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Performance of P91 Weldments Under Steady And Cyclic Load Conditions And Directions For Future Research

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Abstract

P91 or 9CrMoVNb steel is the relatively new high strength martensitic steel originally developed for use in ultra supercritical power plant to operate at temperatures up to about 600^{o}C. However, it is now also being used as a replacement material for the headers being made redundant from some of the existing and ageing plant. One of the advantages of this steel, which was originally introduced to the market on the basis of the high rupture strength of the base metal, was envisaged to be the smaller thickness required for thick section components such as headers and steam pipes thus reducing through wall temperature gradients and therefore damage due to fatigue. However, recent work has shown that the weldments of this steel, the weakest link in the chain, show lower ductility than the traditional ferritic steel weldments and this appears to reduce the resistance of P91 welded components to creep-fatigue cracking. In addition, some of the work has shown that the weldments of this steel can be particularly prone to Type IV cracking. Other research work and recent plant experience has shown that the creep performance of this steel and particularly its weldments can be critically dependent on its tempering and post weld heat treatments. These aspects are discussed in this paper.

In view of these findings and a limited number of in-service failures future work is being proposed to ensure the integrity of the welded components.

1. Introduction

ASTM P91 and P92 and European E911 steels are relatively newly developed 9Cr martensitic steels and are used as high strength steels in the new ultra supercritical high efficiency boilers or as replacement header, secondary super heater tubing and pipe work material in the existing boilers [1]. Of these steels the tube and pipe products pf Grade 91 steel designated respectively as T91 and P91 are the most used at present and have been mainly employed as a replacement material in superheater tubing, steam pipes and headers in the existing boilers at operating at relatively lower steam temperatures of 540 to 570^{o}C. This steel is also used in the new ultra-supercritical plant in Europe and Japan in the region close to 600^{o}C while P92 and E911 could be used at even higher temperatures of up to 620^{0}C.

These 9Cr martensitic steels were introduced on the basis of their superior base metal creep rupture strength compared with the conventional boiler steels. The other benefit of these steels is their envisaged better performance under a plant cycling regime of operation because of smaller wall thickness components compared with the conventional lower strength steels such as P22 (2.25Cr 1Mo) which require large wall thickness. However, as is well known, most components in boilers fail due to problems associated with welds. The situation is similar to that in 1950s in the UK when the power plant industry had rushed in to the use of the new CMV steels and later suffered huge and perennial problems with Type IV cracking in its CMV pipe welds. So it is now opportune to look at the performance of weldments (i.e. weld metals and associated heat affected zone) in the 9Cr martensitic steels.

It has recently emerged that the precise control of the heat treatment of the base material and post weld heat treatment of the welds is crucial to the reliable performance of these steels. Similarly oxidation performance of all martensitic steels with Cr levels below about 11% is now also being questioned.

This paper describes the published findings from a recently completed European Commission funded project 'HIDA' [2] and some of the other studies carried out elsewhere. It also describes some of the plant experience in support of these results. These findings make it necessary to reconsider the assumed benefits of using P91 type steels.

2. Findings from R & D Projects

2.1. HIDA Tests and Results

2.1.1. Tests

Tests were carried out on both seam and circumferentially welded pipes of P91 and P22 steels. The chemical compositions, pipe dimensions, post weld heat treatment (PWHT) and the test regimes are described in Tables 1 to 5. Further details of the test conditions are described in [3, 4]. As is shown in these Tables both materials were within the specified chemical composition and recommended heat treatment. The microstructures and all mechanical properties were also within the expected specifications as described elsewhere [3, 4].

Two notches, one in the base metal and one in the HAZ, had been machined on each pipe and these acted as starter cracks. The notches were machined using the electrical discharge machining (edm) process and were of an elliptical shape and of very fine quality (0.05 mm notch tip diameter). The sharpness of notch/ pre-crack tip was important to meet the requirements of ASTM E1457 standard [5] - the creep crack growth standard on testing. The pre-crack was machined such that its tip was located in the middle of the HAZ. A third shallow notch was also machined in the base metal to study the creep crack initiation; this work has been described elsewhere [2, 3] and will not be discussed here.

