LONG-TERM CREEP RUPTURE STRENGTH PREDICITION AND FAILURE MECHANISMS OF WELDED JOINTS OF BOILER TUBES AND PIPES

KUBOŇ Zdeněk

Material and Metallurgical Research, Ostrava, Czech Republic, EU, creep.lab@mmvyzkum.cz

Abstract

Operating life and reliability of steam boiler and piping systems are considerably determined by long-term creep rupture strength (CRS) of welded joints of boiler tubes and pipes. Consequently, the appreciable research effort has been focused to reveal the most important factors affecting the creep properties of weldments. The presented work deals with the evaluation of creep rupture strength of welded joints in steam boiler piping system made from low-alloy and chromium modified steels. Cross-weld creep rupture tests and, at the same time, comparative creep tests of parent material are considered as the optimum approach how to evaluate the decreasing of creep resistance of weldment towards the base metal and how to quantify this effect e.g. by using strength reduction factor (SRF) and lifetime reduction factor (LRF) of welded joints. The necessary condition for such an approach is that the mechanism of creep damage (type IV cracking) in laboratory tests must be the same that acts in in-plant welded joints of the mentioned steels. The obtained results confirmed that the precipitation strengthened steels (mainly Cr-Mo-V type) show more pronounced decreasing of creep rupture strength of the critical locality of welded joint - intercritical part of heat affected zone when compared to Cr-Mo steels and that they are, therefore, much more prone to the premature failure.

Keywords: Creep, Cr-Mo-V steel, steel P91, strength reduction factor, type IV damage

1. INTRODUCTION

Components in power plants and petrochemical systems operate at high temperatures for long times. A large proportion of steel pressurised components are manufactured using low alloy ferritic steels and chromium modified steels, which are selected for their good combination of high temperature creep resistance and cost. Welded steel pressurised components in particular can experience creep deformation and fracture at high temperature, and the majority of the creep failures of pressurised components are associated with the welds [1]. Therefore, the appreciable attention has been focused on revealing the nature of weldment behaviour during creep exposure and on finding the way how to test them and how to predict the long-term creep strength of weldments in relation to parent material.

2. WELDMENTS AND TYPE-IV CRACKING

It is well-known that the welding leads to the formation of relatively narrow locality in weld joint with minimum creep strength [1-3] that

- is surrounded by weld parts with higher creep rupture strength,
- appears as preferable creep failure zone during in-service loading of welded tubes by internal pressure especially in superposition with additional axial tensile stress,
- limits the economical life of steam boiler piping system.

The critical locality of weldments in heat resistant carbon, low-alloy and chromium modified steels is in most cases the low-temperature (intercritical) part of heat affected zone (IC HAZ), **Figure 1**. Its existence then leads to premature failure designated as type-IV creep failure. This failure type is situated immediately near the transition of HAZ to the parent material and is typical for the complex stress state of circumferential welds of boiler tubes and pipes exposed to internal pressure combined with the axial stress perpendicular to weld axis and originated from tensile and/or bending loading [3, 4].

Heavily tempered and partially retransformed microstructure in this region facilitates the creep failure in IC HAZ. Creep rupture tests using cross-weld specimens at low stresses (<100 MPa for low alloy steels) show that the type-IV creep rupture strength is appreciably less than the parent steel strength [5, 6]. At higher stresses (>140 MPa for 0.5Cr-Mo-V steel), the cross-weld strength and parent steel strengths coincide. Consequently, tests at the high stress levels are unlikely to reveal the Type IV failure mode as cross-weld tests will generally fail in the parent steel or weld metals.

The damage mechanism consists of nucleation, growth and coalescence of grain boundary cavities followed by magistral crack propagation starting usually close to the first subsurface bead at external surface of tube/pipe.

