P. MOHYLA, Z. KUBON, R. CEP, I. SAMARDZIC

ISSN 0543-5846
METABK 53(2) 175-178 (2014)
UDC – UDK 669.15:621.791.057:620.17=111

EVALUATION OF CREEP PROPERTIES OF STEEL P92 AND ITS WELDED JOINT

Received – Prispjelo: 2013-06-04
Accepted – Prihvaćeno: 2013-09-20
Original Scientific Paper – Izvorni znanstveni rad

This work is focused on testing and evaluation of creep properties of P92 base material (BM) and welded joints (WJ) as well. Up to date results of creep rupture test of P92 base metal and welds are presented in this article. Creep rupture strength (CRS) of WJ initially reaches values close to the BM, with longer times to fracture and especially at higher temperatures, creep strength of WJ decreases and the data is closer to the lower 40 % tolerance band.

Key words: Steel P92, welded joint, base material, creep rupture strength, creep tests

INTRODUCTION

The need for increasing of the thermal efficiency of advanced power plants and environmental protection leads to worldwide effort of the development of modified 9 – 12 % Cr steels with very high creep resistant strength (CRS). In Europe, steel X20CrMoV12-1 has been used for thick-walled steel components up to 560 °C in the past. [1] Demands for increasing steam parameters (temperature and pressure) and efficiency of power plants required the development of modern steels with higher CRS and service temperature. Firstly, there was developed a modified 9 % Cr steel, designated as P91. Further development brought alloying of steels by tungsten. Typical representatives of modified chromium steel with tungsten are steels E911, P122 and P92 in particular. Currently considered one of the best modified chromium steel in terms of achieved values of creep rupture strength is steel P92. Initial estimates of CRS of this steel, based on short-term creep tests, were as high as about 190 MPa at 600 °C for 100 000 hours. Detailed analysis of the extensive files of creep data then resulted in the gradual lowering of creep rupture strength [1] and the recent recalculations based on long-term creep tests shows that the CRS of this steel lies between 110 and 120 MPa [2], which is quite high value in comparison to other chromium steels.

High creep resistance of modified chromium steels (including steel P92) takes its origin in the balanced contributions from precipitation strengthening, solid solution strengthening and also from martensitic microstructure with high dislocation density. It was found many years ago that the maximum creep rupture strength is reached with combined content of 1,8 wt. % W and 0,5 wt. % Mo [3]. The latest research shows that to achieve high values of creep rupture strength of steel P92 nitrogen and especially boron is essential. It has been shown that P92 steel without boron has low values of creep rupture strength, even lower than steel P91 [1].

EXPERIMENTAL MATERIAL

Special welded joints of steel P92 were prepared for further experiments. Chemical composition of base material is shown in Table 1. Forged plates with thickness 20 mm were welded by manual metal arc welding (111).

Table 1 **Chemical composition of BM wt. / %**

C	Mn	Si	Cr	Mo	V
0,090	0,50	0,34	8,85	0,50	0,21
W	Ni	Nb	Al	N	
1,90	0,31	0,084	0,008	0,0595	

Covered electrodes Thermanit MTS 616 (EN 12070 - WZ CrMoWVNb 9 0,5 1,5) was used for welding of test joints. Chemical composition is shown in Table 2 and parameters of welding are listed in Table 3.

Table 2 **The chemical composition of the coated electrodes, wt. / % [4]**

C	Si	Mn	Cr	Mo
0,11	0,2	0,6	8,8	0,5
Ni	W	V	Nb	N
0,7	1,6	0,2	0,05	0,05

CREEP Tests

Base material and welded joint of P92 steel were tested in the extensive experimental program of creep rupture tests. Testing temperatures 600, 625 and 650 °C were used in base material as well as weldment and in-

---

P. Mohyla, R. Cep, Faculty of Mechanical Engineering, VSB-Technical University of Ostrava, Czech Republic; Z. Kubon, Materials and Metallurgical Research, Ltd., Czech Rep.; I. Samardzic, Josip Juraj Strossmayer University of Osijek Mechanical Engineering Faculty in Slavonski Brod Croatia