Tests on P91 were carried out at 625°C and on P22 at 565°C. These temperatures were higher than the typical operating temperatures of these materials. This was intentional and was aimed at obtaining results in reasonable time. It is well established now that temperature acceleration gives results/failures more representative of service experience than stress acceleration which can result in notch yielding/blunting.

All pre-cracks were machined in elliptical shape to simulate the real in-service cracks.

While seam welded pipes were tested under internal pressure alone and the butt welded pipes were tested under internal gas pressure and four point bending mode [6]. The four point bending tests on butt welded pipes simulated the system stresses in service which are normally responsible for Type IV cracking.

In tests where cracking from the machined notch did not initiate in reasonable time the internal pressure or bending moment was increased to accelerate the crack initiation, as is shown in Tables 4 and 5.

Tests were carried out both under steady load (creep) and load cycling conditions (creep-fatigue). The cycling tests were carried out at very low frequency of 10^{-4} Hz which amounted to cycling every eight hours between negligible to maximum pressure, the cycling duration lasting for half an hour.

2.1.2. Results

Results for tests on both materials are shown in Tables 4 and 5 and in various Figures. Although edm starter notches in base metal and the HAZ constituent had the same nominal dimensions the growth in the base metal was usually very small and is therefore not the subject of further discussion in this paper.

The results of both the seam and butt welded pipes were analysed in terms of the creep crack growth correlating parameter C*. Various definitions of reference stress calculations (reference stress is used to calculate C* for feature test specimens or components) were used and this aspect is discussed in [3,4].

Seam Welded Pipes

Results for P22 tests in Figure 1(a) show that crack growth rates in steady load tests (darker data points) are faster than those in the cyclic tests (lighter data points). This result in view of the very low cycling frequency used is not unexpected. It basically means that the very low cycling frequency does not show any creep fatigue interaction. However, this low frequency cycling does reduce time at maximum load and thus at creep, resulting in lower crack growth rates in cycling tests.

The trend in P91 feature tests was different as shown in Figure 1(b) in that crack growth rates are faster in the cyclic tests compared with the steady load tests. This shows a detrimental effect of even very low frequency cycling on P91 welded pipes.

Butt Welded Pipes

The results of butt welded pipes are shown in Table 5. As the analysis in terms of creep crack growth correlating parameter C* has not yet been completed therefore no such comparison is possible at this stage. Although nominal pipe and machined notch / pre-crack dimensions were similar for the steady and cyclic load test specimens measured differences in dimensions could make comparison of results difficult without full analysis.

Nevertheless, results in Table 5 show that the trends in crack growth behaviour were similar to those exhibited by the seam welded pipes i.e. for cyclic tests higher crack growth rates for P91 but lower for P22 tests compared with steady load tests.

2.2. Findings From Other Research Projects

These are described in the 'Discussion' section.

2.3. Findings from Plant Experience

In terms of the plant experience, not much can be said with certainty at present because of the relatively short service life of this type of steels. However, there have been at least four P91 Type IV cracking and failures in the UK after only between 20000 to 36000 hours of service at an operating temperature of 568^{o}C! [7, 8]. Although some of these failures were attributed to the design of the components where the welds were situated close to section change and hence higher stress regions. In addition, all failures and cracking was attributed to the metallurgical condition of the affected components which was thought to have resulted from unsatisfactory heat treatment of the base metal. These were thick wall components with longest service experience. Type IV position of P91 is known to be much softer than the base metal even in components given more satisfactory heat treatment. Is it, therefore, possible that P91 and other 9-12Cr martensitic steels will start showing cracking problems at an early stage in life?

The other problem that has been reported from North America [9] is the failures in secondary superheater tubes due to oxide build up on the steam side. Some of these failures occurred as early as two years of service. ETD estimates of temperature build up in these tubes due to the insulating effect of oxide formation are about 9^{0}C per 0.1 mm of oxide thickness [9]. This can lead to a temperature rise of about 100^{0}C for an oxide build up of just over 1mm which has been reported at least by one utility in USA and one in Japan. This is enough to give rise to early tube failures. Similar findings have been reported from a plant in Japan, although in their case the failures started occurring after a longer service duration of 100000 hours. In the of Japanese plant they had paid special attention to the cleanliness of water chemistry.

