ECCC RECOMMENDATIONS - VOLUME 5 Part 2b [Issue 2]

GUIDANCE FOR THE ASSESSMENT OF CREEP RUPTURE, CREEP STRAIN AND STRESS RELAXATION DATA

RECOMMENDATIONS FOR THE ASSESSMENT OF WELD CREEP-RUPTURE DATA

[blank page]

ECCC RECOMMENDATIONS – VOLUME5 Part 2b [Issue 2]

GUIDANCE FOR THE ASSESSMENT OF CREEP RUPTURE, CREEP STRAIN AND STRESS RELAXATION DATA

RECOMMENDATIONS FOR THE ASSESSMENT OF WELD CREEP-RUPTURE DATA

PREPARED BY ECCC-WG1

Mr P Auerkari	VTT, Finland (1997-)
Mr M Askins	Innogy, UK (2001-5)
Dr D R Barraclough	ASTEC, UK (1992-4)
Dr P Bernasovsky	Slovakian Welding Institute (2001-5)
Dr-Ing B Buchmayr	Technische Univ. Graz, Austria (1992-2005)
Dr C K Bullough	ALSTOM Power, UK (1992-96, 2010-)
Ir C Coussement	Belgian Welding Institute, Belgium (1997-99)
Prof E Gariboldi	Politecnico di Milano, Italy (2001-10)
Dr-Ing J Granacher	IfW TU Darmstadt, Germany (1992-2005)
Dr R Hales	ETD, UK (2001-4)
Dr S R Holdsworth	EMPA, Switzerland (1992-2011, 2014-) [Past Convenor]
Mr S Holmström	VTT, Finland (2000-)
Dr-Ing A Klenk	MPA Stuttgart, Germany (1997-)
Dipl-Ing H König	ALSTOM Power, Germany (1992-2000)
Dr P Lombardi	CSM, Italy (2011-)
Dr P McCarthy	ALSTOM Power, UK (2002-5)
Dr P F Morris	CORUS, UK (2000-7)
Dr-Ing G Merckling	Istituto Scientifico Breda, Italy (1992-)
Dipl-Ing K Niel	Siemens KWU, Germany (1992-5)
Mr M Norman	Alstom Power, UK (2011-)
Mr J Orr	TATA, UK (1992-99)
Dr M Ortolani	Tenaris Dalmine,Italy (2011-…)
Mr J H Rantala	JRC IAM Petten (1997-2001)
Mr A Riva	Ansaldo Energia, Italy (2011-…)
Dr D G Robertson	ERA Technology Ltd, UK (1997-2001)
Dr-Ing W Rohde	VDEh, Germany (1992-96)
Prof R Sandström	SIMR, Sweden (1992-)
Dr M Schwienheer	University of Darmstadt, Germany (2001-)
Dr P Seliger	Siempelkamp, Germany (2001-5)
Dr I A Shibli	ERA Technology Ltd, UK (1995-6)
Dr S Spigarelli	University of Ancona, Italy (2001-5)
Mr M W Spindler	EDF Energy, UK (2006-) [Convenor, 2011-]
Mr M Talík	Forschungszentrum Juelich, Germany (2011-)
Dipl-Ing H Theofel	MPA Stuttgart, Germany (1992-6)
Dr A Vanderschaeghe	Stein Industrie, France (1992-4)

EDITED BY: S.R. HOLDSWORTH, A KLENK

APPROVED D.J.-Allen **DATE 07/05/2014**

On behalf of ECCC

[blank page]

ABSTRACT

ECCC Recommendations Volume 5 Part 2b provides guidance for the assessment of weld creep rupture data sets and the derivation of weld strength factors. It recognises that it is not practical to recommend a single assessment procedure for weld data sets and promotes the innovative use of the method for derivation of weld strength factors and the post assessment acceptability criteria to independently test the effectiveness and credibility of weld creep property predictions.

The guidance is based on the outcome of a work programme involving the evaluation of a number of assessment procedures by several analysts using weld creep rupture data sets. The results of this exercise highlight the risk of unacceptable levels of uncertainty in predicted strength values and weld factors without the implementation of well defined assessment strategies including critical checks during the course of analysis. The findings of the above mentioned work programme and other experience are detailed in appendices to the document.

ECCC Recommendations Volume 5 Part 2b user feedback is encouraged and should be sent to:

Dr A Klenk
MPA Stuttgart
Paffenwaldring 32
D 70569 Stuttgart
Tel: +49 711 685 63968
Fax: +49 711 685 63053
E-mail: andreas.klenk@mpa.uni-stuttgart.de

ECCC may from time to time re-issue this document in response to new developments. The user is advised to consult the Document Controller for confirmation that reference is being made to the latest issue.

[blank page]

RECOMMENDATIONS FOR THE ASSESSMENT OF WELD CREEP-RUPTURE DATA

CONTENTS

1. INTRODUCTION

Weld creep rupture datasets are typically sub-size, in terms of the number of weldment sources, the number of $t_{u(W)}(T,\sigma_o)$ data points and $t_{u(W),max}(T)$. In addition, they may be the consequence of iso-thermal and/or iso-stress test matrices. Iso-stress testing is a relatively common way of characterising the creep rupture properties of weldments [1,2]. The consequent $t_{u(W)}(T,\sigma_o)$ data point distributions may restrict the candidate procedures which can be adopted for assessment.

In addition to creep-rupture strength values for a given time and temperature, $R_{u(W)/t/T}$,[1] the associated weld reduction factors are also usually required from the assessment of weld creep-rupture datasets. Four factors are defined in [3c], these being weld strength factor (WSF), weld time factor (WTF), strength reduction factor (SRF) and time reduction factor (TRF), *i.e*.

$$\mathrm{WSF}(t,T) = \frac{R_{\mathrm{u(W)}/t/T}}{R_{\mathrm{u}/t/T}} \tag{1a}$$

$$\mathrm{WTF}(\sigma,T) = \frac{t_{\mathrm{u(W)}/\sigma/T}{}^{*}}{t_{\mathrm{u}/\sigma/T}{}^{*}} \tag{1b}$$

$$\mathrm{SRF}(t,T) = \frac{\left(R_{\mathrm{u}/t/T} - R_{\mathrm{u(W)}/t/T}\right)}{R_{\mathrm{u}/t/T}} \tag{2a}$$

$$\mathrm{TRF}(\sigma,T) = \frac{\left(t_{\mathrm{u}/\sigma/T}{}^{*} - t_{\mathrm{u(W)}/\sigma/T}{}^{*}\right)}{t_{\mathrm{u}/\sigma/T}{}^{*}} \tag{2b}$$

These weld reduction factors may be defined with respect to the properties of the specific parent material(s) to which the $t_{u(W)}(T,\sigma_o)$ data relate or to the alloy mean properties of the parent material(s). Where possible, comparison with heat specific properties is preferred, in particular for datasets comprising results from a small number of weldments.

The $t_{u(W)}(T,\sigma_o)$ data from cross-weld tests may be assessed using the same procedures as those available for parent materials [4a,b]. In Part IIa, four strategies are identified for the assessment of sub-size $t_{u(S)}(T,\sigma_o)$ datasets, i.e. (i) the use of data factors, (ii) the application of statistical modelling, (iii) the complementary use of creep strain data, and (iv) the complementary use of reference $R_{u/t/T}$ curves. Of these, option (iv) is the most applicable to the assessment of weld-creep data.

An important consideration is that the $t_{u(W)}(T,\sigma_o)$ data comprises information collected for the fracture location relevant to the application for which the strength values are required [5b]. For example, if the fracture location in service is in the Type IV region of the weldment, the $t_{u(W)}(T,\sigma_o)$ data leading to the determination of $R_{u(W)/t/T}$ should originate from tests involving specimen failure in the ICHAZ of the test weld or an appropriately simulated microstructure (*e.g*. [6]). Fracture location and the acceptability of simulated microstructures are therefore important additional considerations in the post-assessment of weld creep-rupture data.

The weldment property characteristics of ferritic steels are shown schematically in Fig. 1 in terms of strength reduction factor. Typically for such materials, fracture occurs in the parent material at high applied stresses, and rupture times are coincident with PM $t_u{}^*(T,\sigma_o)$

[1] The terminology used in Part 2b is as defined in [3]

properties, i.e. WSF(t,T) and WTF(σ,T) are close to unity. With reducing stress, the fracture location shifts to the ICHAZ and $t_{u(W)}$*(T,σ_o) rupture times reduce with respect to parent material t_u*(T,σ_o) and the magnitudes of WSF(t,T) and WTF(σ,T) reduce to a lower relatively constant value. With increasing temperature, the magnitudes of, and the time to achieve WSF(t,T)$_{min}$ and WTF(σ,T)$_{min}$ reduce.

In practice, it is unlikely that WSF(t,T) and WTF(σ,T) attain a constant minimum value in ferritic steels, since it is unlikely that metallurgical change will occur in the ICHAZ at exactly the same rate as that in the parent material. Nevertheless, if it can be demonstrated that WSF(t,T)$_{min}$ and WTF(σ,T)$_{min}$ do attain an essentially constant value, the basis for extrapolated $R_{u(W)/t/T}$ strength values is possible if reliable long term $R_{u/t/T}$ data are available (e.g. [7,8]).

Methods available for assessing the creep rupture properties of weldments are introduced in Sect. 2.2. The quantity of data for a specific weldment type/configuration is usually limited. It may be possible to expand the size of the dataset for assessment by also considering 'comparable' data. Guidance on 'comparability' is given in Sect. 2.3. Specific recommendations for weld creep-rupture data assessment (WCRDA) are given in Sect. 2.4.

2. WELD CREEP-RUPTURE DATA ASSESSMENT

2.1 OVERVIEW

The ECCC recommendations for the assessment of weld-creep data are based on a review of WCRDA procedures (Appendix A) and an evaluation of their effectiveness in Annex B.

2.2 ASSESSMENT METHODS

The options for assessing weld-creep data are invariably determined by the scope of available observations and the position in the weldment at which fracture occurs (the fracture location being inextricably linked to the metallurgical constitution of the weldment). In certain circumstances and with care, it is possible to apply the same procedures available for parent material (i.e. Part I), either to assess:

- all weld creep $t_{u(W)}$(T,σ_o) data (irrespective of the fracture location), or
- only weld creep $t_{u(W)}$(T,σ_o) data for a given fracture location (invariably the anticipated in-service fracture location): this being the preferred of these two options.

The ultimate objective of a WCRDA is invariably to determine one or more of the weld factors defined in Eqns. 1 and 2, e.g. WSF(t,T).[2] Consequently, two further options are to examine:

- all $t_{u(W)}$(T,WSF) data, determined using t_u*(T,σ_o) properties for the specific heat(s) of parent steel(s), this being the preferred WSF based option, or
- all $t_{u(W)}$(T,WSF) data, determined using the alloy mean t_u*(T,σ_o) properties.

Potentially the biggest problem associated with the assessment of weld creep data is extrapolation to determine long time $R_{u(W)/t/T}$ strength values. In circumstances where the fracture location shifts from the parent material to the ICHAZ, the weldment properties of ferritic steels are assumed to have the WSF(t,T) characteristics represented by the schematic given in Fig. 1. With a knowledge of reliable WSF(t,T)$_{min}$, it is possible to extrapolate with reference to the long term $R_{u/t/T}$ strength values of the parent material relating to the ICHAZ in which long term fracture occurs.

[2] The text focuses on the use of WSF(t,T) for brevity. It is not the intention to preclude the use of WTF(σ,T), SRF(t,T) and TRF(σ,T).