Table 3 **Parameters of welding**

Weld joint type	butt weld
Welding method	MMAW (111)
Welding position	PA
Shielding gas	ARCAL TIG/MIG (EG-No. 231-147-0)
Consumables	Böhler Thermanit MTS 616 (EN 1599: EZ CrMoWVNb 9 0,5 2 B 4 2 H 5) Ø 2,5; Ø 3,25
Current	80 – 105 / A
Voltage	18 - 24 / V
Welding speed	2 – 5,5 / mm·s^{-1}
Heat input	0,30 – 0,60 / kJ·mm^{-1}
Preheating	200 / °C
Interpass	max. 300 / °C
Postheating	250 °C / 2 h

terval of stresses was chosen that guarantee times to rupture long enough to extrapolate CRS up to 100 000 hours.

Creep rupture strength of base metal and also weldment was calculated by means of Seifert parametric equation, expressing the applied stress or creep rupture strength as a quadratic function of stress-temperature parameter in the following form:

$$\log \sigma = A_0 + A_1 P + A_2 P^2 \quad (1)$$

Parameter P in this equation is defined as:

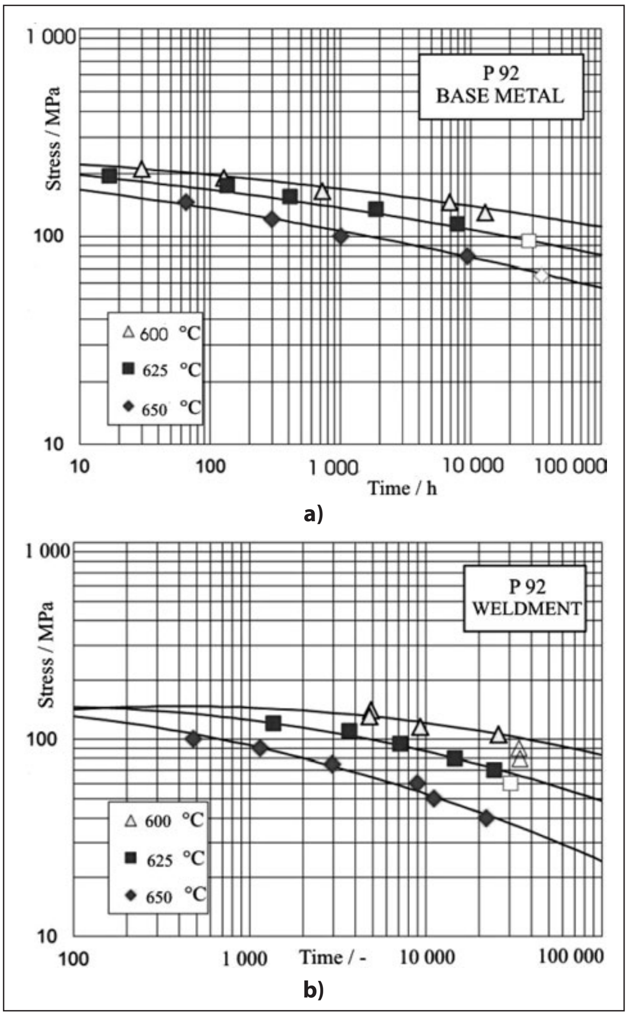
$$P = T \cdot (C + \log t_r) \cdot 10^{-4} \quad (2)$$

Table 4 shows the values of creep rupture strength in 10 000, 30 000 and 50 000 hours determined by using Seifert parametric equations [5]. Values of creep rupture strength in 50 000 hours are given in brackets, because they so far do not fulfill the minimum time to rupture for justified extrapolation according to [6].

Table 4 **Creep rupture strength of forged steel P92**

Temp / °C	600		
Time / h	10^4	$3·10^4$	$5·10^4$
Base metal	140	126	(119)
Weldment	121	104	95
EN 10216-2	153	134	125
Temp / °C	625		
Time / h	10^4	$3·10^4$	$5·10^4$
Base metal	108	95	(89)
Weldment	87	68	60
EN 10216-2	119	101	92
Temp / °C	650		
Time / h	10^4	$3·10^4$	$5·10^4$
Base metal	79	68	(63)
Weldment	53	38	31
EN 10216-2	88	71	64

