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Creep and fatigue crack growth in P91 weldments

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ABSTRACT

Creep and creep-fatigue crack growth tests on the high strength pressure vessel steel P91 (9CrMoVNb) were carried out in the European Commission supported project 'HIDA'. These tests were conducted at 625°C using compact tension (CT) and single edge notch tension (SENT) specimens and large size seam and butt welded pipes with starter notches/defects machined in the HAZ and the base metal constituents. The work has shown that the HAZ region in P91 could be vulnerable to Type IV cracking resulting in large stress reduction factors. This finding is supported by parallel research work carried out elsewhere at lower (service) temperatures.

The use of 9Cr type high strength martensitic steels was first introduced on the basis of their superior base metal design strength. However, the weaker Type IV position does not necessarily support this position with regards to the welded components. Furthermore, adverse effect of low cycle fatigue (with large hold times) on crack growth was observed in feature specimen tests. This can have implications for the so called 'two shifting' operation of power plant which is now becoming more common due to the privatisation and competition in electricity generating industry. The reasons for this and the vulnerability of Type IV position are discussed. Although this work was limited in nature it nevertheless shows the need to evaluate the behaviour of the weldments of this type of steel at service temperatures.

1. INTRODUCTION

A number of steels were tested in the European Commission supported project BE1702 'HIDA'. This paper deals with the steel P91 which is a martensitic steel used as a replacement header and pipe work material in the existing boilers and as high strength steel in the new ultra supercritical boilers. The P91 replacement headers in the existing boilers are used at relatively lower temperatures of 540 to 570°C but in the new ultra-supercritical plant this use could be in the region of 600°C. P91 was introduced as a new high strength material on the basis of its superior base metal creep rupture strength. However, as is well known, most components in boilers fail due to problems associated with welds. So it is now opportune to look at the performance of weldments (i.e. weld metals and associated heat affected zone) in this steel.

Due to competition and privatisation of electricity generating industry world over cycling of power plant to meet customer demand at a short notice is now fast becoming common. This can have serious implications for larger power plants with large headers built for steady load operation, as cycling can induce damage to these components. In terms of cyclic damage, the advantage of P91 over traditionally used ferritic steels such as P22 has been that because of its high strength components can be built in smaller wall thickness and this has been considered to be advantageous from the viewpoint of plant cycling induced fatigue damage, amongst many other benefits. Again, the comparison so far has been based on the base metal performance.

This paper discusses the performance of P91 weldments from the viewpoint of creep and fatigue crack growth as investigated in the project HIDA and supports this with evidence from the work carried out elsewhere on different casts of steel and welds.

2. TEST MATERIAL

All laboratory and feature test specimens were machined from the same cast of material. The pipes were supplied by Mannesman to ASME P91 specification. The chemical composition and tensile properties are given in Tables 1 and 2 and nominal pipe dimensions are shown in Table 3.

Longitudinal and circumferential welds were made using the Shielded Metal Arc Welding (SMAW) process, except for the root run. The weld was 20 to 30 mm wide.

Table 1: Chemical composition of the test material

| Materl | C | Mn | Si | P | S | Cr | Ni | Mo | V | Nb | Ni+Cu |
|---------------|----------|-----------|-----------|----------|----------|-----------|-----------|-----------|----------|-----------|--------------|
| Base | 0.091 | 0.409 | 0.369 | 0.028 | 0.013 | 8.44 | 0.272 | 0.922 | 0.24 | | 0.04 |
| Weld | 0.087 | 0.692 | 0.285 | 0.013 | 0.007 | 9.39 | 0.63 | 0.98 | 0.267 | 0.04 | 0.64 |

Table 2: Tensile properties

| Source | Temp. | 0.2PS (MPa) | UTS (MPa) | A (%) |
|---------------------------|--------------|--------------------|------------------|--------------|
| ASTM (min) | Room Temp. | 415 | 585 | 20 |
| Test Pipe (Mannesmann) | Room Temp. | 505 | 674 | 26 |
| | | 508 | 671 | 28 |