To solve the problem of an appropriate derivation of WSF in the case of a change in fracture location the following suggestions can be made:

- use of data obtained reasonably after the change of fracture location if a sufficient amount of data is available
- additional use of rupture data from heat affected zone simulated material
- use of all data although it is likely that a more conservative result is determined

A method of WCRDA describing these approaches is given in Annex C. The method described considers in more detail how to assess welded joints when a change in fracture location occurs.

In dissimilar metal welds (DMWs), the fracture location may be adjacent to one fusion boundary, either just inside the HAZ or the weld metal and associated with a compositional gradient between the parent and weld metals. If the compositional differences are significant, the combined use of $WSF(t,T)_{min}$ and PM or WM reference $R_{u/t/T}$ strength values may be inappropriate.

For weldment data, for which creep fracture is in the main weld metal, it may be possible in pre-assessment to demonstrate that the properties of the weld metal are comparable to those of a parent material grade of the same pedigree for which there exists long duration $R_{u/t/T}$ strength properties (e.g. [7,8]). In these circumstances, extrapolation may be made with reference to the $R_{u/t/T}$ properties of the 'comparable' reference material.

2.3 COMPARABILITY

The quantity of data for specific weldment types/configurations is usually limited. Nevertheless. it may be acceptable to expand the scope of the dataset to be assessed by including '*comparable*' data.

At a simple level, weldments constructed from parent material(s) procured to the specified requirements with the specified filler metal(s), but with different welding procedures, may be regarded as 'comparable' if (i) the consequent thermal histories result in properties which are contained within a $R_{u(W)/t/T}$±20% scatterband and (ii) fracture locations are in the same metallurgical region of the weld.

It is therefore possible that weld metal pedigree and welding process may be relatively unimportant for weld-creep data for which fracture is in the inter-critical HAZ (e.g. in ferritic weldments). However, this must be verified during pre-assessment using the $R_{u(W)/t/T}$±20% rule.

The concept may be extended in certain circumstances. For example, parent material pedigrees can be relatively unimportant for weld-creep data for which fracture occurs in the main weld at a significant distance from the fusion line (e.g. certain austenitic weldments). In such circumstances, it may be appropriate to use data determined using testpieces removed from 100% weld metal samples. However, there is potentially less scope for combining data from welds produced by different welding processes when the fracture location is in the weld metal. As above, the recommended test for comparability is that the data can shown in pre-assessment to occupy a databand within ±20% of $R_{u(W)/t/T}$.

When the creep fracture location is in the vicinity of a fusion boundary (e.g. in DMWs), there is usually little scope for extending the dataset with 'comparable' data. In these circumstances, properties are sensitive to parent material / welding consumable composition, welding process and heat treatment details.

A common source of comparable $t_{u(W)}(T,\sigma_o)$ data is that determined from simulated material. Microstructures should be thermally simulated using an appropriate method e.g. Gleeble simulation. Ideally parameters for the simulation procedure are based on direct measurements from target weldments. Where this information is unavailable, computer modelling techniques may be used which have been validated for the weldment materials in question and an appropriate range of weld geometries/dimensions [5b]. The peak temperature of the simulation procedure is material dependent and should be selected to ensure that the weakest microstructure occurring in the actual weld is achieved by simulation. It should be confirmed by metallographic examination that the grain size and the transformation product of the simulated microstructure are consistent with that of the weakest location in the weld.

2.4 RECOMMENDATIONS

The ECCC-WG1 WCRDA evaluation activity reported in Appendix B has led to the following recommendations. The following are specifically aimed at assessments leading to strength values to be externally published by ECCC, but may be used for other purposes.

1) At least two WCRDAs should be performed by two independent weld-metallurgical specialists using their favoured proven methodology.

2) Prior to the main-assessment, a pre-assessment should be performed which takes cognisance of the guidance given in Sect. 2.5.

3) The results of the two WCRDAs should predict $R_{u(W)/t/T}$ to within 10% at $T_{min[10\%]}$, T_{main} and $T_{max[10\%]}$ at the maximum test time for each temperature.1[3]

4) Whenever possible and in particular when the variation in WSF(t,T) from cross-weld data is ≥10% between $0.8.t_{u(W),max}$ and $t_{u(W),max}$, long duration test data obtained from cross weld specimens should be used to support long time $R_{u(W)/t/T}$ strength and WSF(t,T) predictions.

   The appropriate weldment microstructure is that in which rupture occurs after long times of design life magnitude at the main application temperatures

5) Long time $R_{u(W)/t/T}$ strength and WSF(t,T) predictions should not be based exclusively on simulated weldment microstructure test data.

6) Test data for simulated weldment microstructures should only be used when material *comparability* has been confirmed by hardness and microstructure integrity checks of hardness, transformation product and grain size.

7) In general an extrapolation of WSF is not recommended. WSF for longer times should be based on assessments of base material and welded joints which can be extrapolated in an appropriate manner.

8) The results of the main-assessment should satisfy the requirements of the post assessment acceptability criteria given in Sect. 2.6.

9) During subsequent use of the master equation derived from the WCRDA, strength predictions based on extended time and extended stress extrapolations must be identified.

[3] $T_{min[10\%]}$ and $T_{max[10\%]}$ refer to the minimum and maximum temperatures for which there are greater than 10% data points. T_{main} is the temperature with the highest number of data points.

Extended time extrapolations are those beyond $3.t_{u(W),max}$ at temperatures within ±25°C of that specified.[4] Results from tests in progress may be included when above the -20% scatterband limit at the appropriate duration.

Extended stress extrapolations are those in the ranges '$0.9.\sigma_{o,min}$ to $\sigma_{o,min}$' and '$\sigma_{o,max}$ to $1.1.\sigma_{o,max}$'.

Quantification of the uncertainties associated with extrapolated strength values and those involving extended extrapolations should be a goal for the future.

2.5 PRE-ASSESSMENT

Where possible, pre-assessment should be performed according to the guidance given in Part I [4a]. However, there are important additional considerations for weld-creep data.

An evaluation of the 'comparability' of weld-creep data is an integral part of pre-assessment and will consider factors such as fracture location and whether the data are consistently contained within a $R_{u(W)/t/T}$±20% databand.

Pre-assessment should include:

(i) confirmation that the data meet the material/process pedigree and testing information requirements recommended in ECCC Volume 3 Part II [5b].

(ii) confirmation that the material/process pedigree of all weldments and/or heats of simulated HAZ meet the specification set by the instigator(s) of the assessment.

It may be permissible to use data for welds in which the weld metal pedigree and welding process are not exactly as specified when fracture is in the inter-critical HAZ (e.g. in ferritic weldments). However, such data must fall within ±20% of $R_{u(W)/t/T}$.

Similarly, it may be permissible to use data for welds in which the parent material pedigree is not exactly as specified when fracture is in the main weld at a significant distance from the fusion line (e.g. certain austenitic weldments). As above such data must fall within ±20% of $R_{u(w)/t/T}$.

When the fracture location is close to the fusion line (e.g. for DMWs), there is rarely scope for considering data for which the material and process pedigree are not exactly as specified.

When data is used for welds which do not specifically meet all material/process pedigree requirements, the evidence for data acceptability should be clearly stated.

(iii) an evaluation of the distribution of broken and unbroken testpiece data points with respect to temperature and time (e.g. eg. Tables A1.2a-5a in Volume 5 Part 1a); identifying $t_{u(W),max}$, $\sigma_{o,min}$, and the temperatures for which there are (a) ≥5% broken specimen test data ($T_{[5\%]}$) and (b) ≥10% broken specimen test data ($T_{[10\%]}$).

If the assessment is performed only on data for which the fracture location is in the target microstructural constituent, a data distribution table should be prepared specifically for the assessed observations. The table heading should clearly state whether it covers (a) all data or (b) data for a specific fracture location.

[4] Note the significant difference between this requirement and that for full-size datasets in Part I [4a].

It is acceptable to consider data for temperatures within ±3°C of principal test temperatures to be part of the dataset for that principal test temperature (e.g. test data for 566°C may be considered together with data for 565°C).

(iv) an analysis of the distribution of welds at each temperature, specifically identifying (a) the main weld, i.e. the weld having the most data points at the most temperatures, and (b) the best-tested welds.

(v) a visual comparison, in isothermal log σ_o versus log t_u diagrams, of all broken and unbroken data points for all relevant available parent material, weld metal, cross-weld and simulated-microstructures. Each cross-weld data point should be identified with respect to fracture location.

(vi) a re-organisation of the data if the results of the first assessment identify the need.

The reason(s) for excluding any individual data points which are acceptable in terms of *(i)* and *(ii)* above, should be fully documented. In practice, it should not usually be necessary to remove data meeting the requirements of [5b], providing the material specification is realistic.

2.6 POST ASSESSMENT

It is unlikely that the results from the main assessment of a weldment dataset will meet all the requirements of the post assessment tests defined for full-size datasets. [5] Of the three main categories listed in Part I, only tests associated with PAT-1 and PAT-2 are applied, i.e. those covering:

- the physical realism of the predicted isothermal lines, and
- the effectiveness of the model prediction within the range of the input data

These are investigated in the following post assessment tests.[6]

Physical Realism of Predicted Isothermal Lines

PAT-1.1a Visually check the credibility of the fit of the isothermal logσ_o versus log t_u* lines to the individual $t_u(T,\sigma_o)$ data points over the range of the data

PAT-1.1b Visually check the credibility of the shape and the relationship of the isothermal log σ_o versus log t_u* data lines with respect to available relevant reference lines, ideally established according to the requirements of Part I.

Predicted $R_{u(W)/t/T}$ values should never exceed $R_{u/t/T}$ values for the specific parent material or the alloy mean $R_{u/t/T}$+20%.

It is unlikely that $R_{u(W)/t/T}$ will fall below x0.4 the alloy mean.

PAT-1.2 Produce isothermal curves of log σ_o versus log t_u* at 25°C intervals from 25°C below the minimum temperature to 25°C above the maximum application temperature.[7]

For times between 10 and 10.$t_{u,max}$ and stresses ≥0.8.$\sigma_{o,min}$, predicted isothermal lines must not (a) cross-over, (b) come-together or (c) turn-back.

---

[5] The underlying background to the development of the original post assessment tests for parent material CRDA

[6] The post assessment tests may be conveniently performed in a spreadsheet such as MS-Excel or the E-PAT tool

[7] The maximum application temperature for which predicted strength values are required

PAT-1.3 Plot the derivative $\partial(\log t_u^*)/\partial(\log \sigma_o)$ as a function of log σ_o with respect to temperature to show whether the predicted isothermal lines fall away too quickly at low stresses (i.e. $\sigma_o \geq 0.8.\sigma_{o,min}$) (e.g. …..

The values of $-\partial(\log t_u^*)/\partial(\log \sigma_o)$, i.e. n_r in $t_u^* \propto (\sigma_o)^{nr}$, should not be $\leq$1.5.

It is permissible for n_r to enter the range 1.0-1.5 if the assessor can demonstrate that this trend is due to the material exhibiting either sigmoidal behaviour or a creep mechanism for which n_r =1., e.g. diffusional flow.

Effectiveness of Model Prediction within Range of Input Data

PAT-2.1 To assess the effectiveness of the assessed model to represent the behaviour of the complete dataset, plot log t_u versus log t_u^* for all input data (e.g. Fig

The log t_u versus log t_u^* diagram should show
- the log t_u = log t_u^* line (i.e. the line representing an ideal fit),
- the log t_u = log t_u^* ± 2.5.$s_{[A\text{-}RLT]}$ boundary lines,[8,9]
- the log t_u = log t_u^* ± log 2 boundary lines,[10] and
- the linear mean line fit through the log t_u versus log t_u^* data points for 100< t_u^* < 3.$t_{u,max}$.

