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The effect of hot bending and thermal ageing on creep and microstructure evolution in thick-walled P92 steel pipe

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ABSTRACT

In this work, the creep behaviour of an actual thick-walled P92 steel pipe bent (90°) using local induction heating was investigated at 600 and 650 °C using uniaxial tension creep tests. Creep specimens were machined from the bend at different positions, namely at the intrados and extrados areas and neutral position and from the straight part of the pipe. Creep tests were followed by metallographic and fractographic analyses of the crept specimens to explain the observed creep behaviour. In order to accelerate the microstructural changes and thus to simulate long-term service conditions, isothermal ageing at 650 °C for 10,000 h was applied to selected creep specimens before creep exposures. The results of the creep tests performed on specimens extracted from the intrados and extrados of the thick-walled bent P92 steel pipe fall into the scatter band of the base P92 steel average line. No substantial differences were found at different positions of the pipe in the minimum creep rate, the time to fracture and creep fracture strain. However, significant detrimental effects on the creep resistance of the pipe were found after long-term static thermal ageing due to the microstructural instability of the material. The large Laves phase particles, which coarsened during ageing and creep testing, served as preferential sites for cavity nucleation leading to an accelerated tertiary stage of creep and/or premature creep fracture. Activation analysis of the creep data leads to the conclusions, that the creep tests were undertaken in the region of the power-law creep regime and the rate controlling creep deformation mechanism is most probably the climb of the intragranular dislocations.

1. Introduction

The large wall thickness of thick-walled components, such as main steam pipes and headers, limits the allowable rate of temperature change. This leads to disadvantages in the operation of power plants. From the material point of view, the wall thickness can be reduced by using of materials with higher creep strength. Further requirements compromise the ease of fabrication processes, including bending, along with improvements in oxidation resistance and other necessary attributes. As candidate materials for thick-walled boiler components, most attention has been paid up to now to the improving of the tempered martensitic creep resistant 9–12% Cr steels [1–11].

The steadily improved creep resistant new modified 9–12% Cr steels have been used to construct new coal-fired ultra-supercritical (USC) power plants with higher efficiency. The tungsten-modified 9% Cr steel P92 (ASTM Grade P92) was introduced in plants in 2001 [3]. Much effort has been applied to investigating the effects of cold bending on thin-walled pipes for line pipe applications [12–14]. It was reported that the tensile properties of the cold bends are different from those of the straight pipes due to work hardening and the Bauschinger effect [12]. An influence of bending can be also expected in the creep resistance. The results of a broad cold bending programme carried out on tubes of advanced ferritic steels including T92 steel were reported by Caminada et al. [12]. The creep properties of large cold bends were assessed by means of the creep specimens directly machined from the extrados and intrados portions of real bends. It was found that both the extrados and intrados exhibited a creep resistance within the lower scatter band of base material isothermal curve [12]. By contrast, a very limited knowledge has been established about the changes in the creep strength and high-temperature behaviour of hot bent thick-walled pipes [13–18]. The common basic topics in the analyses of bending characteristics

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have been addressed such as wrinkling instability, over thinning, cross-section deformation and springback phenomenon. The efficient tube hot bending depends on the knowledge about the mechanical properties of tubular material. Furthermore, the reliable FE modelling and simulation rely critically on the sound understanding and the accurate modelling of the unique material response of each material under hot bending loading. Up to now, most of the tube properties are obtained by uniaxial tension tests. A lack of suitable physical experiments and modelling theory for tubular materials may be attributed to the complexity of the techniques needed to undertake such studies.

Given that the pipe work used in power plants generally operates at high temperatures and is subjected to internal pressure, creep is of great concern and there is clear demand for methods which can be used to estimate the residual creep life in areas of potential weakness such as pipe bends. Accordingly, the present investigation was initiated using uniaxial tension creep testing to provide detailed information on the creep behaviour in the intrados and extrados areas and central (neutral) positions of hot-bent thick-walled P92 steel pipes. The creep behaviour and the microstructure at the extrados and intrados positions were compared with the properties of the unbent pipe.

Under service conditions at high temperatures there is a microstructural evolution in modified 9–12% Cr steels such as precipitation of new secondary phases, growth and coarsening of precipitates, and recovery of the tempered martensite matrix. The effect of microstructural evolution in modified 9–12% Cr steel on the creep strength is not fully understood [2,4,5,10]. It cannot be excluded that any prior working treatment could influence a microstructural evolution and thus affects the creep behaviour of a tubular material. To complete the characterization of creep behaviour and a microstructural evolution in the thick-walled bent P92 steel pipe it was decided to accelerate its microstructural evolution by prior thermal ageing [2,10] of selected creep specimens.

