Low Cycle Fatigue of a Pressure Vessel Steel at Elevated Temperature

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Summary

Load control fatigue data for ASTM A516Gr70 steel were obtained. These data may be used for a ratchetting analysis of a pressure retaining system.

Strain accumulation during cycling is shown to depend on both stress amplitudes and mean stresses. The shift in hysteresis loops is negligible at stress amplitudes below 345 MPa. Strain control conditions can, therefore, be assumed if operating transients are proven to result in stress amplitude values below this limit. Although the final shift in the cyclic loops is shown to depend on the load application sequence, the number of cycles to failure is found to be insensitive to loading sequence. In addition, no shift in the cyclic loops occurs at the low stress levels during high-low-high and low-high loading tests. Therefore, small stress amplitudes at high mean stresses which result from operating transients may be neglected in the finite element ratchetting analysis of a pressure vessel.

1.0 Introduction

Thermal ratchetting is a well defined mechanism of strain accumulation in a structure when subjected to thermal cycling. It is one of several possible modes of cyclic strain accumulation caused by the periodic application of loads and temperature [1]. This phenomenon may cause serious damage if shakedown requirements cannot be satisfied. In particular, the fatigue behaviour of materials under these conditions is not fully understood.

Despite the importance of thermal ratchetting, very little experimental work has been reported in literature [2] and most investigations of ratchetting are computations in which the behaviour of the material is idealized by an elastic-perfectly plastic stress strain relation [1]. In these investigations, no consideration is given to the changes which may occur in the material due to cyclic hardening or softening. However, the material behaviour under cyclic loading is an important element in obtaining a realistic elastic-plastic analysis of a pressure vessel. Therefore, a project was initiated to determine fatigue properties of A516Gr70 steel under strain and load control, to provide a better knowledge of the damsge process under both conditions. This report presents the load control test results for both room and high temperature conditions with emphasis given to the following results:

1. The cyclic behaviour of the material under constant amplitude load control testing with various applied mean stresses.
2. The effect of the loading sequence on cyclic behaviour under load control.

Although the above results are obtained by testing simple uniaxial specimens, they are expected to provide a better knowledge of the degradation process due to ratchetting.

2.0 Material and Experimental Procedure

The material for this test program is ASTM A516Gr70 pressure vessel steel for low and moderate temperature use. Low cycle fatigue test samples were cut from a steel plate with their axes transverse to the final rolling direction of the plate. The chemical and mechanical properties of the material are given in Table 1 and Reference 3. Test specimens with threaded ends and reduced diameter cylindrical test sections were employed. The test sections were 12 mm long and 9.5 mm in diameter.

Cyclic tests were performed under load control with stress amplitudes ranging from 200 MPa to 482 MPa and mean stresses of zero to 69 MPa at both room temperature and 260°C. The stresses acting on the specimens are nominal stresses and are determined by dividing the applied load by the cross sectional area of a specimen. Room temperature strain measurements were carried out using an extensometer attached to the specimen surface. At 260°C, deflections were measured across the threaded ends of the specimen. Strains were then estimated via a calibration curve which relates the deflection at the ends of the specimen to the strain on the specimen test section.

3.0 Cyclic Response Under Constant Amplitude Load

3.1 Strain Accumulation During Cycling

When a metal is subjected to cycles of plastic deformation between fixed limits of stress, a progressive change in the observed hysteresis loops will occur from cycle to cycle, as shown in Figure 1. The axes of the diagram are given in terms of nominal stress and axial strain. The first loading cycle results in a relatively large strain depending on the magnitude of the first stress limit reached. Subsequently the longitudinal strain increases with cycling. Experimental data similar to that shown in Figure 1 were obtained for various stress amplitudes and mean stresses at both room temperature and 260°C. These data have been used to prepare the results shown in Figure 2. In this figure the maximum longitudinal strain is plotted versus cycles. This figure indicates that at fully reversed stress amplitudes ($\Delta\sigma/2$) between 345 and 427 MPa, the maximum strain initially decreases due to cyclic hardening, reaches a steady state and thereafter increases until the specimens fail. However, as the stress amplitudes exceeds 427 mPa, the maximum strain value continuously increases with cycling. Figure 2 also indicates that at stress amplitudes below 262 MPa, maximum strain values remain constant with cycling resulting in a negligible shift in the hysteresis loop. In this case load control and strain control test conditions will yield the same fatigue life as illustrated in the next section. In addition to the above observations, cyclic hardening is also observed to reduce the width of the hystersis loops with continued cycling especially at higher stress amplitudes.