At least one utility in the USA moved back to T22 (2.25Cr1Mo) tubing after having replaced it with T91 tubing only a few years earlier. They reported that the post weld heat treatment (PWHT) of any P91 failed tubes extended the outage period of the plant thus making it uneconomical to use T91 tubing.

Recently failures/cracking also occurred in a plant in two dissimilar metal welds in steam pipes (P91-316 stainless steel using high nickel weld metal) after only 1000 hours of service but high level of cycling.

3. Discussion

3.1. Discussion of the HIDA Results

This is known to be the first study on P91 welded pipes of reasonably large size in terms of the crack growth behaviour of HAZ. Therefore the findings of this work, although limited, are very important.

Further to the results described above, the study showed that crack growth in P91 HAZ in all cases occurred close to the Type IV region in spite of the fact that the initial notch tip in these pipes was placed in the centre of the HAZ. This aspect has been discussed elsewhere [10, 11]. This finding is a cause for concern as it may imply that in in-service situations P91 can be vulnerable to type IV cracking.

3.2. Discussion of Other R& D Studies

Recent work of Tabuchi et. al. [10] has shown that $M_{23}C_6$ precipitates and lave 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.

Furthermore, work carried out elsewhere [12] on the European 9Cr martensitic steel E911, 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^{o}C could be 30% for 8000 hour tests, which can be extrapolated to 50% for 100000 hours tests [12]. This reduction factor is very high and highlights the need to extend such studies on welded 9Cr martensitic type steels using a range of casts, test temperatures and weld types.

It can perhaps be argued that 625^{o}C is a high temperature and that P91 at present is only used at up to 600^{o}C. However, separate work at 600^{o}C has also shown the vulnerability of this steel to Type IV cracking [11]. As at present this steel is also being used as a replacement material in the older power plant at lower temperatures of 540 to 570^{o}C, it can therefore be argued that in the older plant the use of this steel could be safe. On the other hand, it can also be counter-argued that in the presence of any manufacturing or service induced defects stresses at the tip of a defect will relax at a much lower rate at lower service temperatures (due to lower creep rate) and therefore the risk of cracking could be higher in replacement components. Performance in this lower region of service temperatures is not known and therefore plans by European Technology Development are now underway to investigate the behaviour of the weldments of these steels at this lower temperature range.

Results from creep and creep fatigue crack growth tests on three materials (P91, P22 and ASME 316SS) using standard laboratory specimens and tested within the project HIDA have been plotted in Figure 2. Although these data are limited they nevertheless for the first time have shown that the creep fatigue interaction is more severe in P91 than in 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^{o}C this was up to 8% [10]. Thus ductility exhaustion in P91 would be a contributory factor to the enhanced creep fatigue interaction in this steel and therefore its potential vulnerability to cracking due to plant cycling.

The worry now is that, for example, in plant cyclic operation, which is now becoming common due to privatisation and 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.

One serious problem is that type IV cracking is known to start at sub-surface level so detection by NDT techniques such as dye penetrant or replication is not possible. As stated before we do not have much service or cracking experience with these steels but the known failures in the UK have shown that the cracking in P91 had also initiated at the sub-surface level [7, 8]. This therefore requires a greater need to be prepared to face any sudden, unannounced and possibly violent failures.

3.3. Heat Treatment Issues

The tempering heat treatment temperature of P91 is also an important factor to consider. The difference in hardness between the Type IV position and the coarse grain HAZ or the weld metal could be higher than 100^{0}C. Higher tempering heat treatment could reduce this difference to more acceptable levels while too high a temperature, albeit within the Standards' specification, could result in over-tempering of the precipitates. Thus precise tempering temperature control is necessary. Some operators in Europe are now going to the length of using transmission electron microscopy to ensure the right distribution of precipitates for the material with suspect heat treatment, while others advise to use hardness as a criterion [9]. The precise control of PWHT is also now considered essential for similar reasons.