The model equation should be re-assessed:
(a) if more than 1.5% of the log t_u^*,log t_u (x,y) data points fall outside one of the ±2.5.$s_{[A\text{-}RLT]}$ boundary lines,[11]
(b) if the slope of the mean line is <0.78 or >1.22, and
(c) if the mean line is not contained within the ±log 2 boundary lines for 100< log t_u^* <100kh.

PAT-2.2 To assess the effectiveness of the model to represent the behaviour of individual weldments, plot at temperatures for which there are ≥10% data points (at least at $T_{min[10\%]}$, T_{main} and $T_{max[10\%]}$):
(i) log σ_o versus log t_u^* with individual $t_u(T,\sigma_o)$ data points
(ii) log t_u versus log t_u^*, with
- the log t_u = log t_u^* line (i.e. the line representing an ideal fit),
- the log t_u = log t_u^* ± 2.5.$s_{[I\text{-}RLT]}$ boundary lines,
- the log t_u = log t_u^* ± log 2 boundary lines, and
- the linear mean line fit through the log t_u^*,log t_u (x,y) data points for 100 < t_u^* < 3.$t_{u,max}$ (extrapolated to 100kh).

---

[8] $s_{[A\text{-}RLT]}$ is the standard deviation of the residual log times for all the data at all temperatures, i.e. $s_{[A\text{-}RLT]} = \sqrt{\{\sum_i(\log t_{u,i} - \log t_u^*)^2/(n_A - 1)\}}$, where i = 1,2, …. n_A, and n_A is the total number of data points

[9] For a log normal error distribution, 98.75% of the data points would be expected to be within the log t_u = log t_u^* ±2.5.$s_{[A\text{-}RLT]}$ boundary lines.

[10] i.e. the t_u = 2.t_u^* and t_u = 0.5.t_u^* boundary lines

[11] Experience has shown that the ±2.5.$s_{[A\text{-}RLT]}$ boundary lines typically intersect the t_u = 100h grid line at t_u^*≤1kh and t_u^*≥10h respectively [4a]. The explanation for those which do not is either an imbalance in the model fit (and hence the PAT-2.1a criterion) or excessive variability in the data set. In the latter case, consideration should be given to the scope of the material specification (in conjunction with the assessment instigator, e.g. WG3.x)

and identify the individual weldments.

(a) Log t_u versus log t_u^* plots for individual weldments should have slopes close to unity and be contained within the $\pm 2.5.s_{[I\text{-}RLT]}$ boundary lines.[12] The pedigree of weldments with $-\partial(\log t_u)/\partial(\log t_u^*)$ slopes of <0.5 or >1.5 and/or which have a significant number of log t_u*,log t_u (x,y) data points outside the $\pm 2.5.s_{[I\text{-}RLT]}$ boundary lines should be re-investigated.

If the material and testing pedigrees of the data satisfy the requirements of [5b] and the specification set by the assessment instigator (e.g. WG3.x), the assessor should first consider with the instigator whether the scope of the weldment specification is too wide. If there is no metallurgical justification for modifying the specification, the effectiveness of the model to predict individual weldment behaviour should be questioned.

The distribution of the log t_u*,log t_u (x,y) data points about the log t_u = log t_u* line reflects the homogeneity of the dataset and the effectiveness of the predictive capability of the model. Non uniform distributions at key temperatures should be taken as a strong indication that the model does not effectively represent the specified material within the range of the data, in particular at longer times.

The model equation should be re-assessed if at any temperature:

(b) the slope of the mean line through the isothermal log t_u*,log t_u (x,y) data points is <0.78 or >1.22, and

(c) the mean line is not contained within the ±log 2 boundary lines for 100 < log t_u^* <100kh

Repeatability and Stability of Extrapolations

PAT-3 is not regarded as a viable post assessment test for weld creep data, in particular for observations associated with a change in fracture mechanism. For such circumstances, guidance is given in recommendation 7 (Sect.2.4).

3. SUMMARY

ECCC Volume 5 Part IIb provides guidance for the assessment of weld-creep datasets. The recommendations are specifically aimed at assessments leading to strength values to be externally published by ECCC, but may be used for other purposes. The principal objective is to minimise the uncertainty associated with strength predictions by recommending a rigorous pre-assessment, the implementation of post assessment acceptability criteria and the performance of duplicate assessments.

4. REFERENCES

1 Stubbe, J. & van Melsen, C., 1977, 'Practical applications of a short-term creep test method for evaluation of the restlife', *Proc. NIL-Int. Symp. Predictions of Residual Lifetime of Constructions Operating at High Temperature*, The Hague, 95-140.

2 Etienne, C.F. & Heerings, J.H., 1993, ‘Evaluation of the influence of welding on creep resistance’, *IIW doc IX-1725-93*, TNO Metal Research Institute, 12/93.

3 ECCC Recommendations Volume 2, 2001, 'Terms and terminology for use with stress rupture, creep rupture, creep and stress relaxation: Testing, data collation and

[12] $s_{[I\text{-}RLT]}$ is the standard deviation for the n_I residual log times at the temperature of interest, i.e. $s_{[I\text{-}RLT]} = \sqrt{\{\sum_j(\log t_{u,j} - \log t_u^*)^2/(n_I - 1)\}}$, where j = 1,2, …. n_I.

assessment', ed. Morris, P.F, Orr, J., Servetto, C. & Seliger, P., publ. *ERA Technology Ltd, Leatherhead*, (a) Part I 'General terms and terminology and items specific to parent material', (b) Part IIa 'Terms and terminology for welding processes and weld configurations', (c) Part IIb 'Terms and terminology for weld creep testing', (d) Part III 'Terms and terminology for post service exposed creep data'.

4 ECCC Recommendations Volume 5, 2014, 'Guidance for the assessment of creep rupture, creep strain and stress relaxation data', ed. Spindler, M. W., *publ*. *European Creep Collaborative Committee.*

5 ECCC Recommendations Volume 3, 2001, 'Recommendations for data acceptability criteria and the generation of creep, creep rupture, stress rupture and stress relaxation data', ed. Holdsworth, S.R., Granacher, J., Theofel, H., Klenk, A., Buchmayr, B. & Gariboldi, E. *publ. ERA Technology Ltd, Leatherhead*, (a) Part I 'Data acceptability criteria and data generation: Generic recommendations for creep, creep rupture, stress rupture and stress relaxation data', (b) Part II 'Data acceptability criteria and data generation: Creep data for welds', (c) Part III 'Recommendations for creep testing of PE (ex-service) materials'.

6 Buchmayr, B. et al, 1990, 'Experimental and numerical investigations of the creep behaviour of the dissimilar weldment GS-17CrMoV5.11 and X20CrMoV12.1', *Steel Research*, No. 6/90, 268-275.

7 PD6525, 1992, 'Elevated temperature properties for steels for pressure purposes', *British Standards Institution*.

8 ECCC Data Sheets, 2005, Ed. Robertson, D.G. & Holdsworth S. R., *Publ. ETD Ltd, Ashtead, Surrey, UK.*

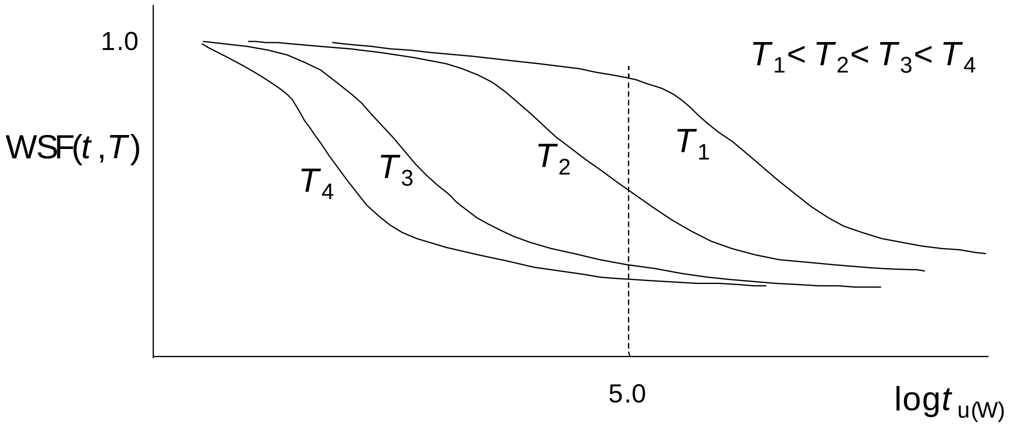


Fig. 1 Schematic representation of weldment property characteristics of ferritic steels

ANNEX A

REVIEW OF WELD-CREEP ASSESSMENT PROCEDURES

P Auerkari

VTT, Finland

1 Introduction

Major high temperature installations make extensive use of weldments for joining components to full-scale functional structures, where the operating medium is contained separate from the outside environment. In addition, welds are necessary and widely used for repairs of defects or other deficiencies that can originate from manufacturing or service.

Unfortunately, particularly in ferritic steels that are common structural materials in high temperature plant, weldments are often the potentially weakest links against creep. This is because of the metallurgical structures produced by common welding processes, especially in the heat affected zone (HAZ) of the weldment. In addition, welding is a common cause of defects that exacerbate this weakness, and often it is not easy to find remedies to alleviate these weak areas.

Although weldments therefore tend to be the weak spots in e.g. pressure equipment operating at high temperatures, their design does not account for the weakness of weldments directly. Instead, design is nominally based on the properties of the parent material and welds are accounted for by e.g. placing them in locations of low stresses. This nevertheless requires a feeling of the actual difference in the design strength between the weldment and the parent material, and for this purpose e.g. so-called stress reduction factors have been used. This stress reduction factor (SRF) is defined as

$$\text{SRF} = \text{creep strength of the weldment / creep strength of the parent material} \qquad (1)$$

whereby creep strength must be defined for the same conditions (e.g. to creep failure in 10^5 h at 550°C in air for a uniaxial standard specimen).

However, it is known that there is also a difference between results from different specimen sizes.

ECCC (European Creep Collaborative Committee) has launched a project to evaluate the methods on assessing weldments for service in the creep regime. As a part of this effort, the current expert opinions and practices worldwide are reviewed on assessment of creep testing results of weldments.

For this purpose, ECCC has circulated a questionnaire (see appendix) in 1998 to explore the views and practices of professional experts involved in assessment of weldments for high temperature service. The resulting individual answers to the questionnaire are held confidential, and used only to evaluate the overall views of the experts. These overall views in turn are used to formulate widely accepted, technically well founded European ECCC guidelines on assessing creep testing results of weldments.

Below, the issue of assessment is treated in the order of the questions in the questionnaire (see appendix). By February 8, 1999, a total of 13 answers was obtained for an inquiry that was sent to more than 50 experts.

2 Assessment of creep testing results

2.1 The questionnaire

The questionnaire is shown in the appendix. This questionnaire has been circulated among the known experts by the secretariat of EC3. In total 13 experts have returned answers, and these are summarised anonymously below.

2.2 Detailed comments on the questionnaire

The actual answers are shown in Tables 1 to 12.

Table 1. The expert answers to question 1.1 regarding importance of creep data assessment for weldments.

Expert No.	Vitally important	Important	Not very important
1	X		
2	X		
3	X		
4	X		
5	X		
6		X	
7	X		
8		X	
9		X	
10			X
11	X		
12	X		
13		X	

Summary to Q1.1: Vitally important 8/13, important 4/13, not very important 1/13.

This result may not be very surprising, as many of the experts represent members of EC3 and the Weld Creep project, and hence have natural interest in the issue of creep data assessment for weldments.

Table 2. The expert answers to question 1.2a regarding frequency of creep data assessment for weldments.