2. Material and experimental procedures

2.1. Material, processing and tensile testing

The material of the pipe under investigations was the W-alloyed 9% Cr steel P92 (ASME Grade 92) for thick-section boiler components and steam lines. The pipe was produced by Productos Tubulares, s.a.u., Spain and its chemical compositions indicates no difference from ASTM A213 (Table 1).

The initial dimensions of this pipe were OD 350 mm × WT 39 mm. Its heat treatment consisted in normalizing at 1050 °C/60 min/air followed by tempering at 740 °C/140 min/air. The hot-bending parameters were as follows: temperature 920–960 °C, R – radius of bend 1050 mm, angle of bend 90° and the rate of bending 7 mm/min. The maximum value of strain accumulated by the material during bending corresponds to the elongation of the extrados $\varepsilon_{extrados}$ and its value $\approx 16.7\%$ was calculated according to the ASME Boiler and Pressure Vessel Code [19]. The post-bending heat treatment was 1050 °C/60 min/air + 775 °C/140 min/air. Tensile testing was performed in accordance with ASTM E 21-09 at a strain rate of $3\times10^{-3}\ s^{-1}$. Every mechanical property was determined from 5 tensile tests. Tensile properties of the pipe in the as-received (AR) state at room temperature can be compared with ASTM A 335 in Table 2. Additional mechanical properties in different positions of unbent and bent parts of the pipe in (AR) state and after thermal ageing at 650 °C for 5000 h will be presented in Section 3 (Tables 3 and 4). In order to accelerate microstructural changes and thus to simulate the degradation of the microstructure under long-term service conditions, longer isothermal ageing at 650 °C for 10,000 h was applied to selected creep specimens prior to creep exposures. The states after isothermal ageing will be denoted as (IA).

Table 1
Chemical compositions of the pipe steel used for hot bending.

Chemical composition in wt%						
Material	C	Si	Mn	P	S	
According to ASTM A 213	0.08 0.13	Max. 0.50	0.30 0.60	Max. 0.020	Max. 0.010	
OD 350 × 39 mm^2	0.11	0.37	0.48	0.013	0.005	
Chemical composition in wt%						
Material	Cr	Mo	V	Nb	N	W
According to ASTM A 213	8.50 9.50	0.30 0.60	0.15 0.25	0.04 0.09	0.030 0.070	1.50 2.00
OD 350 × 39 mm^2	8.58	0.33	0.23	0.06	0.037	1.62

Table 2
Mechanical properties of P92 steel at room temperature-(AR) state.

Material	Yield strength $Rp_{0.2}$ (MPa)	Tensile strength Rm (MPa)	Elongation A_5 (%)
According to ASTM A 335	Min. 440	Min. 620	Min. 20
OD 350 × 39 mm^2	565	735	21.2

2.2. Creep testing

Constant load creep tests in tension were carried out in argon using flat creep specimens having a gauge length of 50 mm and a cross-sectional area of 5 mm × 3.2 mm. Creep specimens were machined from the middle parts of the wall thickness of the pipe at different positions, namely at the intrados and the extrados and at a central position (Fig. 1). For comparison, some creep specimens were also taken from the unbent pipe. The creep testing was conducted at 600 and 650 °C with the testing temperature maintained to within ± 0.5 °C of the desired value. The initial applied tensile stresses ranged from 85 to 250 MPa. All of the tests were continued until the final fracture.

The creep elongations were measured using a linear variable differential transducer (the strain was measured with a sensitivity of 5×10^{-6}) and they were continuously recorded digitally and computer processed.

2.3. Microstructural investigations

The following creep testing samples were prepared for microstructural examination by means of light, transmission and scanning electron microscopy. Transmission electron microscopy

Table 3
Mechanical properties in different positions of unbent and bent parts of pipe (as-received unbent state – AR, as-received bent state – BAR).

Properties	Temperature (°C)	Unbent mother pipe	Bent pipe (BAR)		
			Straight position	Extrados	Intrados
Yield strength	20	565 MPa	550 MPa	553 MPa	546 MPa
	600	325 MPa	313 MPa	311 MPa	310 MPa
Tensile strength	20	735 MPa	715 MPa	718 MPa	708 MPa
	600	345 MPa	730 MPa	330 MPa	327 MPa
Elongation A_5	20	21.2%	22.2%	22.1%	21.3%
	600	29.3%	28.6%	29.5%	28.0%