As the use of 9Cr martensitic steels becomes more widespread and the service period of the material already in use approaches the levels where cracking and failures may start raising their head there will be, in general, a need to adopt the problem solving approach. This will involve tightening the Standards for austenitising and tempering temperatures, critically reviewing the PWHT practices and modify the Standards accordingly.

Weld repair is an aspect that also needs to be studied so that the repairs can be made efficiently and economically.

4. Conclusions

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

1. Weldments of 9Cr martensitic type steels can be vulnerable to failure in the fine grain HAZ (Type IV). This can result in high stress reduction factors for these steels.
2. Creep-fatigue interaction has adverse effect on time dependent crack growth in P91 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 or other similar high strength martensitic steels.
3. Steam side oxidation of T91 superheater tubing has been reported to be excessive.
4. The dependence of T91/P91 welded material on the post weld heat treatment even of thin wall tubing used in, for example, the superheater tubing can result in longer outage periods thus making it uneconomical and sometimes impractical to use this material.

5. Future Work

These findings have led to ETD now formulating a programme of work to conduct a comprehensive evaluation of P91 type high strength martensitic steels for their weldment behaviour at service temperatures. Another problem is the weld repair issue. No known experience exists in the repair welding of P91. No doubt this issue will raise its head in the near future. Cold welding is now well applied in low strength ferritic steels. There is a need to extend this technique, or some variation of it, to high strength 9Cr martensitic steels to avoid the problem of in-situ PWHT and extended outages resulting in lost of income. High nickel weld metals could be an option in this regard. These issues will be explored in the new ETD's industry sponsored project.

6. References

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Material	C	Mn	Si	P	S	Cr	Ni	Mo	V	Al	Nb	Ni+Cu
P22 BM	0.101	0.443	0.206	0.024	0.015	2.07	0.099	0.939	<0.01	<0.01	-	0.18
P22 WM	0.017	0.731	0.407	0.019	0.008	2.38	0.05	1.05	0.02		0.007	0.10
P91 BM	0.091	0.409	0.369	0.028	0.013	8.44	0.272	0.922	0.24	0.07		0.04
P91 WM	0.087	0.692	0.285	0.013	0.007	9.39	0.63	0.98	0.267		0.04	0.64

Table1: Chemical composition of P22 and P91 base and weld materials

Material	**P22**	**P91**
Start temperature (max)	400^{o}C	400^{o}C
Heating rate (^{o}C/h)	<135	<135
Soaking temp/time (^{o}C/h)	710 ±30^{o}C/2 h	760 ±10^{o}C/2 h
Cooling rate (^{o}C/h)	<175	Still air

Table 2: Post weld heat treatment procedure

Pipe Dimensions (mm)	**P91**	**P22**
Outer Diameter (OD)	285	156
Inner Diameter (ID)	225	116
Wall Thickness (t)	20	20
Overall Length	600	600
Defect Dimensions *Defect 'D' in HAZ* *Defect 'E' in Base*	a* x 2c* = 8 x 40 a* x 2c* = 8 x 40	

***** a = notch depth through the wall thickness, ** c = notch length

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

Specimen No.	**Specimen ID**	**Material**	**Test Type**	**Internal Pressure** (MPa)	**Frequency** (Hz)	**Duration** (h) ***Cycles (C)***	**Crack Growth++** (mm)	**Failure Mode**
1	P91/SP-P1	P91	CCG	15	-	1430 h	12.55	Type IV
2	P91/CP-P2	P91	CFCG	0 - 11	10^{-4}	5550 h, *1850 C*	9.06	Type IV
3	P22/SP-P1	P22	CCG	15 17.5	-	5880 h 4320 h*	4.86	Cracking in mid-HAZ
4	P22/CP-P2	P22	CFCG	0 - 17.5 0 - 20	10^{-4} 10^{-4}	4620h , *1540 C* 1600 h*, *533* C*	3.65	Cracking in mid-HAZ

** Time/ cycles at increased load.*
++ For defect D in HAZ; *initial defect depth* $a_0 = 8mm$.

Table 4: Details of feature tests and results on seam welded pipes

Specimen No.	**Specimen ID**	**Load Type**	**Internal Pressure** (MPa)	**External load**		**Frequency** (Hz)	**Duration** (h) ***Cycles (C)***	**Crack Growth++** (mm)
				F, kN	Δ, kN			
1	P91/P1	Steady	20	96	-	-	3648 h	No crack initiation
			20	120	-	-	1440 h*	
2	P91/P2	Cyclic	20	-	96	10^{-4}	3648 h, *12740 C*	
			20	-	120		1440 h*, *4634 C**	3
3	P22/P1	Steady	20	47	-	-	5020 h	4
			20	90	-	-	2800 h*	
4	P22/P2	Cyclic	20	-	47	10^{-4}	5020 h, *1640 C*	No measurable crack growth
			20	-	90		2800 h,* *9655 C**	

**** Time/ cycles at increased load.***

Table 5: Details of tests on butt welded pipes

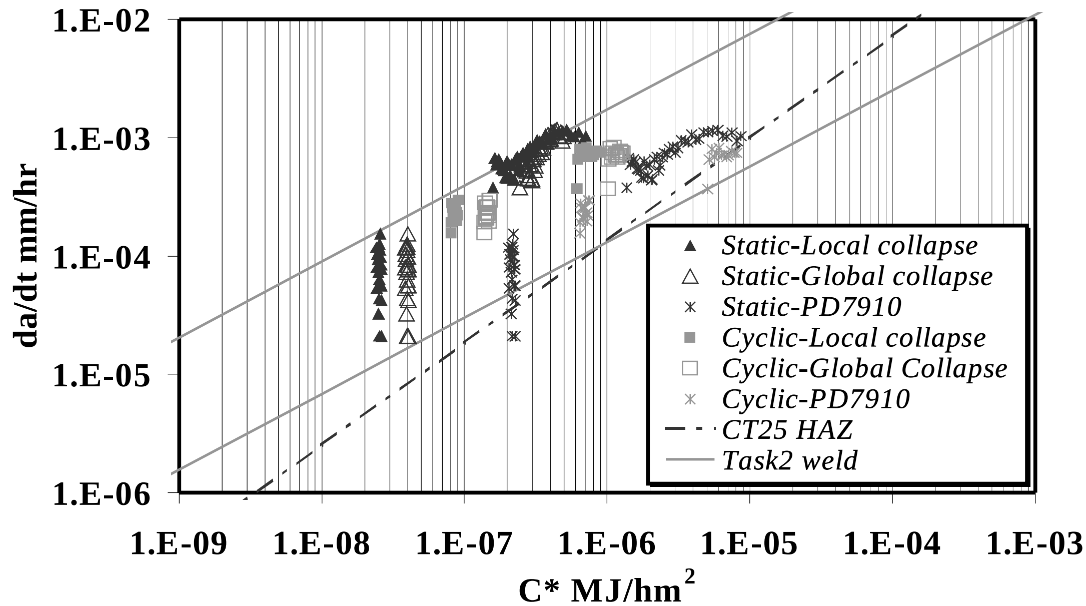

Fig. 1(a). P22: Seam welded pipe test results [4]

