The Behaviour of Stainless Steel Type 316 Under Bree Type Loading at Elevated Temperatures

D.J. Brookfield, D.N. Moreton
University of Liverpool, Division of Applied Mechanics, P.O. Box 147, Liverpool L69 3BX, U.K.

Abstract

Thin strips of stainless steel have been subject to constant axial tension and cyclic curvature change, i.e. Bree type loading. By measurement of the strip length the presence or otherwise of ratchetting could be determined. Some initial results are reported for temperatures of 300, 400 and 500°C. These results are compared with ASME III design rules.

Notation

E	Elastic modulus (measured at room temperature)	R	Radius of wheel
		t	Thickness of strip
σ_b	Bending stress (equivalent to Bree thermal stress)		
σ_d	Direct stress (equivalent to Bree pressure stress)		
σ_y	Room temperature first yield stress		
$\sigma_{0.2}$	0.2% proof stress		
μ	Strain x 10^{-6}		

1. Introduction

In the liquid metal fast breeder reactor the fuel can walls are subjected to internal pressure, which may be considered as constant, and a cyclic through wall thermal gradient. This combination of a steady mechanical load and cyclic thermal strain can result in ratchetting, i.e. the accumulation of strain on each thermal cycle. Such a failure mode was examined by Bree [1] for an elastic/perfectly-plastic material and the now well-known "Bree Diagram" developed.

This type of loading is common in many reactor components where the material properties may not be idealised in this way. Stainless steel type 316 is now often specified and its mechanical behaviour shows marked strain-hardening.

Attempts to reproduce Bree loading in the laboratory are made difficult by the very large thermal power inputs required to produce the necessary thermal gradients. For example, to produce first yield in a stainless steel cylinder of 0.1 m radius and 0.005 m wall thickness requires a thermal input of the order of 60 kW per metre length. Because of this difficulty a method of simulating Bree loading was developed. The basis of this method is the application of a simulated thermal load to a strip of the test material by forming the strip around the periphery of a wheel. A steady tensile axial load simulates the pressure component. Rotary oscillation of the wheel causes two portions of the strip to be alternately formed around the wheel or straightened. This process simulates the cyclic thermal load and ratchetting is observed as an increase in the length of the test strip.

Tests on both elastic/perfectly-plastic and strain-hardening materials using this Bree simulation have been reported by Ng and Moreton [2]. Of particular interest here are the tests on type 316 stainless steel. In these, ratchetting was observed to continue over 10^3 cycles at various combinations of direct and thermal stress. Although the ratchet rate observed during the first 100 or so cycles was a function of the cycling rate, the "steady state" ratchet rate after a greater number of cycles appeared to be independent of this.

The tests reported by Ng and Moreton were, in all but one test, conducted at room temperature. Considerable cold (logarithmic) creep has been observed in stainless steel type 316 [e.g. 3,4] at room temperature. It is likely that a component of the observed strain accumulation would have occurred without cycling due simply to this cold creep. In a fast reactor, however, the operating temperature is such that logarithmic creep is unlikely. Furthermore the properties of stainless steel type 316 change appreciably with temperature. It was thus considered useful to extend the experimental work of Ng and Moreton to the temperatures likely to be experienced in an operational reactor.

2. The Experimental Procedure

The basis of the simulation of Bree loading by deforming a strip to a specified radius has already been reported [2]. The rig employed for room temperature tests was fully described in [5]. To enable tests to be undertaken at elevated temperatures an insulated jacket was constructed to enclose this rig and electrical heating used to provide a maximum power input of 6 kW. The standard of the thermal insulation was such that a temperature of 500℃ could be maintained without difficulty. The modifications for elevated temperature testing are described in [6].

Stainless steel of type 316 is frequently specified for components in nuclear power plant. This material was selected for the tests described here. Strips of test material were prepared by shearing from sheet. Following shearing the strips were stress relieved at 1050℃. Great care was taken to avoid introducing any permanent set into the strips before they were each loaded onto the wheel. Specimens cut from the sheet were analysed and the composition obtained is listed below. This conforms with the appropriate British Standard requirement for such material.