3.2 Stress Life Curves

Results of the experiments outlined in Table 2 are shown in Figure 3. Here the applied nominal stress amplitude is plotted versus number of cycles to failure for mean stresses (σ_0) of zero and 69 MPa. Stress amplitudes measured at half life obtained previously from strain control tests [3] are also plotted against life in the same figure for comparison. Figure 3 indicates that as stress amplitudes increase above 345 MPa, load control test conditions reduce the fatigue life as compared with strain control conditions. The reduction in fatigue life increases with increasing mean stress. However, at stress amplitudes below 345 MPa, load control and strain control life curves are identical.

It appears that the reduction in life of test specimens under load control is related to the amount of shift of the cyclic loops [4-5]. The hysteresis loop shift per cycle increases with incresing mean stresses for a particular stress range and vice versa. Both mean stresses and stress amplitudes produce a combination of cyclic extensional strain sccumulation and alternating plastic strains. Failure under load control conditions is then due to the cyclic accumulation of strain, and fatigue, resulting from alternating strains. Consequently, at stress amplitudes below 345 MPa where the shift in loops is negligible, the predominant mechanics of failure is fatigue. However, as the stress amplitude increases, failure will result from a combination of fatigue and the cyclic accumulation of strains.

4.0 Effect of Loading Sequence on Load Controlled Fatigue Behaviour

4.1 Effect of Loading Sequence on Strain Accumulation

It is of interest to determine the effect of the successive application of two different loading levels, each lasting a given number of cycles. It is also important to determine whether the sequence of application of these different load levels has any effect on the strain accumulation during cycling.

Two types of block loading tests such as high-low-high and low-high were performed to evaluate the effect of the loading sequence on the cyclic behaviour. An example of the cyclic response of the material subject to the high-low-high loading sequence is shown in

Figure 4. Experimental data similar to Figure 4 have been obtained for various stress amplitudes and mean stresses at 260°C (See Table III). High-low-high test results are compared with results obtained under low-high loading sequence and are shown in Figure 5. Figure 5 indicates that the maximum longitudinal strain only increases with cycling at the high level of loading. However, no increase in the longitudinal strain was observed during cycling at the low stress amplitude levels at or below 75 MPa superimposed on a high mean stress level (σ_0). This is true for both loading sequences. Although the application of the low stress level produces no increase in maximum strain values, the final cumulative elongation and hence the final shift in cyclic loops appears to depend on the sequence of load application as shown in Figure 5. This observation may be attributed to a dependency of cyclic strain hardening on the load application sequence. In fact the low-high sequence subsequently increased the amount of cyclic hardening during the application of the high load level.

The above experimental observations are of great significance when considering the ratchetting analysis of a pressure vessel. Pressure retaining systems at nuclear stations operate with many transients which result in many small stress amplitudes superimposed on a mean load. However, the magnitude of the small operating stess amplitudes are much lower than the low stress amplitude levels considered in the sequence loading experiments ($\Delta\sigma/2 \leq 75$ MPa and $\sigma_0 = 350$ MPa). As a result, strain accumulation due to small stress transients may be neglected in the finite element analysis of pressure retaining systems. Therefore, ratchetting resulting from high stress transients need only be considered in an analysis.

4.2 Effect of Loading Sequence on Stress Life Curves

Although the final shift in the hysteresis loops is shown to depend on the load application sequence, the number of cycles to failure of the test specimens is found to be insensitive to the loading sequence as shown in Figure 5.

Summary

Based on the present load control test results on A516Gr70 steel, the following conclusions can be drawn:

1. Strain accumulation during cycling is shown to depend on both stress amplitude and mean stresses.
2. At stress amplitudes below 345 MPa, the shift in the hysteresis loops in negligible. As a result both load control and strain control data are identical in this region.
3. From high-low-high and low-high block loading tests, it is shown that no shift in the cyclic loops occurs during cycling at the low stress amplitude level ($\Delta\sigma/2 \leq 75$ MPa) superimposed on high ($\sigma_0 = 350$ mPa) mean stresses.
4. Small stress cycles at high mean stresses resulting from operating transients may be neglected in a finite element ratchetting analysis of a pressure retaining system.
5. The final shift in the cyclic loops is shown to depend on the load application sequence, however, the number of cycles to failure is found to be insensitive to loading sequence.