In these equations σ represents stress in MPa, T is the absolute temperature in K, t means time to rupture in hours and A_0, A_1, A_3 and C are material constants. The results of creep rupture tests of base metal and also weldment are summarized in Figure 1 together with the curves calculated for the individual testing temperatures by Seifert parametric equation. Empty symbols in this figure represent still running creep tests. Creep tests results of base metal and weldment were recalculated in the form of Larson-Miller parameters in order to compare them [7]:



a)

b)

Figure 1 Results of creep rupture tests of P92 a) base metal and b) weldment

$$P_{LM} = T \cdot [C + \log t] \quad (3)$$

The meaning of the symbols in this equation is the same as in the former ones, and constant $C = 26{,}8$ was calculated by using the least squares method from the creep data provided in [2], a value that can be considered as usual for this type of steel.

Results of creep tests stated in the form of stress dependence of Larson-Miller parameter are shown in Figure 2 for both base metal and weldment. Individual testing temperatures are represented by different color; moreover, base metal is distinguished by triangles and welds by circles. Open symbols then represent still running tests. Solid line in this figure represents standardized mean creep rupture strength of P92 steel according to [2], dashed line shows allowed – 20 % scattering band round the mean value valid for base material and dotted line represents allowed – 40 % scattering band for welds. Figure 2 shows that the results of creep tests of base metal lie below the mean value line, but practically all of them are situated in the scattering band between mean values and – 20 % scattering band. How-

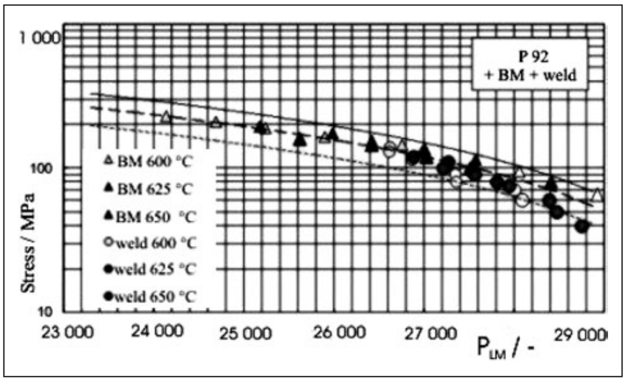


Figure 2 Relationship of stress and Larson-Miller parameter value for the BM and welds of steel P92

ever, with increasing value of the L-M parameter (and hence at higher temperature and longer time to rupture), the experimental results lie close to the mean standardized value and thus give very good prospects for use of this steel in the most demanding conditions of the coal fired power plants.

STRENGTH REDUCTION FACTOR

Welding procedure effect on long-term creep rupture properties of creep resistant materials can be expressed in the form of weld restriction coefficient W_r and this parameter should be utilized during the calculation of minimum design thickness of boiler tubes S_v:

$$S_v = \frac{p \cdot D_i}{(2\sigma_D - p) \cdot W_r} \qquad (4)$$

Here p means design steam pressure in MPa, D_i is internal tube diameter in m and σ_D represents allowable stress at design temperature *T*. W_r coefficient has its maximum value for fully loaded welds exposed to the applied stress in direction perpendicular to weld axis. The most desirable way how to express maximum parameter W_r is to perform cross weld creep tests simultaneously with creep tests of base material and to compare the creep rupture strength values of weldment R_{mT}(W) and creep rupture strength of base metal R_{mT}(BM):

$$W_r^{\max} = SRF = \frac{R_{mT}(W)}{R_{mT}(BM)} = f(t_r, T) \le 1 \; (5)$$

where *SRF* is strength reduction factor [8, 9] is the quite realistic measure of creep rupture strength decrease of weld in comparison to base material. As BM and WJ of P92 steel were both tested in the experimental program of creep rupture tests, it is possible to calculate SRF factor of this steel based on the creep experiment. The numerical values of SRF factors are stated in Table 5 for all three testing temperatures and times to rupture 10 000, 30 000 and 50 000 hours and the tendency of SRF factor on temperature and time to rupture are summarized in Figure 3. It is clear that with increasing temperature and time to rupture strength reduction factor decreases. Of course, the reliability of the calculated SRF factor critically depends on number and quality of creep rupture test results and therefore, the presented values are restricted maximally up to 50 000 hours.