Elem	C.	Si	S	P	Mn	Ni	Cr	Mo
	0.019	0.400	0.003	0.021	1.60	12.06	17.81	2.53

The tensile properties of the strip at room temperature were obtained using adhesive mounted strain gauges and dead weight loading. First yield, defined as the departure from linearity of the stress/strain curve, was found at a stress of 84 MNm^{-2}. The room temperature elastic modulus was 186 x $10^9 Nm^{-2}$. Tensile testing at elevated temperatures was complicated by difficulty in measuring the elongation of the specimen. Although work is currently being undertaken to measure the tensile properties of the strip at the elevated temperatures used in the cyclic tests, the room temperature elastic modulus is used here in calculating the bending stress from the wheel radius. Similarly, both the bending and direct stresses are normalised with respect to the room temperature first yield stress. It is important to appreciate that whilst the direct stresses shown are correct, the bending stress are fictitious elastic being calculated from

$$\sigma_b = \frac{ET}{2R}$$

In this series of tests, the procedure followed was to mount the strip on to the wheel and attach weights to its free ends. The temperature of the strip and the wheel was then raised to the test temperature and maintained for approximately one hour before oscillation of the wheel was started. The wheel speed was adjusted so that a cycle of bending and straightening was completed in 42 s. The length of the strip was monitored using displacement transducers mounted outside the hot zone of the rig.

3. Results

The initial intention of the test programme was to establish ratchetting boundaries on the Bree diagram at 300℃, 400℃ and 500℃. Of the nature of the test rig it was impossible to experimentally determine other Bree boundaries as alternating plasticity, for example, could not be detected. In the room temperature tests previously reported [2] and [5] a clear ratchetting boundary was observed with ratchetting ceasing within 100 cycles to the left of the boundary. It rapidly became clear that such a boundary was not to be found in the elevated temperature test results. In each of the 50 or so tests with different combinations of direct stress, bending stress and temperature conducted to date, "shakedown" was achieved within fewer than 100 cycles. It is important to appreciate that shakedown in this context refers purely to the cessation of ratchetting.

Because continued ratchetting was not observed, the important result from each test was the strain accumulated in achieved "shakedown". These strains have been determined for two wheel radii, at three temperatures and over a wide range of direct stresses.

Fig. 1 shows typical strain accumulation data from a test at 400℃. The rapid decay in the ratchet strain rate is clearly visible. This can be compared with the room temperature strain accumulation for this steel reproduced from [2] as Fig. 2. It can be seen that although ratchetting ceased during the elevated temperature test, the accumulated strains are considerably greater than those observed in the room temperature tests with similar combinations of bending and direct stress. A similar result was obtained in each of the tests.

Figs. 3-8 show the total ratchet strains accumulated during each test as a function of the applied direct stress. Within the limits of experimental error these appear to be a linear function of the normalised direct stress. A least squares routine has been used to fit straight lines to the data for each bending stress/temperature combination. The coefficients of these lines have then been used to find the best estimate of the applied direct stress at which a specified total strain accumulation occurs.

4. Discussion

The results obtained in the elevated temperature tests were clearly very different from those reported from previous tests at room temperature. Although the present results show "shakedown" in every case, the accumulated strains are very large compared with those over the same number of cycles at room temperature. In some of the tests shown in Figs. 3-8 the accumulated strains exceeded 3%.

A 1% strain limit was proposed by Townley [7]. Fig. 9 shows the 1% strain accumulation boundary at 400℃ obtained using the least squares coefficients from Figs. 5 and 6. The 0.2% proof stress has to date only been measured at room temperature. However, a mean 0.2% proof stress of 160 MNm^{-2} at 400℃ was found by Sikka and Booker [9] in surveying tests on American samples of 316 stainless steel. Fig. 9 shows a portion of an ASME III design curve based on this. It can be seen that the 1% boundary occurs at a lower direct stress than the ASME curve.

5. Conclusions

The response of 316 stainless steel to Bree loading of 300℃, 400℃ and 500℃ has been investigated. It has been shown that at two simulated thermal stresses ratchetting ceases within 100 cycles over a wide range of direct stresses.

An ASME III design curve is shown to be non-conservative with respect to the 1% strain accumulation boundary at 400℃.

6. References

/1/ BREE, J., "Elastic-Plastic Behaviour of Thin Tubes Subjected to Internal Pressure and Intermittent High Heat Fluxes with Application to Fast Nuclear Reactor Fuel Elements", J. Strain Anal., Vol. 2, No. 3, 226-238, (1967).

/2/ NG, H. W., MORETON, D. N., "The Bree Diagram - Origins and Literature: Some Recent Advances Concerning Experimental Verification and Strain Hardening Materials", Recent Advances in Creep and Fracture of Engineering Materials and Structures, Wilshire, B. and Owen, D. R. J. (eds.), Pineridge Press, Swansea, 185-230, (1982).

/3/ MORETON, D. N., MOFFAT, D. G., "Shakedown of Three Stainless Steel Pressure Vessel Components", 3rd Int. Conf. on P.V. Tech., 233-245, (1976).

/4/ BROOKFIELD, D. J., MORETON, D. N., MOFFAT, D. G., "Shakedown and Cold Creep of Stainless Steel Type 316 Torispherical Drumheads Subjected to Internal Pressure", 5th Int. Conf. on P.V. Tech., A.S.M.E., (September 1984).

/5/ MORETON, D.N., NG, H. W., "The Extension and Verification of the Bree Diagram", 6th Int. Conf. SMiRT, Paris, Paper L10/2*, (August 1981).

/6/ NG, H. W., BROOKFIELD, D. G., MORETON, D. N., "A Technique for Conducting Shakedown Tests at Elevated Temperatures", Strain, J. of the Brit. Soc. for Strain Meas., Vol. 20, No. 1, 7-14, (1984).

/7/ TOWNLEY, C. H. A., "Designing Pressure Vessel Details", The Engineer, 438-445, (March 1969).

/8/ AMERICAN SOCIETY OF MECHANICAL ENGINEERS, "Boiler and Pressure Vessel Code", Sec. III, Div. 1, ANSI/ASME BPV-III-1-NC, (1976).

/9/ SIKKA, V. K., BOOKER, M. K., "Assessment of Tensile and Creep Data for Types 304 and 316 Stainless Steel", J. Press. Vess. Tech., A.S.M.E., 298-313, (May 1977).

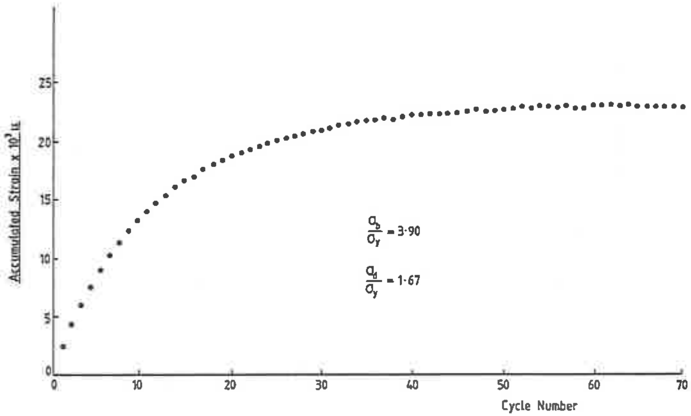

Fig. 1. Accumulated Ratchet Strain at 400℃.

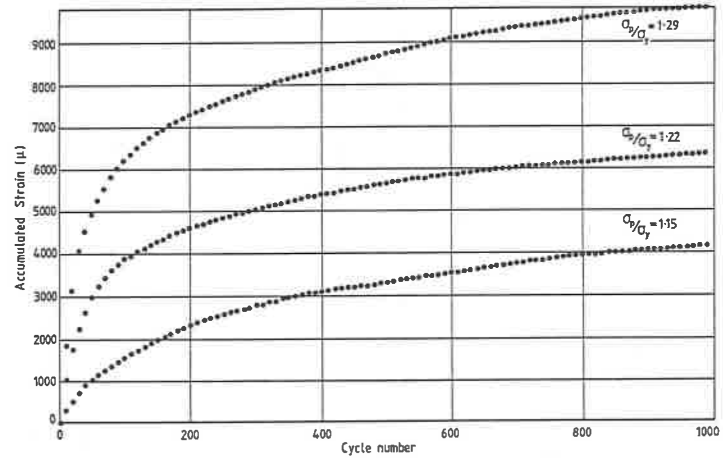

Fig. 2. Room Temperature Strain Accumulation (from (2)).

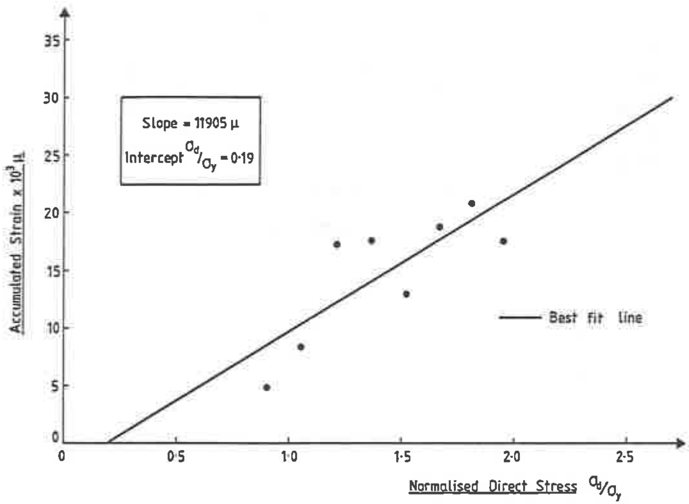

Fig. 3. Strain Accumulation σ_b/σ_y = 2.86 at 300℃.