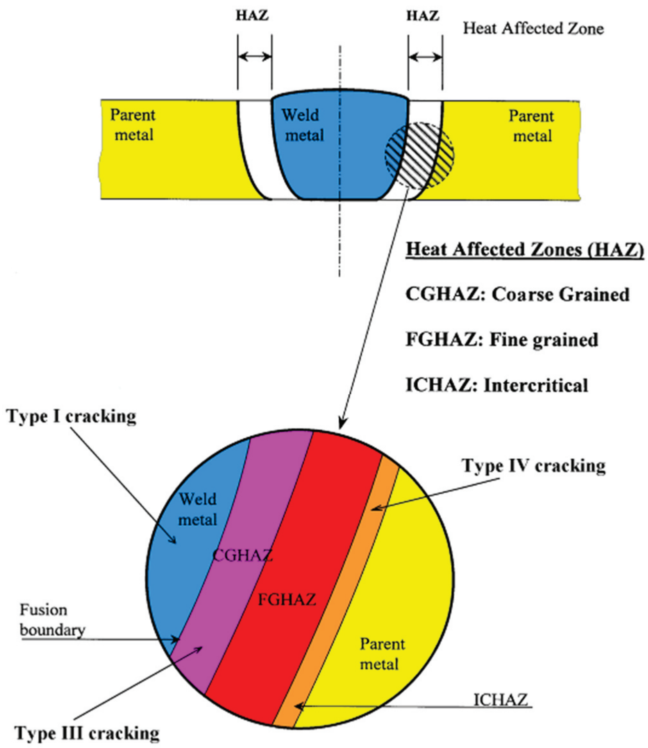

Figure 1 Schematic drawing of weldment parts

Probability of type-IV cracking appearance grows when its operating service oversteps approximately $5 \cdot 10^4$ hours, which is evident e.g. in cases of welded boiler tubes of low-alloy Cr-Mo-V steels precipitation strengthened by small particles of carbides and/or nitrides [1, 4, 7]. Owing to thermal effect of welding cycle, type IV zone is characterized by:

- local decrease of precipitation strengthening in consequence to the particles of minor phase particles, especially of MX type,
- grain size refining in IC HAZ with partly austenitized microstructure enhancing grain boundary sliding and Coble diffusion creep.

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 leads to the local initiation of multiaxial stress state. Creep failure is then controlled by the combination of multiaxial stress in superposition with the maximum principal stress that simultaneously influence both the grain boundary sliding and cavitation damage accompanied by crack growth [5, 8]. This failure mechanism is typical for weld joints of boiler tubes from low-alloy vanadium bearing or vanadium free Cr-Mo(V) steels and chromium modified steels of martensitic type In these cases, the typical feature of preferential type-IV cracking is the pronounced decrease of stress sensitivity of time to rupture occurring in the region of relatively low stresses and creep lives over 10^4 hours [1, 3-5, 8-10]. The great attention shall be also focused to the influence of testing condition including the size factor of test bars [5, 7, 11]. It was found that it is necessary to keep the minimum ratio of cross section of test bar compared to the width of the weakest weld locality, typically IC HAZ. The narrower width of IC HAZ (x) and the higher test bar diameter (d), the more pronounced stress redistribution occurs in the course of creep. Identical failure mode was found in circumferential welds of boiler tubes during in-plant service and laboratory cross-weld tensile creep tested bars if the $x/d \geq 2$ [12, 13].

3. ESTIMATION OF CREEP RUPTURE STRENGTH DECREASE IN WELDS OF TUBES/PIPES

The effect of welding on creep strength of steel can be expressed in the form of weld restriction coefficient W_r. This parameter should be also utilized at the calculation of minimum design thickness of tubes S_v:

$$S_v = \frac{p \cdot D_i}{(2\sigma_D - p) \cdot W_r} \qquad (1)$$

where p = design steam pressure [MPa]

D_i = internal tube diameter [mm]

$W_r \leq W_r^{max} = f(T, t_r) \leq 1$ σ_D = allowable stress at design temperature T [MPa].

where t_r = creep life (time to rupture) [h].

W_r^{max} is the maximum value of W_r, and is defined for full loading by applied stress σ in perpendicular direction to weld axis.

The estimate of W_r^{max} parameter is based on the results of cross weld creep rupture tests. This procedure enables to evaluate temperature as well as time to rupture dependence of both creep rupture strength values $R_{mT}(W)$ and the weakest (critical) weld locality. The more desirable (but also expensive) way how to express W_r^{max} is to perform cross weld creep tests simultaneously with creep tests of the base material used for weld joint preparation and to compare the creep rupture strength of weldment R_{mT} *(W)* and creep rupture strength of base metal R_{mT} *(BM)*:

$$W_r^{max} = SRF = \frac{R_{mT}(W)}{R_{mT\,(BM)}} = f(t_r, T) \leq 1 \qquad (2)$$

where *SRF* represents the strength reduction factor [3] as a quite realistic measure of creep rupture strength decrease of weld in comparison to the respective parent material.

As quite justified we can consider introducing of W_r parameter in eq. (1) in cases of circumferential welds of boiler tubes characterized by significant increase of axial tensile stress during long-term creep exposure. An additional axial loading originated in self-weight of tube bundle and/or bending moment action cannot be avoided, too. In such cases we can expect substantial decrease of long-term creep rupture strength and shortening of creep rupture life of welds in accordance with experimentally evaluated SRF parameters.