Acknowledgements

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References

[1] Miller, D.R., 'Thermal Stress Ratchet Mechanism in Pressure Vessel', Trans. ASME, J. of Basic Eng. 8, pp. 190-196 (1959).

[2] Lebey, J. and Roche, R., 'Tests of Mechanical Behaviour of 304 L Stainless Steel Under Constant Stress Associated With Cyclic Strain', Fatigue of Engineering Materials and Structures. 1, pp. 307-318 (1979).

[3] El Haddad, M.H., 'Strain Controlled Fatigue Behaviour of ASTM A516Gr70 Steel at Room and High Temperature', Ontario Hydro Research Division Report, 80-365-K, (1980).

[4] Pile, D., Reik, W., Mayer, P. and Macherauch, E., 'Cyclic Induced Creep of a Plain Carbon Steel at Room Temperature', Fatigue of Engineering Materials and Structures. 1, pp. 227-245 (1979).

[5] Oldroyd, P.W.J. and Radon, J.C. 'Reversal of Cyclic Creep in Mild Steel and Copper', Fatigue of Engineering Materials and Structures. 1, pp. 297-306 (1979)..

TABLE I

Material Properties and Chemical Composition of the A516Gr70 Steel Plate

Physical Properties

Yield Strength, Sy 315 MPa
Tensile Strength, Su 506 MPa
Elongation in 5 cm 30%

Chemical Composition

C	Mn	S	P	Si	Cr
0.26	1.02	0.02	0.007	0.22	0.12

TABLE II

Fatigue Data From Constant Load Control Tests

Stress Amplitude $\Delta\sigma/2$, MPa	Mean Stress σ_o, MPa	Test Temperature °C	Cycles to Failure N_f
482	0.0	22	63
400	0.0	22	926
345	0.0	22	4681
269	0.0	22	66843
241	0.0	22	512190
427	0.0	260	123
407	0.0	260	368
350	0.0	260	5824
345	69	22	1097
262	69	22	27075
207	69	22	3206760
379	69	260	49
372	69	260	91
358	69	260	436
345	69	260	3200

TABLE III

Effect of Loading Sequence on Load Controlled Tests - At 260°C

1. High-Low-High

$\Delta\sigma_1/2$* MPa	σ_{o1} MPa	n_1 cycles	$\Delta\sigma_2/2$** MPa	σ_{o2} MPa	n_2 cycles
422	zero	65	214	214	1000
422	zero	160	69	351	2000
396	zero	1116	62	338	2000
372	69	145	69	365	2000
356	69	986	76	351	2000
354	69	2663	69	351	2000

2. Low-High

$\Delta\sigma_1/2$	σ_{o2}	n_2	$\Delta\sigma_1/2$	σ_{o1}	n_1
69	345	2000	396	zero	440
214	214	1000	422	zero	516
69	351	2000	354	69	3796

* $\Delta\sigma_1/2 \rightarrow n_1 \rightarrow$ High stress level

** $\Delta\sigma_2/2 \rightarrow n_2 \rightarrow$ Low stress level

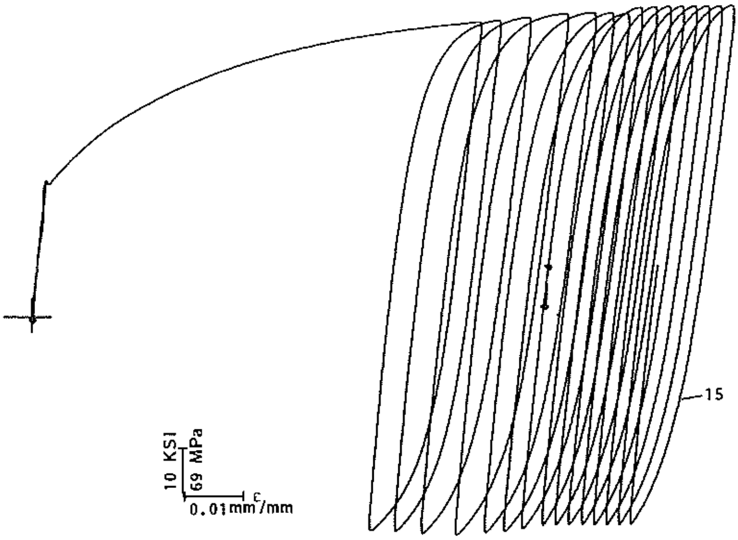

Figure 1 Cyclic loops during constant amplitude load control tests at σ_o and $\Delta\sigma/2$ = 372 MPa.