Table 3: Nominal dimensions of the test pipes, including the initiation defect size

| | | |
|----------------------------|------------------------|------|
| Specimen Dimensions | Outer Diameter OD (mm) | 285 |
| | Inner Diameter ID (mm) | 225 |
| | Wall Thickness t (mm) | 20 |
| | Overall Length (mm) | 600 |
| Defect Dimensions | | |
| <i>Defect 'D' in HAZ</i> | a x 2c (mm) | 8x40 |
| <i>Defect 'E' in Base</i> | a x 2c (mm) | 8x40 |
| <i>Defect 'F' in Base</i> | a x 2c (mm) | 5x25 |

3. EXPERIMENTAL WORK

All tests were conducted at 625°C.

Uniaxial creep rupture tests were carried out on base metal, weld metal and cross weld (containing base and weld metal and HAZ) specimens. For brevity this paper describes the results of the cross weld specimens only. These specimens were taken out of both the seam and butt welded pipes and are respectively identified as transverse (T) and longitudinal (L) specimens in Table 4. Table 5 gives the rupture location which will be discussed later.

Table 4: Creep rupture results for cross-weld specimens

| Orientation | Stress (MPa) | Test duration (h) | Elongation (%) |
|-------------|--------------|-------------------|----------------|
| T | 51/80* | 9713/10492** | |
| T | 80 | 1996 | 2.7 |
| L | 100 | 323 | 2.8 |
| L | 60 | 3906 | |

* 51 MPa then 80 MPa (51 MPa was due to an error of loading)

** cumulated duration. The specimen remained 779 hours under 80 MPa.

Table 5: Rupture location in the cross-weld specimens

| Total width* (mm) | HAZ width between the crack and the weld* (mm) | HAZ width between the crack and the unaffected base metal* (mm) |
|-------------------|--|---|
| 2.0 | 2.0 | ≈ 0 |
| 2.3 | 1.9 | 0.4 |
| 1.9 | 1.5 | 0.4 |
| 2.0 | 1.5 | 0.5 |

* average value computed from 5 measurements.

Creep and fatigue crack growth tests were carried out on Compact Tension (CT) specimens (of two sizes, $W=25$ and 50 mm) and on Single Edge Notch Tension (SENT) specimens. Tests both under static and cyclic loads (frequency range of 0.001 to 0.1 Hz) were conducted. Details of laboratory testing have been described elsewhere [1]. It suffices to state here that the tests were performed according to ASTM E1457 high temperature CCG testing standard [2].

In the case of feature tests, all pipes contained three elliptical shape initiating defects introduced by electrical discharge machining (edm) [3], the notch root radius being 0.05 mm. (EDM was also the technique used for CT and SENT laboratory specimens). Two notches, one machined in the base metal and one in the centre of the HAZ, were of the same size and had been machined to compare the behaviour of the base and weld metal constituents, while the third notch was a shallow notch and had been machined in the base metal to study the metallography of crack initiation, Table 3.

Two tests were conducted on seam welded pipes under internal gas pressure. One pipe was tested under steady load and the second under load cycling conditions. The load cycling component was introduced by cycling the pressure eight times in twenty-four hours giving a frequency of 10^{-4} Hz. Full details of these tests are given in [3] and [4]. The test information together with the results (to be discussed later) is given in Tables 6 and 7.

Table 6: Results of CCG tests on axially-notched pipes with longitudinal seam welds

| Pipe | Internal Pressure (Mpa) | Frequency (Hz) | Duration (hrs) Cycles | Crack extension (mm) (for Defect D* in HAZ) | Failure mode |
|-------|-------------------------|----------------|---------------------------|---|--------------|
| SP-P1 | 15 | 0 | 1430 (hrs) | 12.55 | Type IV |
| CP-P2 | 0 - 11 | 10^{-4} | 5550 (hrs) 1850 cycles | 9.06 | Type IV |

*Initial defect depth $a_0 = 8$ mm.