Expert No.	Daily	Few times a week	Few times a month	Few times a year	Less often or never
1			X		
2			X		
3				X	
4				X	
5				X	
6					X
7			X		
8			X		
9				X	
10					X
11		X			
12			X		
13				X	

Summary to Q1.2a:

Few times a week 1/13; few times a month 5/13; few times a year 5/13; less often/never 2/13.

Table 3. The expert answers to question 1.2b regarding quantity of creep data assessment for weldments.

Expert No.	None	1-10 welds a year	11-100 welds a year	More than 100 welds a year
1		X		
2		X [1)]		
3			X	
4		X		
5			X	
6		X		
7		X		
8			X	
9		X		
10	X			
11			X	
12		X		
13		X		

1) = procedures

Summary to Q1.2b: None 1/13; 1-10 / year 8/13; 11-100 / year 4/13

Table 4. The expert answers to question 1.3 regarding the purpose of assessment.

Expert No.	Design assessment	Qualification of mat's/manufact.	Ex-service life assessment	Other
1		X	X	
2		X	X	X[1)]
3	X	X	X	
4				X[2)]
5			X	
6	X	X		
7	X	X		
8	X		X	
9	X	X		
10				
11		X	X	X[3)]
12			X	X[4)]
13	X	X		

1) comparison uniaxial/multiaxial & repair welding
2) provision of creep rupture data for life assessment of welds in service using R5
3) development of new procedures/processes
4) creep modelling for life assessment

Summary to Q1.3: Design 6/12; qualification 8/12; life assessment 7/12; other 4/12

Table 5. The expert answers to question 1.4 on written guideline/qualification procedure for assessing the creep testing results of weldments.

Expert No.	No	Yes Description
1	X	
2		X: partly Stoomwesen rules but these are insufficient
3		X: CEGB doc. OED/STB(s)/87/0022/R, adapted for cross-welds [1)]
4		X: PD6605 & EC3 guidelines; see also [2)]
5	X	
6	X	
7		X: confidential
8		X: internal procedure
9	X	
10	X	
11	X	
12		X: EC3 guidelines
13	X	

1) also R5 type assessments are sometimes used
2) Hales, Osgerby & Dyson, 1997: Proc. 7^{th} Int Conf Creep and Fracture of Eng Mater and Structures, Univ. of California, p. 749-758

Summary to Q1.4: No 7/13; Yes 6/13

Table 6. The expert answers to question 2.1 regarding preassessment criteria.

Expert No.	None	ECCC criteria	PD 6605 criteria	Case-specific or more general
1				X 1)
2		X		X 2)
3				X 3)
4		X	X	
5				X 4)
6		X		
7		X		
8		X		
9				X
10	X			
11				X 5)
12		X		
13				X 6)

1) using creep properties of parent metal and French standard NF A89-010
2) code values and extrapolated values within the scatterband of the code
3) testing by external testing houses, BS standard criteria apply; results must also reflect the likely in-service failure mode
4) data is often sparse and criteria have to be relaxed
5) validation in terms of parent/weld properties and composition, appropriate weld procedure, metallography to exclude anomalous results due to defects etc.
6) criteria of German "Arbeitsgemeinschaft Warmfeste Stähle", similar to ECCC criteria

Summary to Q2.1: None 1/13; ECCC 6/13; PD 6605 1/13; other 7/13

Table 7. The answers to question 3.1 on assessing the results from creep tests on weldments.

Expert No.	Procedure description
1	Cross-weld and weld metal specimens
2	Cross-weld, isostress and/or component tests; also BM, sim. HAZ and WM
3	No fixed method, usually to compare weld procedures, heat treatments etc.
4	PD6605, cross-weld and weld metal specimens
5	Normally sampling of cross-welds to ensure all potential failure sites
6	Parametric fitting to determine optimum model representation and/or ISO type approach, depending on size of dataset. Data from cross-welds or from weld pads, weldments prepared in line with procedure of interest. Do not assess simulated structures.
7	Comparison with parent and relationship to standard; influence of test duration
8	-
9	Cross-weld
10	-
11	Cross-weld to identify failure mechanisms, other and biaxial for details
12	BM and WM for CDM model, combined for XW, multiaxial verification
13	Comparison of cross-weld and corresponding parent material results

Summary to Q3.1: No answer 2/13; some description 11/13

Table 8. The answers to question 4.1 on acceptability criteria on testing results when using the results for interpolation/extrapolation of data.

Expert No.	**Acceptability criteria**
1	Same as for parent metal
2	On average 5 specimens, 100 – 4000 h, fracture location & supporting info
3	Increasing caution with increasing range of extrapolation
4	ECCC and PD6605
5	Usually PD 6605
6	ECCC PATs 1 and 2; PAT3 impractical for small datasets
7	Extrapolation factor ≤ 3 in time, sufficient no of specimens, scatter
8	Data within a scatterband of ± 20% (in stress) of published data
9	Extrapolation, at least 30 kh of testing time
10	-
11	Anomalous results investigated by metallography
12	Often consider one cast at one temp; ECCC PATs apply only selectively
13	Compare to parent (with scatterband of steel) to obtain stress reduction factors

Summary to Q4.1: No answer 1/13; description 12/13

Table 9. The expert answers to question 4.2 on supporting metallography.

Expert No.	**No**	**Yes Description/reference**
1		X
2		X: location of fracture and damage, possible defects
3		X: all failures to ensure that failure mechanism is relevant
4		X: methods are different for ferritic, austenitic and DMWs [1)]
5	X	
6		X: at least to define fracture path / location in weldment
7		X: fracture location
8		X: to distinguish weld, fusion line and HAZ
9		X: location of fracture
10	X	
11		X: to examine anomalous results such as early failures, weld defects
12		X: failure location, creep damage characteristics
13		X: rupture location

1) for ferritic type IV failures: Coleman & Miller, 1994. Maintenance and Repair Welding in Power Plant, AWS-EPRI Conf Nov 30-Dec 2, Orlando Florida; for austenitic welds: Senior, 1990. Cavitational damage in AISI type 347 type weld metal arising from creep deformation. Mater. Sci and Eng A130, pp 51-58.

Summary to Q4.2: No 2/13; Yes 11/13

Table 10. The expert answers to question 4.3 on supporting FE analysis or comparable.

Expert No.	No	Yes Description/reference
1	X	
2		X: sometimes together with component testing
3		X: mostly independently of testing, sometimes to support experiments
4		X
5	X	
6	X	
7	X	
8	X	
9		X: only in single cases
10	X	
11		X: only in specific programs where creep strain is addressed
12		X: for component test modelling
13	X	

Summary to Q4.3: No 7/13; Yes 6/13 (many for limited applications)

Table 11. The expert answers to question 4.4 on other supporting methods.

Expert No.	None	Yes Description/reference
1		X: bending tests
2		X: component tests especially for repairs
3		X: cavitation levels sometimes used; internal procedures apply
4		X: see ref in 1.4
5	X	
6	X	
7	X	
8	X	
9	X	
10	X	
11		X: ductility levels are investigated
12		X: Component testing
13	X	

Summary to Q4.4: None 7/13; Yes 6/13

Table 11. The expert answers to question 5 on other supporting guidelines

Expert No.	None	Yes Description/reference
1	X	
2		X: CSR tests
3	X	
4	X	
5		X: R5 vol 6 & 7
6	X	
7	X	
8	X	
9	X	
10	X	
11		X: with sufficient data many statistical methods
12	X	
13	X	

Summary to Q4.4: None 10/13; Yes 3/13

Table 12. The expert answers to Section III question on additional comments

Expert No.	None	Yes Description/reference
1	X	
2		X: avoid too high stress, more info needed of austenitic & DMW
3		X: questions related to inter-outage periods rather than design life
4		X: XW simplistic
5	X	
6	X	
7	X	
8	X	
9	X	
10	X	
11		X: size effects!
12		X: small data sets important
13		X: stress reduction factors should be used

Summary to Q4.4: None 10/13; Yes 3/13

APPENDIX: QUESTIONNAIRE ON ECCC WELDMENT ASSESSMENT

EXPERT QUESTIONNAIRE

I. Introduction

ECCC (European Creep Collaborative Committee), the European body to prepare guidelines and materials assessment for service in the creep regime for e.g. European standardisation, has launched an effort to evaluate the methods on weldments in this area. As one part of the effort, the current expert opinions and practices worldwide are reviewed on assessment of creep testing results of weldments.

For this purpose, ECCC asks for your expert help. Please answer the following questions, and add any comments you may have. All individual answers are held confidential and treated in such a way that no individual recipient of the questionnaire can be later identified. The results of the questionnaire (but not individual answers or names of recipients) are used to formulate the European ECCC guidelines on assessing creep testing results of weldments. The review will become public, and will be published also in the Information Days of ECCC. Your effort is much appreciated, as the results aim to provide widely accepted, technically well founded guidelines for assessment of the creep testing results of weldments.

II. Questionnaire

1. Background information

1.1 How important for you is the correct assessment of creep testing data of weldments?

[ ] vitally important [ ] important [ ] not very important

1.2 How extensively do you need to assess experimental creep data of weldments?
frequency:
[ ] daily [ ] few times a week [ ] few times a month [ ] few times a year [ ] less often / never
quantity per year:
[..] none [ ] 1 to10 welds a year [ ] 11-100 welds a year [ ] more than 100 welds a year

1.3 What is the purpose of the assessment in your case? (multiple choices are possible)

[ ] Design Assessment
[ ] assessment/qualification of materials or manufacturing procedures
[ ] life assessment of ex-service welds
[ ] other (please specify)
....

1.4 Do you have a written guideline or qualification procedure for assessing the creep testing results of weldments?

[ ] no [ ] yes (please provide description/reference if possible) ....

....
....

....
....

2. Pre-assessment criteria of creep testing results from weldments

Pre-assessment criteria include typically those for e.g. confirmation of the material and testing specifications and grouping of the test results for initial testing of the data quality.

2.1 What pre-assessment criteria do you require for the creep testing results of weldments?

[ ] none [ ] ECCC criteria [ ] PD 6605 [ ] case-specific or more general criteria (please specify)

....
....

....
....

3. The main assessment methods and criteria

3.1 How do you normally assess the results from creep tests of weldments (e.g. cross-weld specimens, weld metal specimens, other)? Please specify / provide a reference.

....
....

....
....

4. Post-assessment: criteria and analysis of weld creep testing data, and supporting methods

Post-assessment refers here to acceptability for predicting creep behaviour of the data, such as extrapolation and interpolation, and the quality of predictions e.g. in terms of physical realism and repeatability.

4.1 When you predict creep behaviour beyond the data, by extrapolation or interpolation, which acceptability criteria you would use for the results ?

....

....

4.2 Do you use metallographic assessment to support the assessment of weld creep testing results?

[ ] no [ ] yes (please specify and provide reference if possible) ....

....

....

4.3 Do you use finite element (FE) calculations or comparable methods to support the assessment?

[ ] no [ ] yes (please describe briefly and provide reference if possible)

....

....

4.4 Which other methods or techniques do you use for the assessment of weld creep testing results? Please specify and provide reference if possible.

....

....

5. Other supporting guidelines

5.1 Do you know of alternative methods or approaches for assessment of creep testing results from weldments? Please provide a reference.

....
....

....
....

III. Additional expert comments and recommendations

Please provide here any additional comments, recommendations or other information you may have on the subject of assessment of creep tests for weldments:

....
....

....
....

....
....

THANK YOU !

Please return this questionnaire to:

Pertti Auerkari
VTT Manufacturing Technology
PO Box 1704, FI-02044 VTT, Finland
fax +358-9-456 7002

If you have any questions or other comments, please do not hesitate to send them to the above address, or via e-mail to Pertti.Auerkari@vtt.fi, or or by phone +358-9-456 6850.