4. EVALUATION OF WELD RESTRICTION PARAMETERS OF TUBES/PIPES MADE OF VARIOUS CREEP RESISTANT STEELS

Four types of Cr-Mo and/or Cr-Mo-V creep resistant steels representing crucial boiler tube/pipe steel grades were chosen to demonstrate the long-term behaviour of weld joints and the significance of strength and life reduction factors. They were:

- low-alloy 0.3 % Mo bearing steel (16Mo3 according to EN 10 216-2),
- low-alloy 2.25 % Cr - 1 % Mo steel (10CrMo9-10 according to EN 10 216-2),
- low-alloy Cr-Mo-V steel grade corresponding to 14MoV6-3 steel according to EN 10 216-2,
- martensitic grade P 91 steel (X10CrMoVNbN9-1 according to EN 10216-2).

Detailed information concerning the fundamental parameters of experimental material, welding technologies, filler material and PWHT regimes, mechanical properties of weld joints and particularly the results of creep rupture tests were stated elsewhere [11, 14, 15]. The methods of preparing the welds comprised TIG technology in orbital automated or manual version and manual arc welding (MMAW) technology. The long-term creep rupture strength of both weld joints (cross weld stress rupture tests) and parent material used was investigated on creep test bars of 3.2 to 10 mm in dependence of actual tube/pipe thickness. Test temperatures and applied stresses were chosen with respect to standardized creep rupture strengths of individual boiler material and to necessity of extrapolation of creep rupture strength at time over 10^4 hours. The usual mathematical statistics treatment of creep rupture data was applied to describe stress-temperature dependence of time to rupture including the long-term creep rupture strength parameters evaluation. For these purposes, Seifert parametric equation [16] was chosen in which the applied stress (or rupture strength R_{mT}) is expressed by quadratic function of the parameter *P* in the form:

$$logR_{mT} = A_0 + A_1 \cdot P + A_2 \cdot P^2 \quad (3)$$

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

where *T* is the absolute temperature (K), t_r is time to rupture (h) and *C*, A_0 to A_3 are optimized constants.

The fundamental characteristics of all examined welds are presented in **Table 1** together with the results of creep rupture strength and also SRF evaluation. The example of time-temperature dependence of creep rupture strength of weld and corresponding boiler tubes/pipes altogether with resulting SRF values are shown also in **Figure 2** for the weld made of steel 14MoV6-3.

Table 1 Specification of boiler tubes/pipes and welding, results of evaluation of CRS and SRF

Boiler tube/pipe		Welding process	Filler material	Temp. (°C)	R_{mT} (MPa)		SRF	
Steel grade	Dimension				10^4 h	10^5 h	10^4 h	10^5 h
16 Mo3	ø51 x 5 mm	141 (TIG)	Union I Mo (ø 0.8 mm)	500	152	82	0.84	0.77
				525	86	34	0.78	0.71
10CrMo9-10	ø320 x 20 mm	111 (MMAW)	OK 76.28 (ø 2.5 to 4 mm)	550	94	61	0.94	0.95
				575	69	41	0.91	0.92
				600	49	27	0.86	0.87
14MoV6-3	ø 38 x 5 mm	141 (TIG)	C-321 (ø 0.8 mm)	550	120	65	0.92	0.75
				575	80	40	0.76	0.65
P91	ø 324 x 32 mm	111 (MMAW)	Fox 9CMV (ø 3.25 to 4 mm)	550	150	111	0.87	0.79
				575	113	81	0.82	0.75
				600	83	58	0.77	0.70
				625	60	40	0.73	0.66
				650	42	27	0.69	0.62