Table 7: Crack extension in the HAZ and base material in the seam welded pipes

| Test designation | SP-P1 | | CP-P2 | |
|----------------------|---------|--------|---------|--------|
| | D (HAZ) | E (BM) | D (HAZ) | E (BM) |
| Crack Extension (mm) | 12.55 | 0.66 | 9.06 | 1.2 |

Two tests were conducted on butt welded pipes under internal gas pressure and four point bending mode. One pipe was tested under steady load and the second under load cycling conditions, Table 8. The cycling component was introduced by cycling the bending

moment on the pipes while pressure in the pipes remained steady. The test frequency used was 10^{-3} Hz.

Table 8: Details of tests on butt welded pipes

| Specimen No | Test type | Internal pressure (MPa) | External load | | Frequency Hz | Duration h | Crack growth |
|-------------|-------------|-------------------------|---------------|-------|--------------|-----------------------------------|---------------|
| | | | F, kN | D, kN | | | |
| P91/P1 | Steady load | 20 | 96 | - | - | 3648 h ----- 1440 h* | No initiation |
| | | 20 | 120 | - | | | |
| P91/P2 | Cyclic load | 20 | - | 96 | 10^{-3} | 3648 h 12740 cycles - ----- | 3 mm growth |
| | | 20 | - | 120 | 10^{-3} | 1440 h* 4634 cycles* | |

* Time/ cycles at increased load.

4. RESULTS

4.1. Laboratory Specimen Tests

In the case of uniaxial creep rupture tests the cracking in the cross-weld specimens was observed to be in the Type IV position, Table 5, and the ductility was very poor, 2.7 %, Table 4. The low ductility can be attributed to the Type IV region, as the ductility for the tests on the base metal and the all-weld metal specimens obtained from the same pipes and at the same temperature was found to be in the region of 8 to 24% respectively [5]. The cross-weld specimens also showed very low creep rupture strength, exhibiting a strength drop of between 30 to 40% [5].

In the case of creep and fatigue crack growth tests the cracking rate was correlated with C^* for the CT and the SENT specimens, Figure 1. For cyclic tests only data for low frequencies (up to 0.01 Hz) have been presented in this paper. It is clear that, within the typical range of scatter for cracking data, no specimen size or geometry effect is observed both for base and HAZ material conditions tested under static and low frequency cyclic loading. No effect of low frequency cycling was observed either.

However, the crack growth rate in the HAZ was higher by a factor of about 5 compared with the base metal. The respective best fit lines are shown in Figure 1.