Your contact information: **Date:**

Name:

Company/affiliation:

Address:

Tel: **Fax:** **E-mail:**

ANNEX B

REVIEW OF WG1 WELD-CREEP DATA ASSESSMENT EXPERIENCE

S R Holdsworth, A Klenk

1 Introduction

Welded joints are important constituents of plant components. Especially in the case of the design of high temperature components welds are often the critical locations since they exhibit lower strength due to metallurgical changes occurring during and after the welding process. Up to now a time and temperature independent weld strength reduction factor for the long term rupture strength of 0.8 has been assumed according to regulations or standards. Recent investigations as for example in /MAI84,MAI04/ and the compilations in /ETI94,SCHU05/ demonstrate that this factor is dependent on material, temperature and time and can be either higher or lower than 0.8. It is therefore important to know the long term characteristics of specific welded materials. It is necessary to reliably measure and analyse them. In particular the determination of welded joint factors is necessary for fully loaded welds in components designed against creep strength.

Guidelines and recommendations for creep data assessment have been compiled based on extensive assessment work on parent material data sets done by ECCC-Working Group 1 [ERV05]. This was followed by special considerations of small data sets. The procedures developed especially Post Assessment Tests have been applied to various data sets and proved to be highly effective as part of assessment procedures for parent material data sets.

The design of many components operating in the creep region must account for the presence of welded joints. In most ferritic and ferritic-martensitic welds and often in dissimilar welds the joint is the limiting element with respect to creep rupture behaviour since the creep performance of heat affected zones is worse than parent or weld metal. Creep tests using crossweld specimens as described in [ERV3] have been performed to obtain information on the long term behaviour of welded joints. In principle the data obtained with these test may be assessed in the same manner as parent or weld metal data. In doing this it is likely that problems are encountered mainly due to the following reasons

- crossweld data sets are usually small
- variations in weld process details (including post weld heat treatment procedure, weld / parent metal combination etc)
- variations in fracture location in the same welded joint as a function of testing time and temperature.

The latter one is related to welds in ferritic and ferritic-martensitic materials where the base material is most affected forming different zones which can be characterized by their microstructure, e.g. Figure 1. Special consideration of the weakest zone (i.e. the intercritical zone) is needed.

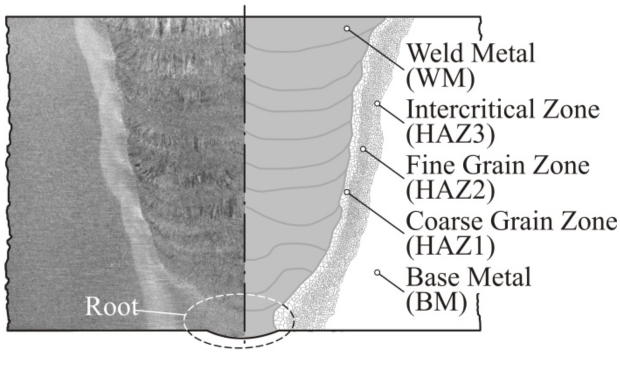


Figure 1: Heat affected zone in ferritic or ferritic-martensitic materials

In view of this background, it is necessary to have reliable testing techniques in order to get reproducible results. To support this aim, recommendations /ERV03/ on specimens and testing techniques have been established, including guidance on heat affected zone simulation which is an important tool for determination of the reliable long term properties of welds. Assessments of data obtained using these methods have been investigated within ECCC Working Group 1. In this document beside a short description of techniques for experimental determination of creep rupture properties of welded joints and heat affected zone simulation the main focus lies on the description of the intercomparisons of the assessments.

2 Experimental determination of creep rupture properties of welded joints

The creep-rupture properties of weldments are usually determined by performing tests on specimens which have been sectioned either from actual welds or from material with the thermally simulated heat affected zone microstructure of interest. It is strongly recommended that tests on cross-weld and/or thermally simulated specimens are accompanied by tests on the parent material(s) from which the welded joint of interested has (have) been manufactured.

2.1 Stress rupture testing with cross-weld specimens

The most effective way of determining weldment stress-rupture properties is to test specimens which have been extracted directly from actual welded joints. In this way, material is tested which has been produced as a consequence of the specific welding parameters of interest.

The parallel length of the testpiece, lc, should exceed 5.do and do ≥8mm is recommended to ensure that crossweld deformation behaviour is representative of the welded joint. If this minimum diameter requirement cannot be met due to limited material availability, the consequent ratio of fine grain HAZ width to diameter ratio may cause different stress enhancement or stress redistribution and hence influence the rupture time

Depending on the respective dimensions of the weld and the testpiece, the parallel length of cross weld rupture specimens will sample the full width of weld metal in the joint, both heat affected zones and sections of parent material associated with each HAZ. It is recommended that each length of parent material occupies at least 2.5.do of the testpiece gauge section to ensure that rupture occurs in the parent material if this is the weakest component of the welded joint in creep. Often this means that the parallel length has to comprise sections of parent material, weld metal and only one heat affected zone.

Typically the testpiece is cut from the weld with its axis perpendicular to the centre line of the weld. Alternatively, and only for specimens sampling one heat affected zone, the axis of the testpiece is taken perpendicular to the fusion boundary.

These recommendation are intended to ensure reliable and comparable test results. However, it should be noted, that contrary to specimens sampled from homogeneous material, the stress and strain distribution is influenced by the inhomogeneous material properties of weld metal, heat affected zone and parent metal. Therefore the measurement of elongation of a measuring length is recommended to control the test properly, but it is not a test result which can be compared or evaluated. The inhomogeneous strain distribution is illustrated in Figure 2 which shows a comparison of the effective strain distribution in a cross-weld specimen after 3,000 h at 130 Mpa and 10,000 h at 100 MPa. From this picture the reason of the change in fracture location becomes obvious. At 3000 h there is a concurrent strain development in heat affected zone and adjacent base material, in the later stage at 10,000 h the strain concentrates in the intercritical zone provoking Type 4 cracking due to stress and strain redistributions. The figure shows the strongly inhomegenous stress and strain distribution in the specimen, changing during the test. Finite element simulation taking into account different material properties of heat affected zones using an axisymmetric geometrical model (specimen center on the left side, outside surface on the right) was used to obtain these results /BAU01/.

The inhomogeneous stress and strain distribution results also in differences in creep rupture strength, Figure 3. A minimum diameter of at least 8 mm is therefore recommended.

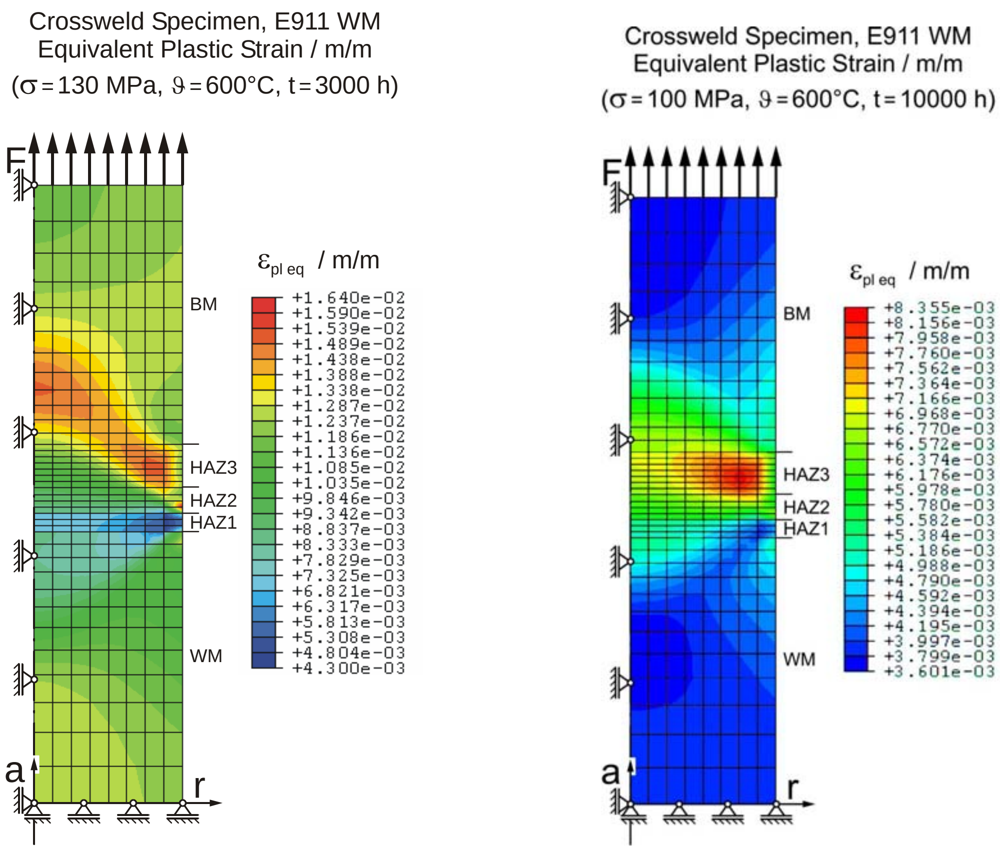


Figure 2: Effective strain distribution in a crossweld specimen after 3000 h and 10.000 h

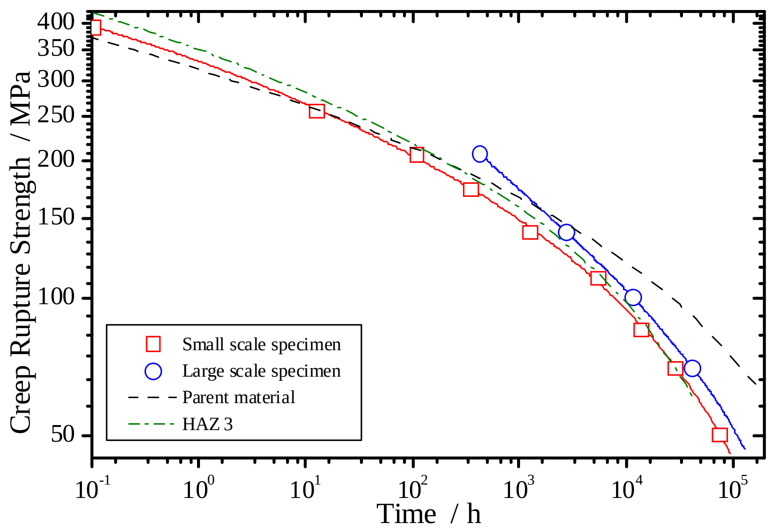


Figure 3.: Creep rupture strength of small scale and large scale specimens taken from one melt /MAI85, BUC90/

2.2 Simulation of heat affected zones

In addition to crossweld testing, creep testing of weld simulated structures is performed in order to characterise the creep behaviour in the distinct sub-regions of the heat affected zone. Thereby, the weld thermal cycle in various sub-zones of a weldment is applied in a heat simulation process and thus can be transferred to a specimen, so that the testing volume is significantly enlarged. This practice reduces the influence of surrounding zones and therefore the scatter. Furthermore results on heat affected zone behaviour may be obtained at shorter times which will enhance the evaluation procedure, see section 3. The mechanical properties including also the creep properties of a weldment depend on many influencing parameters mainly related to the specific parameter of the welding process and the geometry of the weld. The basic idea of HAZ simulation is to take into account the most important parameters, whereas disturbing parameters are eliminated as far as possible. There is a direct correlation between the mechanical properties and the HAZ microstructure, which depends on the cooling rate and the material dependent transformation kinetics, which in turn are influenced by the austenite grain size /ERV2/. The austenite grain size is determined by the peak temperature or by the distance from the fusion line, respectively. The weld thermal cycle is simply characterised by the cooling time $t_{8/5}$ between 800 and 500°C and the peak temperature. The cooling time $t_{8/5}$ depends on the plate thickness, the welding process (thermal efficiency), the joint type, the welding parameters (current, voltage, travel speed, or heat input) and the preheating temperature. There are many means to calculate the weld thermal cycle, as summarised in Figure 4.