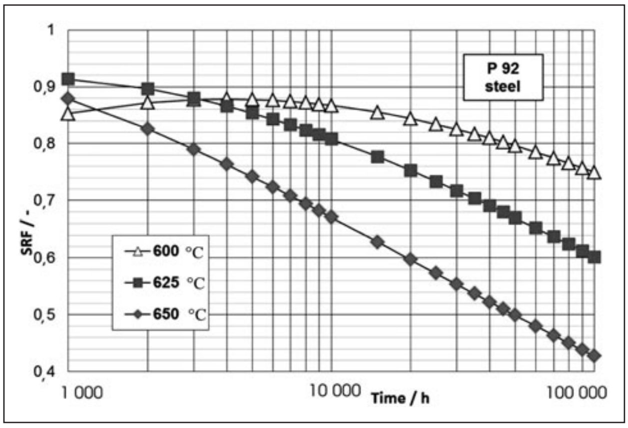


Figure 3 Time-temperature dependence of SRF factor of steel P92

Table 5 **Values of SRF factor of P92 weldment**

Temp / °C	600		
Time / h	10^4	$3 \cdot 10^4$	$5 \cdot 10^4$
SRF	0,86	0,82	(0,80)
Temp / °C	625		
Time / h	10^4	$3 \cdot 10^4$	$5 \cdot 10^4$
SRF	0,80	0,72	(0,67)
Temp / °C	650		
Time / h	10^4	$3 \cdot 10^4$	$5 \cdot 10^4$
SRF	0,67	0,59	(0,49)

DISCUSSION OF RESULTS

The results of P92 BM creep tests show that the experimental results lie within the allowed - 20 % scattering band round the mean standardized CRS values. With increasing Larson-Miller parameter (and thus prolonged time to rupture), CRS of BM tend to be closer to the mean standardized value. Short-time CRS of welded joints lies close to that for the BM, but with increasing time to rupture, and especially at higher testing temperatures, the creep strength of welded joint is situated between 20 % lower band of the mean CRS value and the – 40 % scattering band applicable for welds. Even, according to the most recent results, the data have fallen below this lower boundary . Therefore, originally optimistic expectations about the creep resistance of welded joints of new advanced chromium modified steels and steel P92, too, need to be corrected. The locality with minimum creep strength and thus the critical locality of weldments in chromium modified steels is in most cases the low-temperature (intercritical) part of heat affected zone (IC HAZ), where so-called type IV creep failure appears. This is typical for the circumferential welds of boiler tubes exposed to internal pressure of steam combined with the axial stress perpendicular to weld axis and originated from tensile and/or bending loading. [8-

10] Heavily tempered and partially transformed microstructure in this region facilitates the creep failure in IC HAZ also due to local decrease of precipitation strengthening as the result of partial dissolution and/or coarsening of minor phase particles. Refined grains in IC HAZ also enhance grain boundary sliding and Coble diffusion creep. The damage mechanism consists of nucleation, growth and interlinking of cavities followed by main crack propagation starting usually close to the first subsurface bead at external surface of the tube. Probability of type IV cracking grows at operating service more than 50 000 hours [1 1]. Relatively „soft"zone in IC HAZ is deformed practically without constraint effect (i.e. independently on the adjacent „hard"zones of weld with higher creep strength) during decisive fraction of creep life. In this zone the accumulation of creep deformation and continual cavitation ahead of creep crack tip lead to the local initiation of multiaxial stress state. Creep failure is then controlled by the combination of multiaxial (von Mises equivalent) stress in superposition with the maximum principal stress that simultaneously influence both the grain boundary sliding and cavitation damage accompanied by main crack growth [12]. The experimental results show possible risk that could result in premature service life exhaustion of boiler tube weld joint due to fast development of Type IV cracking. Thermal cycle during welding causes partial dissolution of dispersed particles of secondary (vanadium rich) MX phase, coarsening of primary (niobium rich) MX phase and tempering of martensitic. These processes significantly reduce precipitation strengthening especially in IC HAZ and tend to the explicit action of Type IV cracking controlling the rupture life of weld joints [8, 13]. SRF values calculated in this work correspond well with the values recommended e.g. by Etienne and Heerings [8] for steel P 91 and also with our previous results obtained on the same steel. [13] Then, it seems that the values of SRF at 600 °C for 100 000 hours really lie close to the value 0,50 or even less also in all newly developed chromium modified creep resistant steels.