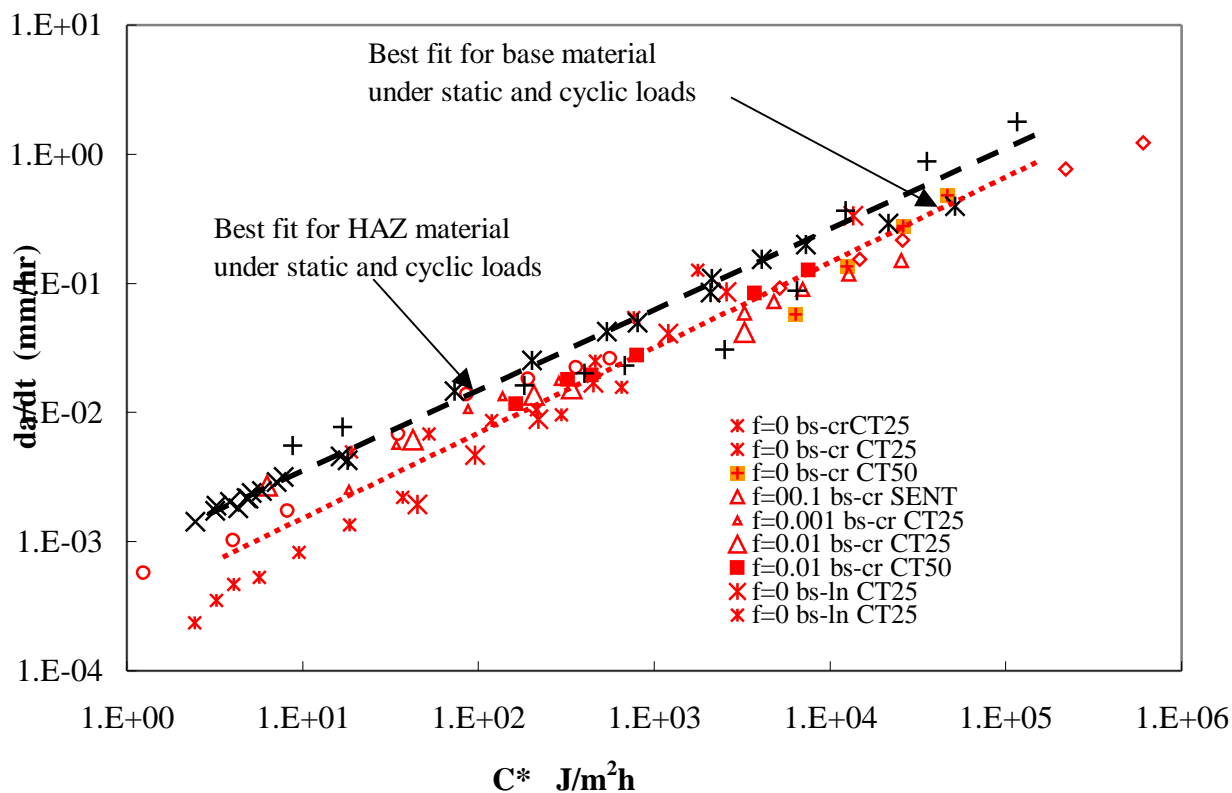


Fig. 1: Creep and fatigue crack growth rates for the laboratory specimen tests

(**Note:** CT25 = CT specimen W=25mm, CT50= CT specimen W=50mm, SENT=single edge notch tension specimen, f=frequency in Hz, bs-cr and bs-ln are base metal specimens with notch orientations parallel respectively to pipe circumferential and longitudinal directions, HAZ-cr and HAZ-ln are specimens with initiation notch in the centre of the HAZ.).

4.2. Feature Test Results

4.2.1. Seam Welded Pipes

In this case crack growth through the HAZ was faster by a factor of 10 [4]. The maximum crack growth in the base and HAZ metal constituents is shown in Table 7. As the crack growth in the base metal was small for both the steady and cyclic load conditions only crack growth in the HAZ metal was analysed in terms of C^* correlation.

The analysis for crack growth in the HAZ region is shown in Figure 2. This correlation of the component CCG data was found to fall within HIDA Task 2 scatter band as shown. The HIDA Task 2 scatter band was established within the project HIDA from the published and unpublished laboratory data accessed from organisations in various countries [6].