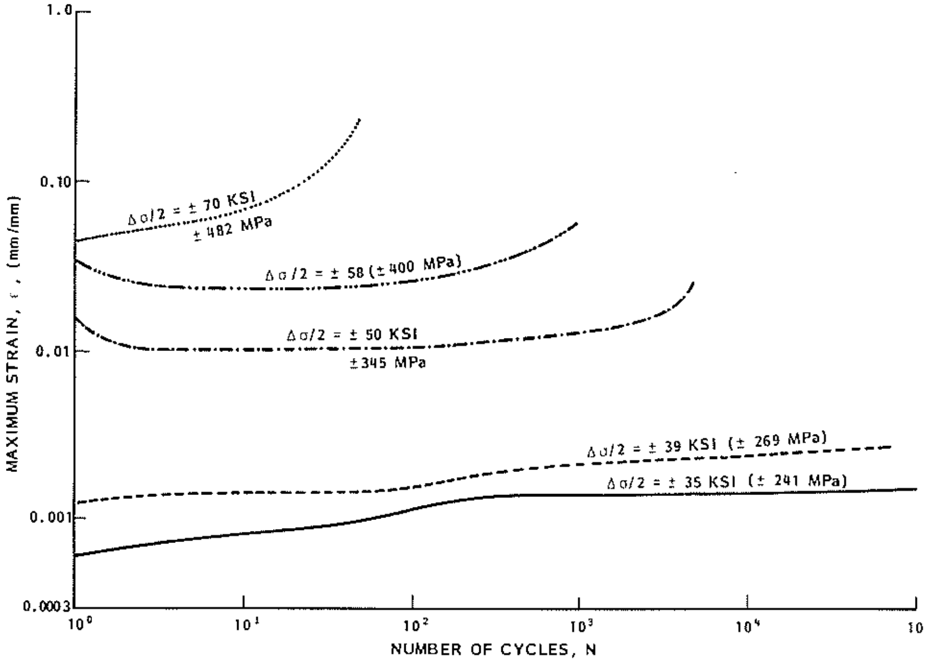

Figure 2 Fully reversed load control tests at room temperature.

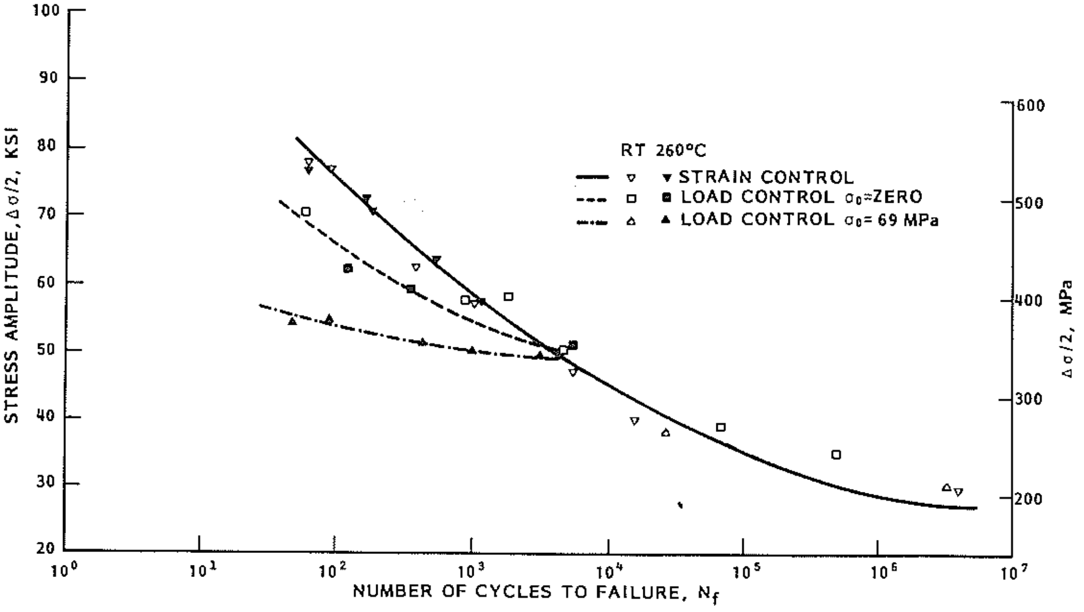

Figure 3 Comparison between load control and strain control tests.