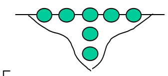
1. **Analytical Solution (Rosenthal, Rykalin)** $T - T_o = \frac{E / v}{2 \cdot \pi \cdot \lambda \cdot \rho \cdot t} \cdot \exp(-r / 4at)$
2. **Analytical Solution for modified heat sources** 
3. **Cooling time concept t8/5 (SEW088)** $t_{8/5} = \frac{\eta \cdot E}{2 \cdot \pi \cdot \lambda} \cdot \left[\frac{1}{500 - T_o} - \frac{1}{800 - T_o} \right] \cdot F_3$
4. **Finite difference method** $T_{i+1,\,j} = f\,(T_{i,\,j-1}, T_{i,\,j}, T_{i,\,j+1})$
5. **Finite element method (2D, 3D)** $[C] \cdot \{\dot{T}\} + [K] \cdot \{T\} = \{\dot{Q}\}$

Figure 4: Approaches mainly used for the calculation of the weld thermal cycle /ERV3/

The most-widely used procedure to predict the weld thermal cycle is the standardised cooling time concept according to the German standard SEW088, which is based on the analytical solution derived by Rosenthal. The Rosenthal equation can also be used to determine the dimensions of the heat affected zone in a given geometry. Figure 5 shows as an example temperature courses derived by a mathematical tool /BUC92/ taking into account the most important parameters. This information about the weld thermal cycle can be used for the thermal simulation procedure. There are different methods in industrial use to apply the weld thermal cycle, like Gleeble HAZ simulation, induction heating and cooling in an oil bath and heating in a hot salt bath and cooling in a moderate tempered salt bath. Advantages and disadvantages of the methods are given in more detail in /ERV3/.

To illustrate the effect of peak temperature an investigation on 1CrMoV steel is shown in Figure 6. For various HAZ-structures, being exhibited to different peak temperatures, the rupture strength for specific times are compared with the lower BM-scatter band values for the same times to failure. Minimum creep strength was determined in peak temperature range between 850°C and 950°C. However this temperature range is dependent on Ac1-temperature.

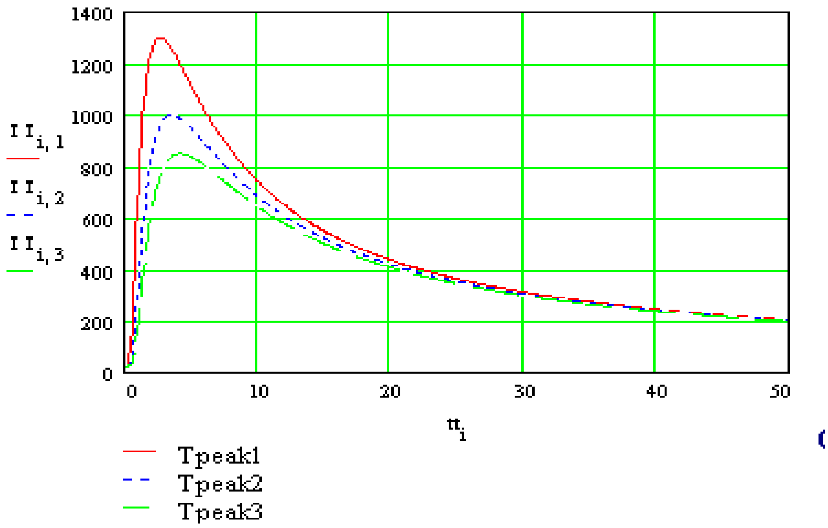


Figure 5: Algebraic calculation of the weld thermal cycle using the Mathcad tool HAZ calculator developed in /BUC99/

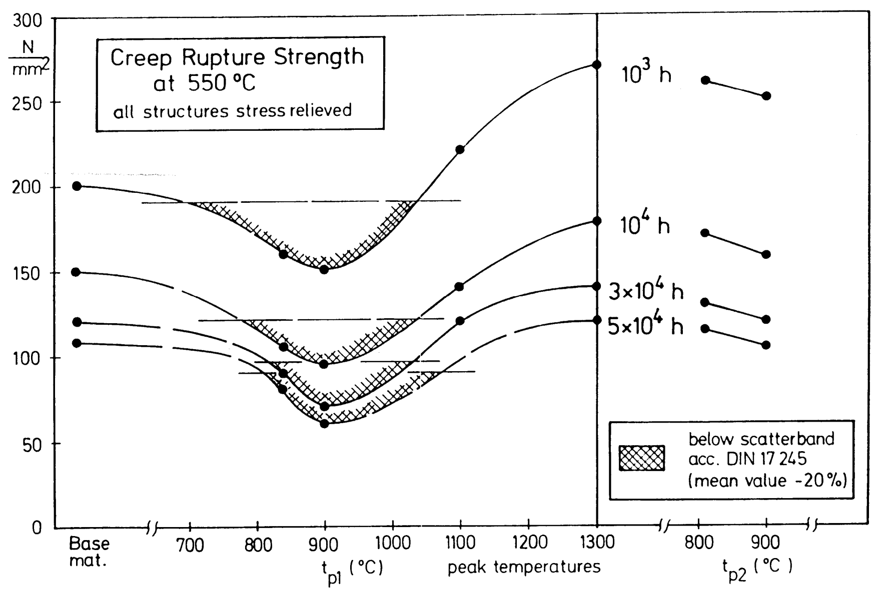


Figure 6: Influence of peak temperature on creep rupture strength of 1CrMoV steel /THE88/

3 Results and experience from Data assessments

2.1 Problems of data sets from welded joints

The main problems associated with weldment data sets relate to their size, and their potentially limited scope. For the assessment of parent materials, in particular to determine creep strength values for standards, datasets are typically large in size, containing large numbers of data points (e.g. ~1000), collected at several test temperatures in the application range, from many casts of the specified material, and with maximum test durations in excess of 100kh /SRH99/. Typically, weldment datasets are relatively small in size (e.g. <<~30 data points), collected at a small number of temperatures (~1-3) , for a small number of weldment conditions, and with maximum testing durations rarely beyond 20-30kh. Consequently, weldment datasets are generally insufficiently extensive to rigorously underpin ≥100kh fully characterised weldment type properties over the full application temperature range.

2.2 Data sets under investigation

Two datasets were evaluated by WG1 to provide guidance on weldment stress-rupture behaviour. Despite the observation above about the typically limited size of weldment datasets, working group 1 did manage to compile a large weldment dataset for the advanced 10%Cr martensitic stainless steel E911. Since the main objective of the ECCC assessment working groups is to base creep rupture strength values on the largest possible dataset, the evaluation of the large E911 weldment dataset was regarded as legitimate. A second dataset for a class of dissimilar metal welded (DMW) joint was evaluated. The dataset for DMW joints of 1Cr/12 steel was small by comparison to the E911 weldment dataset, but it was still relatively large for a weldment dataset.

2.3 E911 Weldment Dataset

The WG1 E911 weldment dataset comprised 172 cross-weld rupture data points for 11 weldments (of type GTAW, MAW, SAW and SMAW) at 12 temperatures in the range 550 to 670°C. The data had originated from a number of different European sources. Despite this size, the maximum rupture test duration was only 26kh (with 11 additional data points having test durations between 20 and 30kh in the temperature range 550 to 625°C, a number of which represented the results of unbroken tests), Table 1.

Longer term tests exhibited a reduction in time to rupture relative to equivalent parent material specimens loaded to the same stress at the same temperature. In some cases, available post test inspection results confirmed that this reduction was due to a shift in the rupture location from the parent material to the Type-IV zone. However, this evidence was not always available and this influenced the way in which the data assessments were performed by the five WG1 assessors. In certain cases, all x-weld data was assessed, and in other cases only rupture data associated with Type-IV rupture were assessed. The results of an assessment of all the cross-weld data are shown in Figure 7.

It is evident that there is a reduction in weldment strength with time, and the metallographic evidence from those longer time cross-weld testpieces which were inspected indicated that rupture in these testpieces was in the vicinity of the intercritical and fine grain HAZ. Assessments based only on the results from those testpieces for which the fracture location was known indicated a less conservative weld strength factor than that indicated by the assessment of all data, Figure 8.

Table 1: Summary statistics of E911 weldment stress rupture dataset

TEMP °C	No. of Heats	NUMBER OF TESTS WITH DURATIONS SPECIFIED <10kh B	<10kh UB	10-20kh B	10-20kh UB	20-30kh B	20-30kh UB	30-50kh B	30-50kh UB	$t_{u,max}$ h B	$s_{o,min}$ MPa B	$s_{o,max}$ MPa B	TOTALS B	TOTALS UB	TOTALS B+UB	%B of TOTAL
550	3	12		4		4				25859	175	230	20	0	20	11
575	3	6		3	1		1			15,527	150	200	9	2	11	5
600	8	39		11		2	2			22,102	100	220	52	2	54	30
625	5	23		3			2			16,087	60	140	26	2	28	15
630	2	4								1,042	120	120	4	0	4	2
640	3	5								636	120	120	5	0	5	3
645	1	1								145	100	100	1	0	1	1
650	10	42		4						13,631	45	120	46	0	46	26
655	1	1								341	100	100	1	0	1	1
660	4	5								128	100	120	5	0	5	3
665	1	1								61	100	100	1	0	1	1
670	2	2								40	100	120	2	0	2	1
680	1	1								5	100	100	1	0	1	1
690	1	1								3	100	100	1	0	1	1
TOTALS	11	143	0	25	1	6	5	0	0	25859	45	230	174	6	180	100

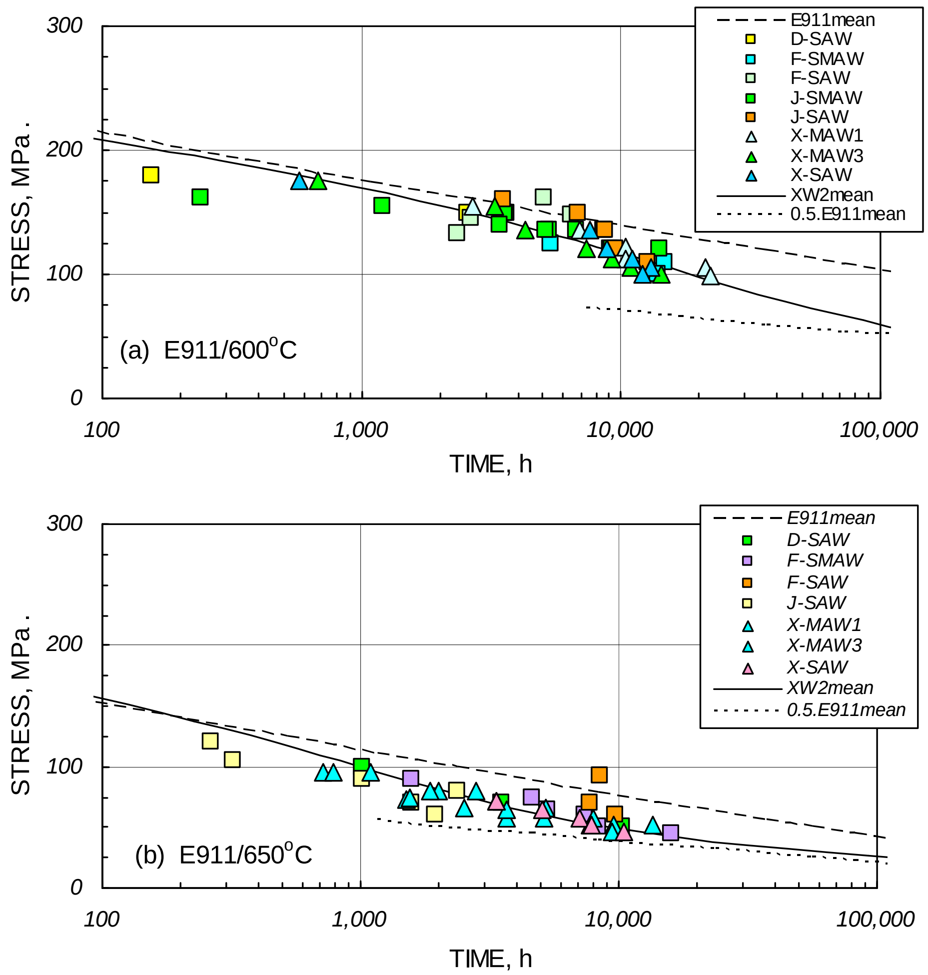


Figure 7: Creep rupture data assessment of all cross-weld data available from an E911 dataset