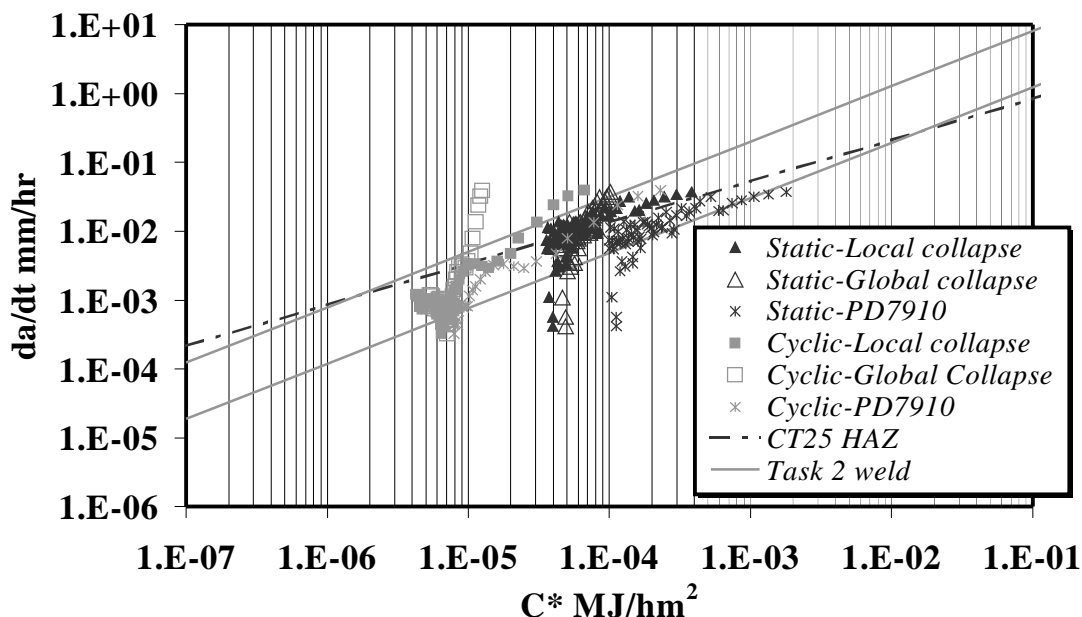


Fig. 2: Creep and fatigue crack growth rates in HAZ of the seam welded pipes (based on the minimum creep rate of the cross-weld specimen tests)

Three reference stress solutions - based on limit load concepts - were selected for the formulation of C^* -Integral. Although the BS7910 formulation gave a better correlation with conventional data, the difference was small, implying that it is unimportant exactly how the stress state is characterised at the notch tip. Furthermore, both minimum and average creep rate laws were used to accommodate the strain rate in the C^* relationship in the analysis. A better correlation was obtained when using the average creep rate law, confirming the extensive creep cavitation observed for tested pipes.

As can be seen in Figure 2, for a given reference stress solution, the P91 steel exhibits higher crack growth rates under cyclic loading.

In post-test metallography tip of the original notch was observed to be in the centre of the HAZ. However, crack growth was observed to occur along the fine grain HAZ/ Type IV position. This was observed in both the pipes (i.e. steady and cyclic load tests) and a typical case is shown in Figure 3.

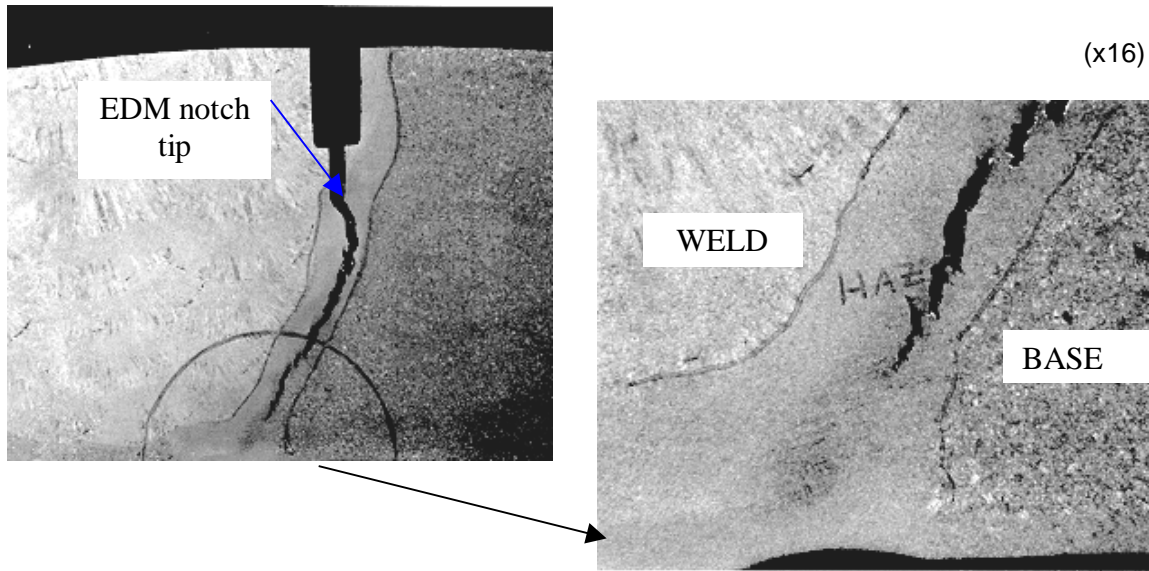


Fig. 3. Seam welded pipe test – crack growth through the pipe wall thickness

4.2.2. Butt Welded Pipes

In this case, because of the tests running for longer durations full analysis of the data is being carried out only now and will be reported in future publications. Therefore only preliminary analysis will be reported here.

The comparison of the test results of the two four-point bending pipes, one tested under steady load and the second under cyclic load, showed crack growth of 3mm in the HAZ of the cyclic test i.e. pipe P91/P2. In contrast the steady load pipe P91/P1 did not even show crack initiation during the same testing time and same maximum loads, Table 8. However, differences in wall thickness between both pipes in the area of the starter notches were observed. The wall thicknesses were 29.9 mm for P91/P1 steady load test, and 25.5 mm for P91/P2 cyclic load test. The eccentricity of the pipe P91/P1 was much larger than that of P91/P2.

Although detailed metallography is in progress preliminary examination has revealed the cracking to be in the Type IV region, as was the case with the laboratory specimens and the seam welded pipes.

5. DISCUSSION

a) The feature tests showed the crack growth rate in the HAZ to be higher by a factor of 10, although the prediction from the laboratory specimens was a factor of 5 only. This can perhaps be attributed to the higher constraint situation in the feature tests and thus highlights the importance of conducting feature tests for validation purposes. This work

has shown that Type IV position in P91 steel is much more vulnerable to crack growth than the base metal.

b) The finding with regard to the crack growth occurring close to the Type IV position in the laboratory specimen tests and in the tests on pipes, when the starter notch was placed in the centre of HAZ, is a cause for concern. This may imply that in in-service situations P91 can be vulnerable to type IV cracking.

Recent work carried out elsewhere [7] on high alloy martensitic steels of 9-12%Cr type testing uniaxial creep rupture specimens has shown that type IV cracking in longer term tests could be a serious problem in these steels. As a result it has been shown that stress reduction factor due to this type of cracking in E911 steel, when tested at 625°C could be 30% for 8000 hour tests (similar to that reported in this paper for P91), which can be extrapolated to 50% for 100000 hours tests [7]. This reduction factor is very high and highlights the need to categorise P91 and other similar steels for their weldment behaviour.

It also throws light on the short sightedness of designing plant on the basis of the base metal strength and behaviour. It can perhaps be argued that 625°C is a high temperature and that P91 at present is only used at up to 600°C. However, work at 600°C has also shown the vulnerability of this steel to Type IV cracking [7a]. This steel is also being used at present as a replacement material in the older power plant at lower temperatures of 540 to 570°C. It can be therefore be argued that in the older plant the use of this steel will be safe. On the other hand, it can also be argued that in the presence of any manufacturing or service induced defects stress at the tip of the defect will relax at a much lower rate (due to lower creep) and therefore the risk of cracking at lower temperatures could be higher. Performance in this region is not known and therefore plans are now underway to investigate the behaviour of the weldments of these steels at service temperature range.

All this is contrary to the belief in some quarters that Type IV cracking is not expected to be a major problem in high strength steels as the strength loss at a test temperature decreases with increasing material strength [8].

c) Another aspect of concern is that the low cycle feature test in seam welded pipes showed higher crack growth rate than the steady load test. This inspite of the fact that the cyclic test sees shorter time at high stress than the steady load test. Similar tests carried out on P22 (2.25Cr1Mo) steel at its typical service temperature of 565°C showed slower crack growth in the cyclic tests [4]. Although tests on butt welded pipes are still being analysed in terms of C*, the preliminary indications, notwithstanding the differences in pipe nominal wall thickness and eccentricity, are that the cyclic test is showing higher crack growth rate. As can be seen from Figure 1 this difference was not shown by tests on the standard laboratory specimens, which again shows the significance of conducting validation type tests using feature specimens.

Results from creep and creep fatigue crack growth tests on three materials tested within the project HIDA have been plotted in Figure 4. Although these data are limited they

nevertheless for the first time have shown that the creep fatigue interaction is more severe for P91 than for P22 or AISI 316 stainless steel. The HIDA work has shown that the cross weld creep rupture ductility of P91 tests was only about 2.7% while that of cross weld P22 specimens tested at 565°C this was up to 8% [5]. Thus ductility exhaustion in P91 would be a contributory factor to the potential vulnerability of this steel to cracking due to plant cycling.

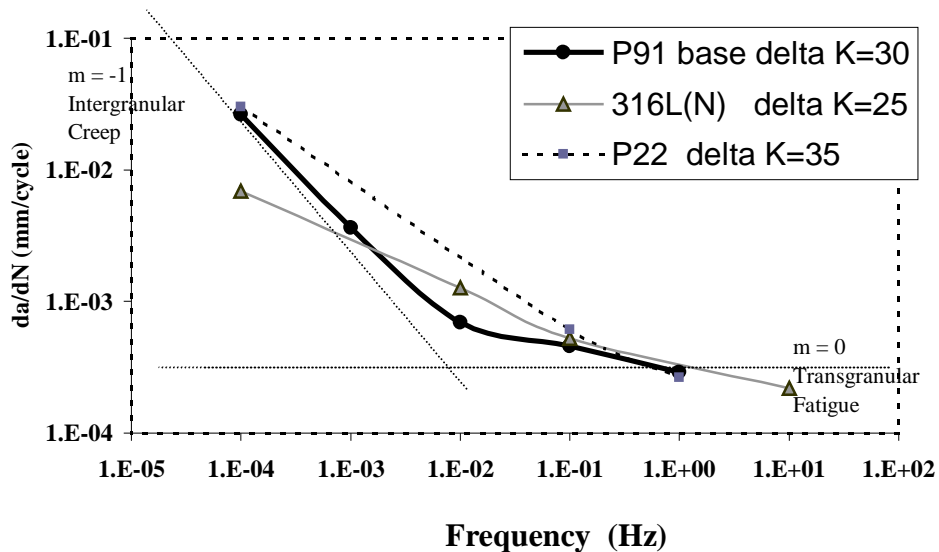


Fig 4. Creep-fatigue crack growth curves for some of the high-temperature alloys (including P91)

The worry now is that, for example, in plant cyclic operation, which is now becoming common due to privatisation and is resulting in sever competition in the electricity generating industry, P91 could show Type IV cracking at a reasonably early stage in life. In the past P91 was considered to be advantageous steel for the plant cyclic operation as thinner wall and smaller component size were supposed to reduce thermal gradients and hence the adverse effect of cycling.

Furthermore, recent work of Tabuchi et. al. [9] has shown that $M_{23}C_6$ precipitates and laves phases form faster at the fine grain HAZ region in 9Cr martensitic type steels and this makes the Type IV position in these steels very vulnerable.

d) In terms of the plant experience, not much can be said with certainty at present because of the relatively short service experience of this type of steels. However, there has been one P91 Type IV failure in the UK after only 36000 hours of service at 568 °C ! [10]. Although this was attributed to the design of the endplate and the metallurgical condition of the forging, could it possibly be due to the higher vulnerability of P91 to Type IV cracking? Type IV position of P91 is known to be much softer than the base metal. Is it, therefore, possible that P91 and other 9-12Cr steels will start showing cracking problems at an early stage in life?

There is also an observation that in-plant oxidation of P91 could be high and this also makes this steel vulnerable [11, 12].

In the light of the new information emerging the question that we face is, "Are P91 and other 9Cr type martensitic steels still considered to be the wonder materials for use in high temperature plant?"