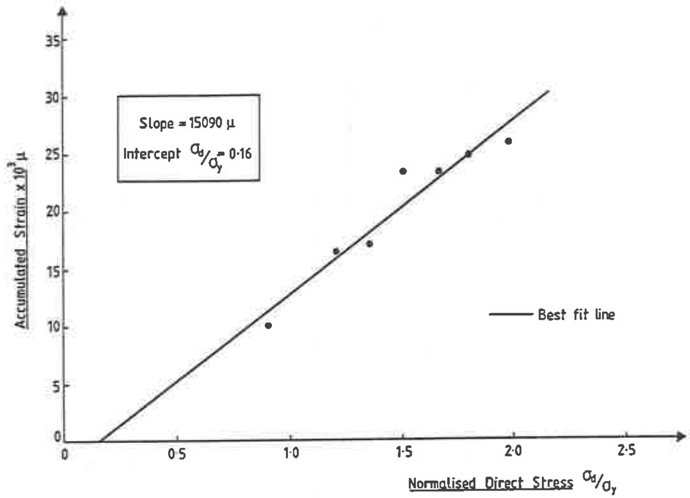

Fig. 4. Strain Accumulation σ_b/σ_y = 3.90 at 300℃.

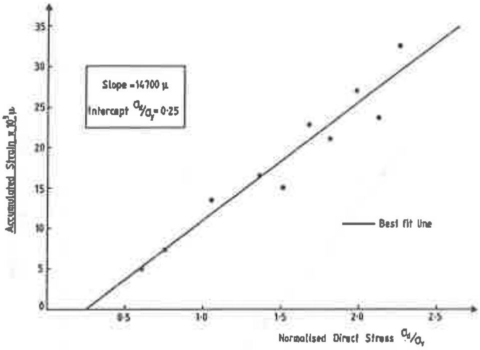

Fig. 5. Strain Accumulation σ_b/σ_y = 2.86 at 400°C.

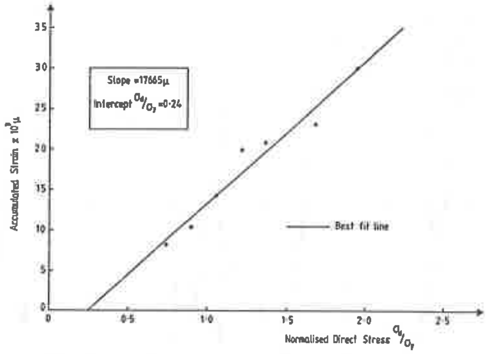

Fig. 6. Strain Accumulation σ_b/σ_y = 3.90 at 400°C.

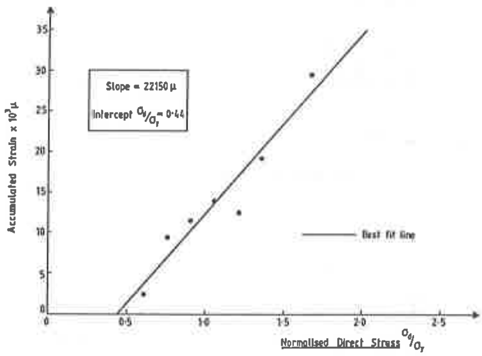

Fig. 7. Strain Accumulation σ_b/σ_y = 2.86 at 500°C.

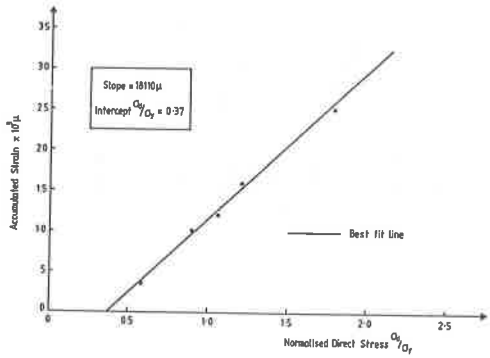

Fig. 8. Strain Accumulation σ_b/σ_y = 3.90 at 500°C.

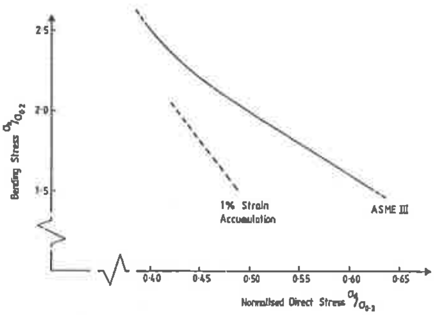

Fig. 9. 1% Strain Accumulation Boundary at 400°C.