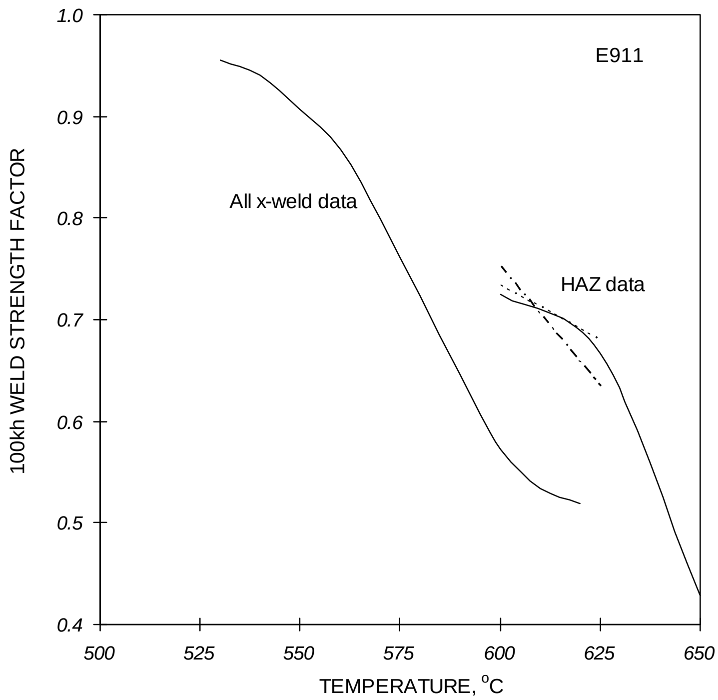


Figure 8: Comparison of 100kh weld strength factors determined from E911 cross-weld dataset, considering a) all data, and b) data with known ICHAZ fracture location

2.4 1Cr/12Cr DMW Dataset

The second evaluated dataset was smaller, was provided by MPA Stuttgart and originated from investigations on a dissimilar weld joining a 1CrMoV cast steel (G17CrMoV5-11) and a 12CrMoV steel (X20CrMoV12-1). Several weldments had been produced for /THE83,THE86/ using different welding processes and consumables (ferritic materials with different Chromium content and a Ni-based weld metal). The dataset comprised 39 cross-weld rupture data points associated with 5 weldments. The data had been collected at 2 test temperatures (500 and 550°C) and there was a significant number of test results to characterise the properties of the two specific casts of adopted 1CrMoV and 12CrMoV steels and the 5 different weld metals, Table 2. A key feature of this weldment dataset was that the rupture locations for all failed cross-weld tests were known. This dataset was assessed by 5 assessors.

With increasing time, the rupture strength exhibited by the cross-weld tests reduced. The post test inspection results indicated that this was associated with the fracture location changing from the 1CrMoV parent material (or the weld metal in the case of joint D) in short term (higher stress) tests to the intercritical heat affected zone on the 1CrMoV side of the weld in longer times.

The cross-weld results from this dataset were well characterised in terms of their associated fracture location. All assessors performed 2 assessments, a) for all the cross-weld data, and b) for the data for which it was known that fracture was in the intercritical heat affected zone. For this weldment dataset, the fits to both a) and b) were almost identical, e.g. Figure 9.

Table 2: Summary of material and test conditions for 1Cr/12Cr DMW dataset

Material	Material / Weld Mat.	Total number of tests	Number of tests at 550°C	Number of tests at 500°C
PM1	GS17CrMoV-5-11	5	5	0
PM2	12Cr	5	5	0
12 Cr WM	Weld Material for B1	4	4	0
12 Cr WM	Weld Material for B3	2	2	0
Ni-based	Weld Material for C	4	4	0
5 Cr WM	Weld Material for D	5	5	0
Joint				
B1	12Cr WM (MMA)	9	7	2
B2	12Cr WM (MAG)	7	5	2
B3	12CrWM (SAW)	10	8	2
C	Ni based WM (MMA)	7	5	2
D	5 Cr WM (MMA)	6	4	2
Data distribution	**Time**			
	0-10,000 h	27	18	9
	10,000 h – 20,000 h	4	3	1
	20,000 h – 30,000 h	2	2	
	30,000 h – 50,000 h	1	1	
	50,000 h – 70,000 h	1	1	
	70,000 h – 100,000 h	1	1	

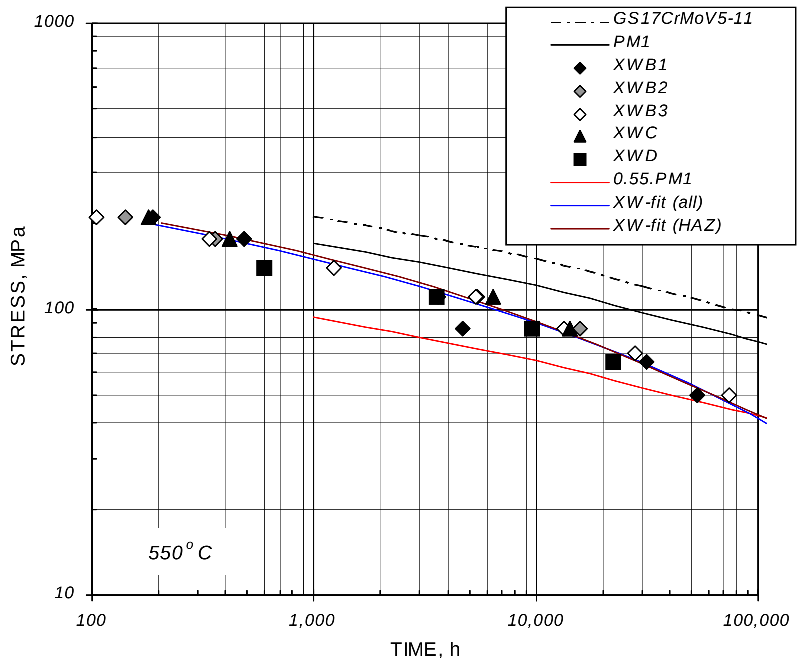


Figure 9: Cross-weld creep rupture strength determined from 1Cr/12Cr data set

In Figure 10 the obtained creep rupture strength at 10,000 h, 30,000 h and 100,000 h for parent metal and welded joints are compared showing also small differences only. As expected the differences in the extrapolated 100,000 h values are more pronounced. In this context it should be pointed out that the extrapolation factors of up to 7 are quite high.

The derivation of weld strength reduction factors was made in different ways:

- the available parent metal data were assessed to get the parent metal reference
- parent metal data were taken from multi-heat assessments available in literature, in one case by using a reduction factor an adaptation with respect to the weak 1CrMoV parent metal was made.

A comparison between weld strength reduction factor, Figure 11, derived from the different assessors seems only to be meaningful if they are referred to individual parent metal data.

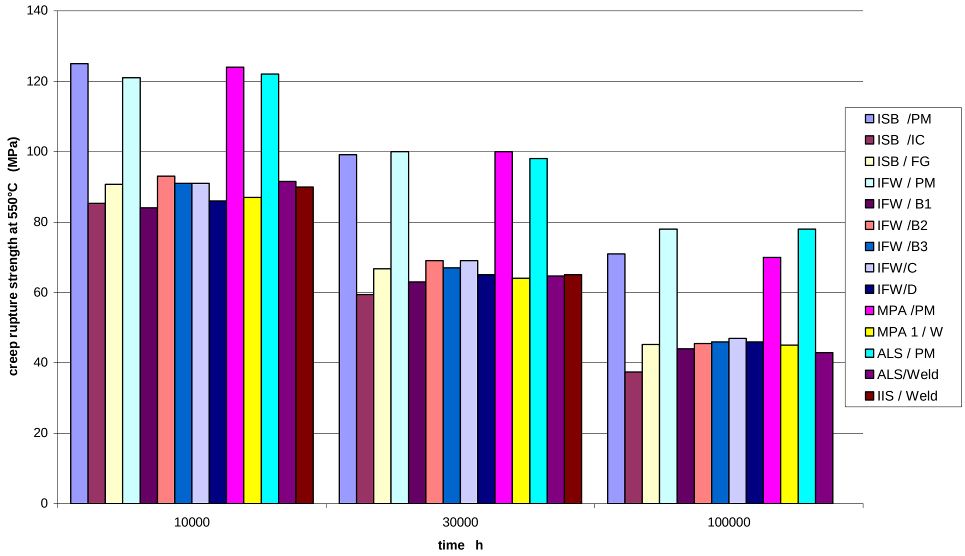


Figure 10: Creep rupture strength at 10,000 h, 30,000 h and 100,000 h

One set of weld reduction factors which was derived by referring to 21CrMoV multi heat assessment could not be compared. The scatter of the derived weld reduction factors is more pronounced, since deviations of two assessments (parent metal and welded joint) are used for the derivation. In general decreasing weld reduction factors with time were observed. Two assessments show, that the decrease is getting smaller with longer times. Weld reduction factors as low as 0.5 were derived for the weakest joint (5 Cr filler, fracture location in ICHAZ).

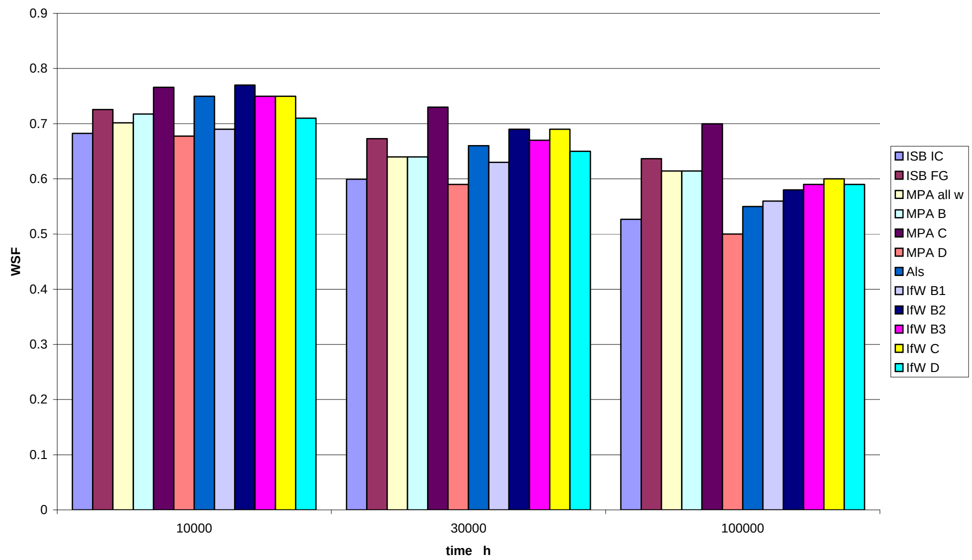


Figure 11: Comparison of weld strength reduction factors for a dissimilar weld 1Cr-12Cr

It has to be noted, that the data used for these round robin assessments were provided from a research project which was aimed to show differences in weld creep strength of joints welded using different welding consumables. The weld materials used for the joint showing the smallest weld strength reduction factors usually will not be used for this kind of weldment. Therefore the weld strength reduction factors determined should not be used for general application in design without consideration of materials and consumables involved.