6. CONCLUSIONS

Creep and fatigue crack growth work on laboratory and feature test specimens of P91 steel weldments tested at 625°C has shown the following:

1. P91 weldments are vulnerable to failure in the fine grain HAZ (Type IV). This can result in large stress reduction factors for this steel.
2. In the feature tests both creep and creep-fatigue crack growth rates were 10 times faster in the HAZ compared with the base metal.
3. Creep fatigue interaction has adverse effect on time dependent crack growth in this steel. Limited comparison has shown that this effect can be more severe than that in the traditional P22 (2.25Cr1Mo) steel used in power plant. This has implications for the cyclic operation of power plant now using P91 and other similar high strength martensitic steels.
4. This work has shown the importance of conducting feature tests which under higher constraint can show behaviour more severe than that predicted by testing laboratory size specimens.
5. These findings highlight the need to do comprehensive evaluation of P91 type high strength martensitic steels for their weldment behaviour at service temperatures.

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8. REFERENCES

1. M Tan, N J Cellard, K M Nikbin, G A Webster, 'Comparison of creep crack initiation and growth in four steels tested in the HIDA project', 2nd International HIDA Conference on Advances in Defects Assessment in High Temperature Plant, 4-6 Oct. 2000, MPA, Stuttgart, Germany.

2. ASTM E1457-92, Standard Test Method for Measurement of Creep Crack Growth Rates in Metals, ASTM, Philadelphia, PA 19103, USA.
3. N Le Mat Hamata , I A Shibli, Creep Crack Growth of Seam-welded P22 and P91 Pipes with Artificial Defects. Part I: Experimental Study and Post-Test Metallography, 2nd International HIDA Conference, Advances in Defects Assessment in High Temperature Plant, 4-6 Oct. 2000, MPA, Stuttgart, Germany.
4. N Le Mat Hamata, I A Shibli, Creep Crack Growth of Seam-welded P22 and P91 Pipes with Artificial- Part 2: 2nd International HIDA Conference, Advances in Defects Assessment in High Temperature Plant, 4-6 Oct. 2000, MPA, Stuttgart, Germany.
5. I A Shibli, HIDA Final Report.
6. Al-Abed B. HIDA Project Task 2 – Collation and Review of High Temperature Crack Growth Data from Research Experience. ERA Report 97-0586, Leatherhead, ERA Technology Ltd, July 1997.
7. Allen D J, Fleming A. ‘Creep performance of similar and dissimilar E911 steel weldments for advanced high temperature plant’, Published in the Proceedings of the 5th Charles Parsons 2000 Conference on ‘Advance materials for 21st century turbines and power plant’, 3-7 July, Churchill College, Cambridge, UK. Pp 276-290.
- 7a. I A Shibli, N Le Mat Hamata, ‘Creep crack growth in P22 and P91 welds – overview from SOTA and HIDA projects’, 2nd International HIDA Conference, Advances in Defects Assessment in High Temperature Plant, 4-6 Oct. 2000, MPA, Stuttgart, Germany.
8. J Hald, ‘Integrity of high temperature ferritic steel weldments’, paper presented at International conference on 'Integrity of High Temperature Welds', 3-4 November, 1998, Nottingham, UK. Organised by the Institute of Materials, London.
9. Masaaki Tabuchi, Takashi Watanabe, Kiyoshi Kubo, Masakazu Matsui, Junichi Kinugawa and Fujio Abe, ‘Creep Crack Growth Behavior in HAZ of Weldments for W containing High Cr Steel’, 2nd International HIDA Conference, Advances in Defects Assessment in High Temperature Plant, 4-6 Oct. 2000, MPA, Stuttgart, Germany.
10. Brett S J, Allen D J, Pacey J, Failure of a modified 9Cr header endplate, Proceedings of the International Symposium on case histories on Integrity and failures in Industry, Milan, Italy, 28 Sep. -1 Oct. 1999.
11. B Dooley, EPRI, Palo Ato, California, USA. Private Communication.
12. A Fleming, R V Maskell, L W Buchanan, T Wilson, ‘Materials development for supercritical boiler and pipework’, Published in Conference Proceedings of Materials Congress, UK, 1998, on session on ‘Materials for high temperature power generation and process plant applications’, Edited by A Strang.