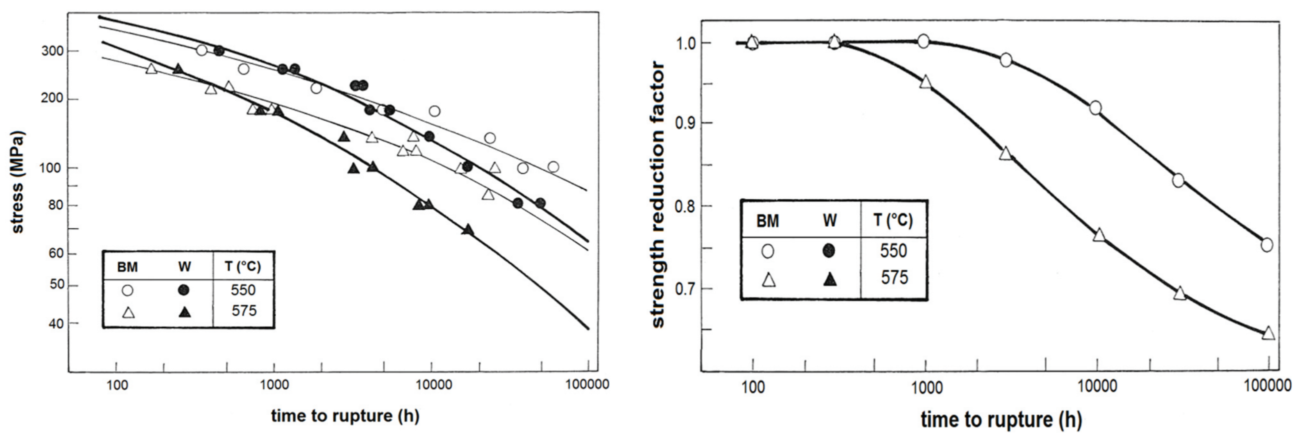

Figure 2 Temperature-time dependence of stress (left) and SRF (right) of 14MoV6-3 steel weldment

It is evident that regardless of the applied welding technology the highest SRF values, among tested steel grades, has low-alloy Cr-Mo steel. Either Mo-bearing grade 16Mo3 or Cr-Mo-V steel 14MoV6-3 show stronger decrease of creep rupture strength of weldments compared to parent material. It also seems that increasing vanadium content in the steel enhances creep rupture strength but, on the other hand, also decreases SRF factor in comparison to Cr-Mo steels. Although chromium modified steels have higher creep rupture strength than above mentioned steels, this is counterweighted by more pronounced decrease of SRF being only from 0.6 to 0.7 for time to rupture 10^5 hours at 600 to 650 °C. The increase of both temperature and time to rupture is then accompanied by decrease of SRF in all cases of the examined weld joints.

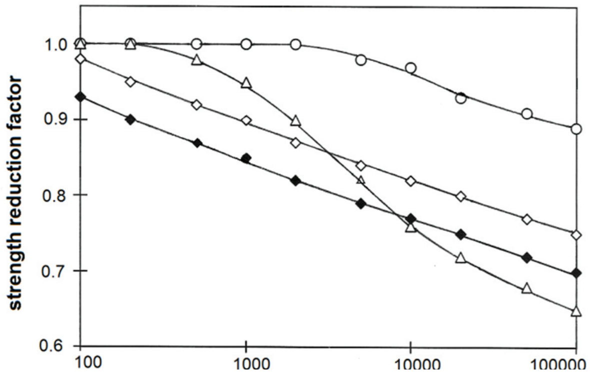

Figure 3 Time dependence of SRF of the tested steels

The typical feature of all boiler tube welds is the preferable type IV mechanism of creep failure indicating that the IC HAZ is the weakest weld locality from the viewpoint of its long-term rupture strength (**Figure 3**). This fact corresponds very well with the observed decrease of stress sensitivity of time to rupture that is more intensive in weldments compared to parent metal. The decreasing tendency of time-temperature dependence of SRF is in many cases evident already at times to rupture above 10^3 hours

Type IV cracking (as the principal failure mode of creep specimens in our experiment) is fully comparable with damage mode and operation life exhaustion of in-plant welded boiler tubes/pipes. This confirms the suitability of the above described approach to the testing of creep properties of welds. Finally, the minimum diameters of creep specimens were 3.2 mm and, simultaneously, the width of the IC HAZ was lower than 1 mm, i.e. in all examined cases the required geometrical condition $d/x<2$ was fulfilled. Type IV cracking occurs significantly before the expected creep life of the parent steel especially when there is significant tensile stress in axial direction originated either in self-weight of tube bundle or in additional bending load, when maximum design allowable stress did not take into account stress restriction in the weldments, when the creep rupture properties are low due to substandard metallurgical quality, when circumferential welds of boiler tubes/pipes were made with applying improper welding fillers, heat input and post weld heat treatment regime and also when the component is in long-term operation at temperatures over 580 °C. Such a behaviour is typical mainly for strongly precipitation strengthened low alloy and martensitic steels when thermal cycle during welding causes partial dissolution of dispersed particles of secondary (vanadium rich) MX phase and tempering of martensite. 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 [3, 15, 17].

5. CONCLUSION

Creep life prediction of piping systems in power plants can be evaluated by direct assessment of creep properties of boiler tubes and their welded joints. Such an attitude gives very precise and reliable results provided that weld joint is the critical part of the piping system due to the existence of IC HAZ. The size of test specimens can be neglected, if these diameter is at least twofold compared to the thickness of the IC HAZ. In this case the same failure mode appears in both creep tests as well as in-service parts. Creep rupture strength reduction in welds can be then expressed by means of SRF factor.