3 Recommendations for data assessment

From the weld data assessment inter-comparisons the following conclusions can be drawn: The dissimilar weld data set is made up from different welds made using different weld metals. A careful pre-assessment is therefore needed. Different damage mechanisms yield different fracture locations. However for long terms all joints fail in the heat affected zone of the weaker parent metal (1Cr). One of the filler metals (5Cr) showed the worst creep fracture behaviour. The pre-assessments came to different approaches using a different data selection. However the outcome demonstrates that except a small difference taking into account the weakest filler metal or not, the predictions using heat affected zone data only came to quite similar results. If a lower bound value covering all investigated materials and joints should be provided the individual assessments on the joints and the assessments using only ICHAZ data are in good agreement. Furthermore only small differences were found between assessments taking into account the change in fracture location, however it must be pointed out, that this is a propriety of this special dataset. In this case the determination of weld strength reduction factors seems only to be meaningful if they are referred to the related parent metal which is near or at the lower bound of the scatter band of 1CrMoV-steels.

As a main outcome of the assessments on the E911 data sets it became obvious that in this case results using heat affected zone data only and the complete data set may differ strongly. Taking into account that the heat affected zone is in principle a different material it might be consequent to use such data. However, it has to be noted, that the inhomegenous stress and strain distribution as shown in Figure 2 plays an important role in the behaviour of the specimen which cannot be transferred to component behaviour directly. The strain development with time shows that the change in fracture location is a process. This indicates that the support from the (stronger) parent metal influences the creep rupture strength detected with the specimen showing first fracture in the heat affected zone. Therefore in one of the assessments it is proposed to neglect the results in this transition region as well, see Figure 12. The green dotted lines are showing the envelope containing omitted data.

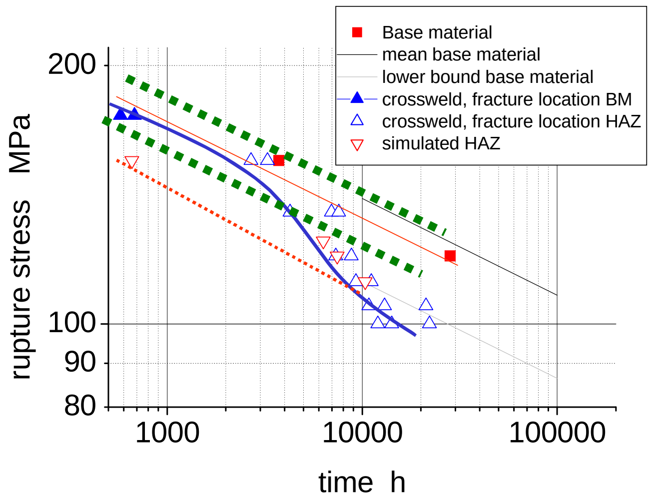


Figure 12: Data assessment using selected data fractured in HAZ

This yields a method using data points only showing predominantly strain or damage concentration in the HAZ. However two difficulties may occur. The number of data points is reduced drastically for a proper assessment and the time span covered by this may rather small. As a consequence the method derived from this experience can only be applied if there are sufficient data in this region covering at least a time span of 20.000 h or more (dependent on the time when the change in fracture location occurs. In Figure 12 it becomes obvious that this method can be strongly enhanced if data from heat affected zone simulated material can be used. In the case of having not sufficient number of data, the more conservative approach using all available data is recommendable. The procedure for the for these assessment routes is given in more detail in Annex C.

4 Derivation of weld creep strength factors

In addition to creep-rupture strength values for a given time and temperature, $R_{u(W)/t/T}$, the associated weld strength or weld strength reduction factors [STU77, ETI93] are also usually required from the assessment of weld creep-rupture datasets, the respective formula are given in the main document.

These weld reduction factors may be defined with respect to the properties of the specific parent material(s) to which the $t_{u(W)}(T,\sigma_o)$ data relate or to the alloy mean properties of the parent material(s). Where possible, comparison with heat specific properties is preferred, in particular for datasets comprising results from a small number of weldments.

An important consideration is that the $t_{u(W)}(T,\sigma_o)$ data comprises information collected for the fracture location relevant to the application for which the strength values are required. For example, if the fracture location in service is in the Type IV region of the weldment, the $t_{u(W)}(T,\sigma_o)$ data leading to the determination of $R_{u(W)/t/T}$ should originate from tests involving specimen failure in the ICHAZ of the test weld or an appropriately simulated microstructure. Fracture location and the acceptability of simulated microstructures are therefore important additional considerations in the post-assessment of weld creep-rupture data.

Weld creep strength factors may be defined in different ways [SCHU01]. If sufficient parent material data of the same melt are available, melt and temperature specific factors can be derived, which is the preferred option. Examples are shown in Figure 13 for E911-steel. If the number of data points for the respective parent material is not sufficient, at least the position of creep rupture strength values in the scatterband should be known.

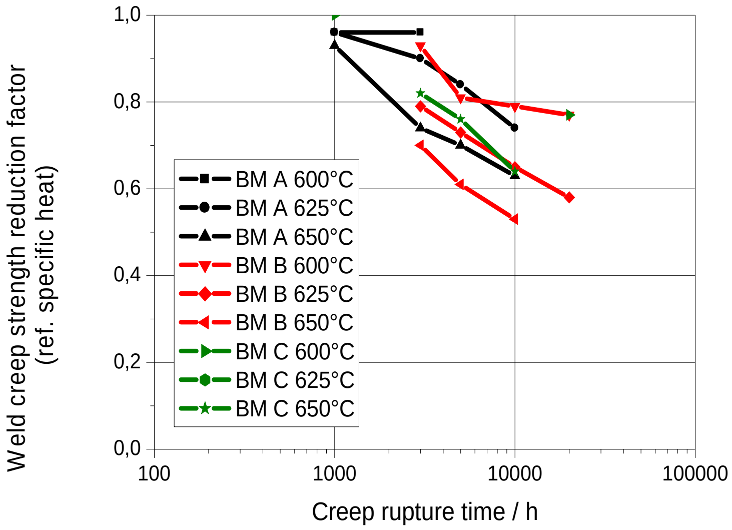


Fig. 13: Melt specific weld strength factors for E911

If there is a multi heat assessment for both parent material and welded joint available the factors can be derived from these assessments using the data points at distinct temperatures of the respective rupture curves.

5 Summary and conclusions

Weld creep rupture properties are ideally determined using cross weld testpieces, but may also be determined by testing material with simulated weldment microstructures. Test data for simulated weldment microstructures should only be used when material comparability has been verified by hardness and microstructure integrity checks of hardness, transformation product and grain size. Test data from material with verified simulated weldment microstructure can provide useful creep rupture properties to complement those determined from cross-weld tests.

On completion of every cross-weld creep rupture test, it is important to determine the microstructural location in which final fracture occurs. In many ferritic/martensitic steel weldments, the location of creep rupture changes from the parent or weld metal in short time (high stress) tests to the heat affected zone (and often the intercritical HAZ) in longer times (at lower stresses). When there are sufficient results from cross-weld tests to characterise the rupture properties associated with the long time fracture location, these (in conjunction with relevant results from simulated microstructure tests) should be used to determine long time rupture strength values. When there are insufficient cross-weld test results to characterise the strength properties in the long time fracture location regime, the results of all cross-weld tests should be used for data assessment.

Weld strength (time) factors for individual weldments are ideally determined on the basis of rupture strength (time) data for the specific cast of parent material. When this is not possible, weld strength (time) factors should be determined with reference to alloy mean rupture strength (time) data for the parent material. Weld strength (time) factors for weldment classes are determined by normalising mean weld rupture strength (time) by the alloy mean rupture strength (time) of the parent material.

6 Acknowledgements

Discussions and contributions of the ECCC-Working Group 1 members are highly appreciated especially the contributions to the assessments described. The work was partly funded by the European Commission under the projects WELD CREEP and ADVANCED CREEP.

7 References

/BAU06/ M. Bauer, A. Klenk, K. Maile und E. Roos: Optimierung der Zeitstandfestigkeit von geschweißten Komponenten aus modernen martensitischen Stählen, 29. Vortrags-veranstaltung der Arbeitsgemeinschaft warmfeste Stähle und der Arbeitsgemeinschaft Hochtemperaturwerkstoffe im VDEh, 24. November 2006, Düsseldorf

/BUC90/ Buchmayr, B., H.Cerjak, M.Witwer, K.Maile, H.Theofel, W.Eckert: "Experimental and numerical investigations of the creep behaviour of the dissimilar weldment GS-17CrMoV 5 11 and X20CrMoV 12 1", steel research 61, 1990, 6, 268-273

/BUC92/ Buchmayr, B.:"HAZ-CALCULATOR - A software package for metallurgical aspects of weldability", Workshop Computer Aided Welding, 8.9.1992 Madrid; IIW-Doc.XII-1304-92

/ERV2/ ECCC Recommendations Vol. 2, 2005, Terms and Terminology for use with stress rupture, creep rupture, creep and stress relaxation : Testing, data collation and assessment, eds. Morris, P.F., Orr, J., Servetto, C. Seliger, P., Holdsworth, S.R. & Brown, T.B., publ. ECCC, (a) Part I: General terms and terminology and items specific to parent material, (b) Part IIa: Terms and terminology for welding processes and weld configurations, (c) Part IIb: Terms and terminology for weld creep testing, (d) Part III: Terms and terminology for post service exposed creep data, (e) Part IV: Terms and terminology for creep crack initiation testing and data assessment, (f) Part V: Terms and terminology for multi-axial features and components.

/ERV3/ ECCC Recommendations Vol. 3 Part II, 2005, Data acceptability criteria and data generation: creep data for welds eds. Klenk, A. and Buchmayr, B., published ECCC

/ETI94/ C.F. Etienne and J.H. Heerings: Evaluation of the influence of welding on creep resistance, Steel Research, 65(1994), 5, 187.

/HYD03/ T H Hyde, W Sun and J A Williams: Creep analysis of pressurised circumferential pipe weldments – a review, J. Stain Analysis, 38 (2003) No 1

/KLE03/ A Klenk, K Karpat, C R Das: Feature tests and Finite Element simulations to assess structural integrity of weld repairs. 2nd Int. Conf. On Integrity of High Temperature Welds, 10-12 November 2003, London, pp. 381-390, IOM communications

/KUS91/ K. Kußmaul, K. Maile and W. Eckert: Influence of Stress State and Specimen Size on Creep Fracture of Similar and Dissimilar Welds, ASTM-Symposium on Constraint Effects in Fracture, May 8-9, 1991, Indianapolis, Indiana

/MAI85/ G. Maier, K. Maile, H. Theofel: Zeitstandfestigkeit und Kriechverhalten von Schweiß-verbindungen an warmfesten CrMoV-Stählen mit 1% und 12% Chromstahl und Eisen 105 (1985) 21, pp 1105-1110

/MAI07/ K. Maile, A. Klenk, M. Bauer, E. Roos: Consideration of Weld Behaviour in Design of High Temperature Components, 5th Int. Conference on Advanced in Materials Technology for Fossil Power Plants, 3-5 October 2007, Marco Island, