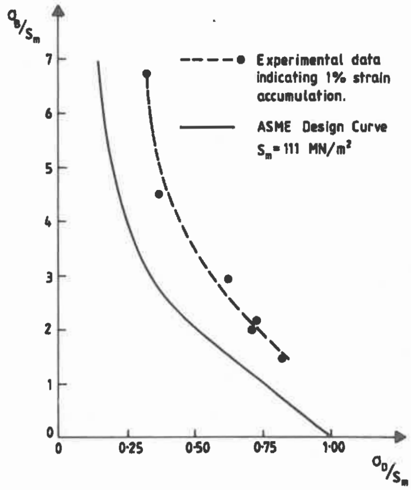

Fig. 2 Data for 400°C

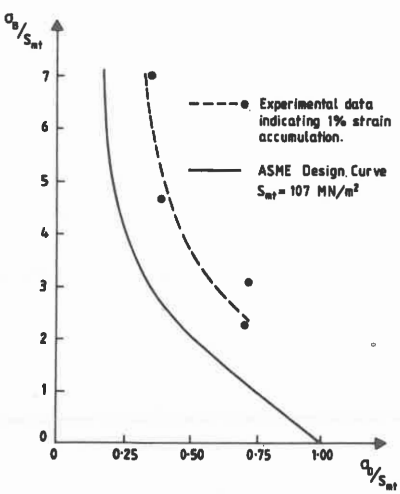

Fig. 3 Data for 500°C

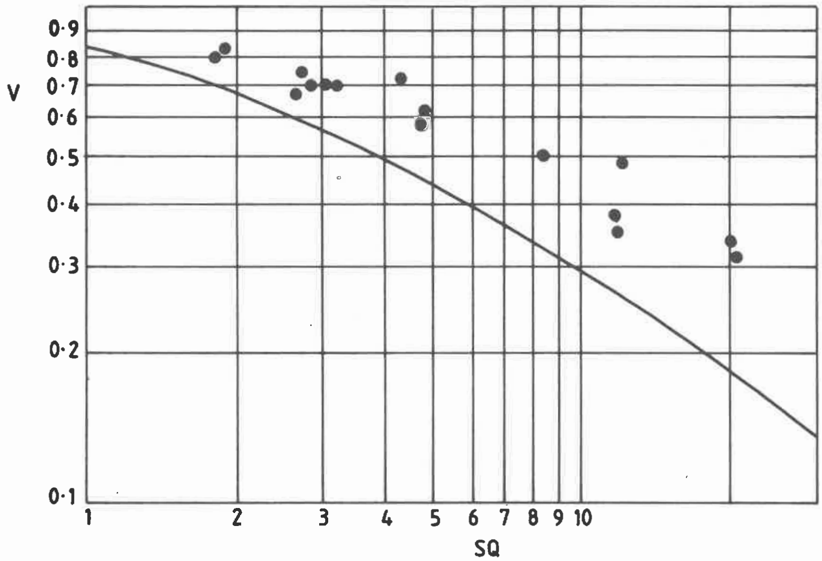

Fig. 4 1% Strains Plotted on Efficiency Diagram at Clement et al. (1984)

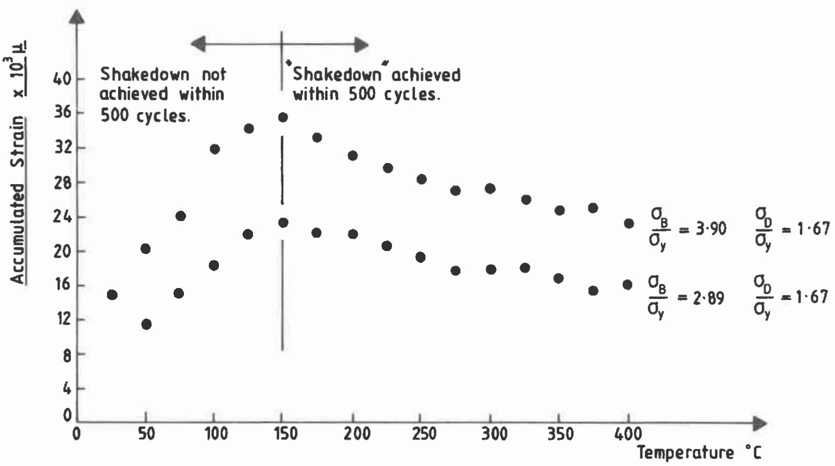

Fig. 5 Shakedown/Ratchetting Behaviour with Changing Temperature