CONCLUSIONS

The results of creep tests show that analyzed heat has good prospects to meet demand for creep strength level of steel P92, as is defined in the relevant material standard. The experimentally determined CRS lies close to the mean standardized value and with increasing temperature and time to rupture CRS even oversteps the required value. It turns out that the behavior of analyzed weld is similar to the behavior of all the group of Cr-Mo-V steels, where occurs significant drop of creep strength of weld joints in comparison with the base material as a result of microstructural changes especially in the intercritical part of HAZ. IC HAZ is the softest part of weldment and the fine and dispersed particles of secondary phases (especially vanadium nitride and niobium carbonitride) partly coarsen and partly dissolve during welding. However, almost all presented results of creep tests are in the allowed 40 % scattering band around the mean standardized values of CRS of steel P92.

Acknowledgement

This work presented in this article was supported by the Ministry of Industry and Trade of Czech Republic in the frame of the project FT-TA4/021.

REFERENCES

[1] V. Foldyna, et all. Development of Advanced Creep Resistant Ferritic Steels and their Weldability. In: Proceedings of conference Advanced Metallic Materials and their Joining. (2004), VÚZ Bratislava

[2] EN 10216-2+A2 - Seamless steel tubes for pressure purposes - Technical delivery conditions - Part 2: Non-alloy and alloy steel tubes with specified elevated temperature properties. CEN. 2008

[3] T. Fujita, et all. Creep Rupture Strength and Microstructure of Low C-10Cr -2Mo Heat Resisting Steels with V and Nb. Metallurgical Transactions, 12A (1981)6, 1071–1076

[4] EN 1599. Welding consumables - Covered electrodes for manual metal arc welding of creep-resisting steels - Classification, CEN 1999.

[5] W. Seifert. Statistische Kenngrössen aus der Ausvertung von Zeitstandversuchen. In: Warmfeste metallische Werkstoffe, Zittau, Kammer der Technik, (1987), 129-135

[6] ISO 6303 Pressure vessel steels not included in ISO 2604, Parts 1 to 6 - Derivation of long-time stress rupture properties, 1981

[7] F. R. Larson - J. A. Miller. Time-Temperature Relationship for Rupture and Creep Stresses. J.Trans. ASME, 74(1952), 765-775

[8] C. F. Etienne - J. H. Heerings. Evaluation of the influence of welding on creep resistance, International Institute of welding, (IIW), Document IX-1725-93, Steel Research, 65(1994)5, 187-196

[9] T. H. Hyde – W. Sun – J. A. Williams. Life estimation of pressurized pipe bends using steady-state creep reference rupture stresses. Int. J. Pres. Ves. and Piping, 79(2002)12, 799-805

[10] C. J. Middleton, et all. An assessment of the risk of Type IV cracking in welds to header, pipework and turbine components constructed from the advanced ferritic 9 % and 12 % chromium steel. Proc. of the 3rd Conference on Advances in Materials Technology for Fossil Power Plant, University of Wales, Eds. R. Viswanathan, W. T. Bakker, J. Parker, (2001), 69-79

[11] S. T. Tu – R. Wu R. Sandström. Design against creep failure for weldments in 0.5Cr0.5Mo0.25V pipe. Int. J. Pres. Ves. and Piping, 58(1994)3, 345-354

[12] D. J. Smith, et all. "Type IV creep cavity accumulation and failure in steel welds", Int. J. Pres. Ves. and Piping, 80(2003)9, 617-627

[13] Z. Kuboň – J. Sobotka. Assessment of long-term creep properties, creep failure and SRF of boiler tube weldments. In.: BALTICA VI-Life Management and Maintenance for Power Plants, Helsinki-Stockholm, Eds. J. Veivo-P. Auerkari, (2004), 477-490

Note: The responsible translator for English language is K. Slamova (Department of Languages, VŠB - Technical University of Ostrava, Czech Republic)