ACKNOWLEDGEMENTS

This paper was created in the frame of the Project No. LO1203 "Regional Materials Science and Technology Centre - Feasibility Program" funded by Ministry of Education, Youth and Sports of the Czech Republic.

REFERENCES

[1] KIMMINS, S. T., COLEMAN, M. C., SMITH, D. J. An overview of creep failure associated with heat affected zone of ferritic weldments. In: Creep and Fracture of Engineering. Materials and Structures. London: The Institute of Materials, 1993, pp. 681-694.

[2] PRICE, A. T.-WILLIAMS, J. A. Influence of Welding on Creep Properties of Steels. In: Recent Advances in Creep and Fracture of Engineering Materials and Structures. Swansea: Pineridge Press, 1982, pp. 265-353.

[3] ETIENNE, C. F., HEERINGS, J. H. Evaluation of the influence of welding on creep resistance. Steel Research, 1994, vol. 65, no. 5, pp. 187-196.

[4] BREAR, J. M., MIDDLETON, C. J. The applicability of weld failure prediction maps to new and exposed welds. In 3rd International HIDA and Integrity Conference, Lisbon: ISQ-Oeiras, 2002, pp. 401-412.

[5] SMITH, D.J., WALKER, N.S., KIMMINS, S.T. Type IV creep cavity accumulation and failure in steel welds. Int. J. Pres. Ves. and Piping, 2003, vol. 80, no. 9, pp. 617-627.

[6] FRANCIS, J. A., MAZUR, W., BHADESHIA, H. K. D. H. Type IV cracking in ferritic power plant steels. Materials Science and Technology, 2006, vol. 22, no. 12, pp. 1387-1395.

[7] HYDE, T. H., SUN, W., BECKER, A. A., WILLIAMS, J. A. Life prediction of repaired welds in a pressurised CrMoV pipe with incorporation of initial damage. Int. J. Pres. Ves. Piping, 2004, vol. 81, no. 1, pp. 1-12.

[8] ALBERT, S. K., et. al. Variation in the type IV cracking behaviour of a high Cr steel weld with post weld heat treatment. Int. J. Pres. Ves. Piping, 2003, vol. 80, no. 6, pp. 405-413.

[9] HYDE, T. H., BECKER, A. A., SUN, W.-WILLIAMS, J. A. Finite-element creep damage analyses of P91 pipes. Int. J. Pres. Ves. Piping, 2006, vol. 83, pp. 853-863.

[10] YAGUCHI, M.-MATSUMURA, T.-HOSHINO, K. Evaluation of Long-Term Creep Strength of Welded Joints of ASME Grades 91, 92 and 122 Type Steels. In ASME Pressure Vessels and Piping Conference: Volume 6: Materials and Fabrication, Parts A and B. New York: ASME, 2012, pp. 317-326.

[11] SOBOTKA, J. et al Influence of vanadium on creep rupture SRF of boiler tubes. In: Mathematical Modelling of Weld Phenomena 5, London: IOM Communications, 2001, pp. 479-494

[12] STORESUND, J., TU, S. T. Geometrical effect on creep in cross weld specimens. Int. J. Pres. Ves. Piping, 1995, vol. 62, no. 2, pp. 179-193.

[13] PARKER, J. D., STRATFORD, G.C. Strain localization in creep testing of samples with heterogeneous microstructures. Int. J. Pres. Ves. and Piping, 1996, vol. 68, no. 2, pp. 135-143.

[14] SOBOTKA, J et al. Evaluation of creep resistance of weldments with respect to remnant life prediction of power equipment (Hodnocení žárupevnosti svarů ve vztahu k predikci životnosti energetických zařízení). In Zváranie v energetike. Trnava: ESAB Slovakia-MtF STU Trnava, 2004, pp. 62-81 (in Czech).

[15] KUBOŇ, Z., SOBOTKA, J. 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: VTT Industrial Systems, 2004, pp. 477-490.

[16] SEIFERT, W. Statistische Kenngrössen aus der Ausvertung von Zeitstandversuchen. In. Warmfeste Metallische Werkstoffe 6, Zittau: Kammer der Technik, 1987, pp. 129-135.

[17] PARKER, J. Factors affecting Type IV creep damage in Grade 91 steel welds. Materials Science and Engineering A, 2013, vol. 578, pp. 430-437.