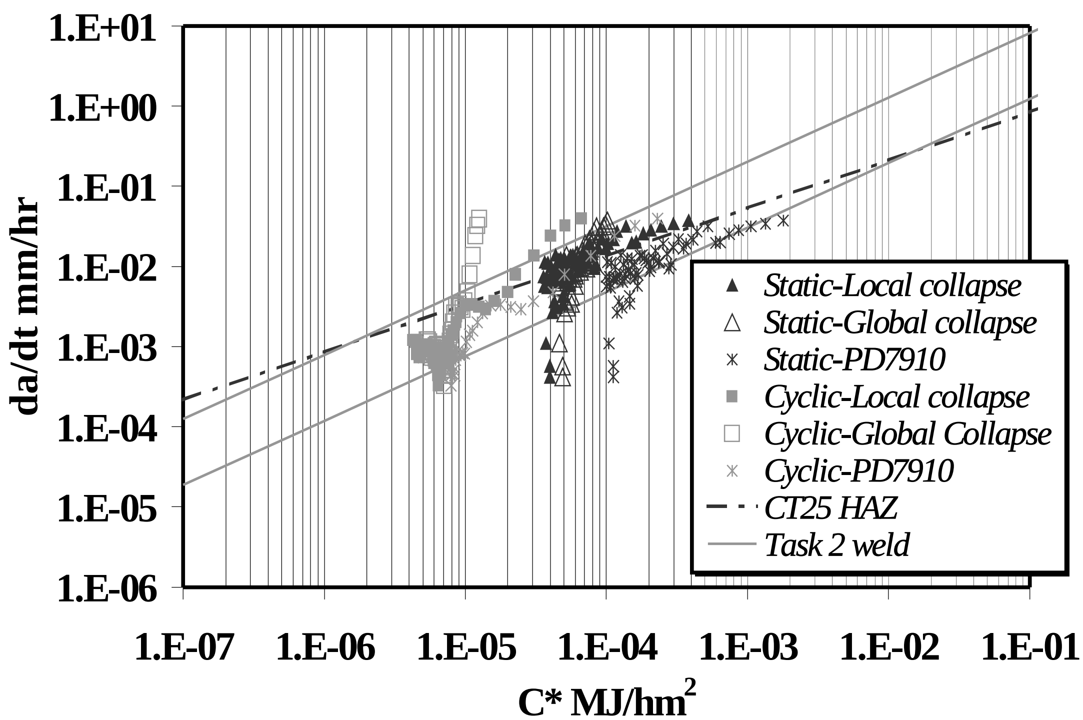

Fig 1(b). P91: Seam welded pipe test results [4]

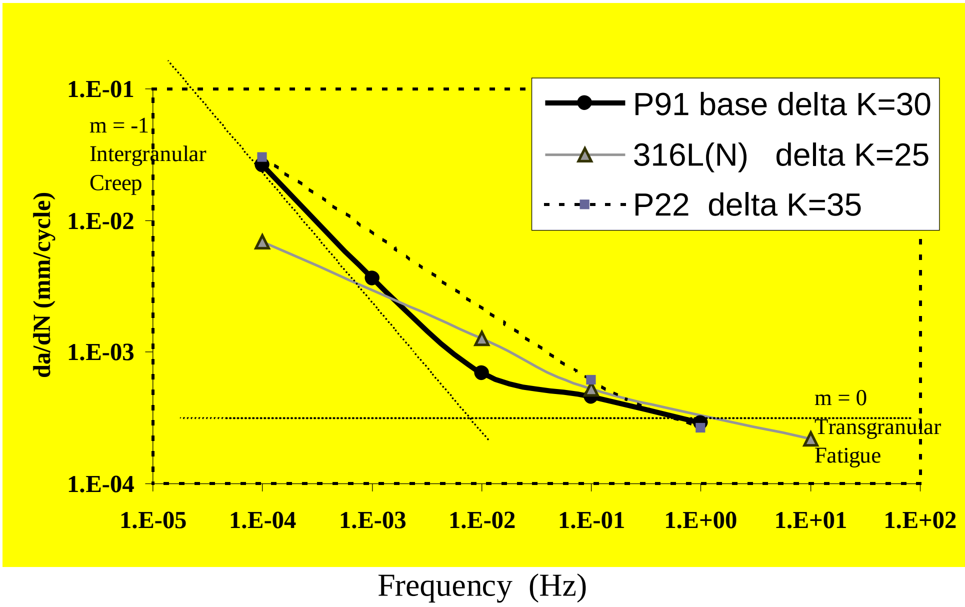

Fig 2. Creep-fatigue crack growth curves for some of the high-temperature alloys (including P91) [10]