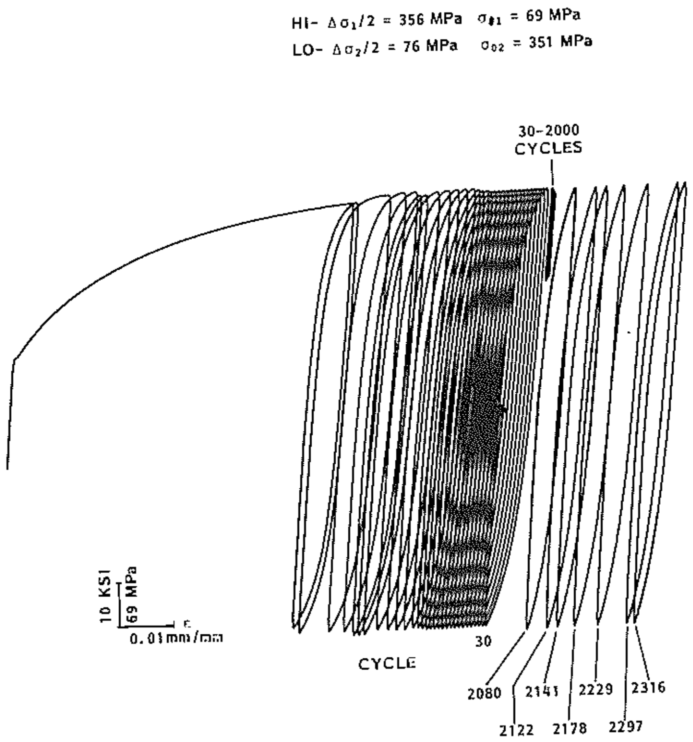

Figure 4 Cyclic loops during high-low-high loading at 260°C.

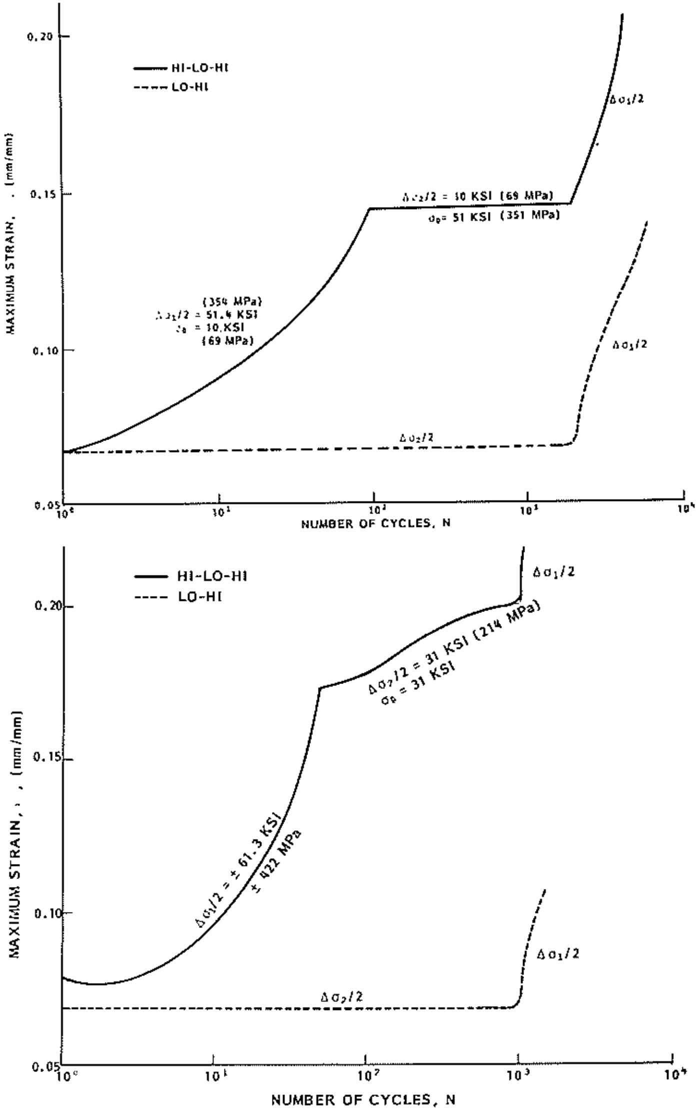

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Figure 5 Effect of loading sequence on maximum strain at 260°C.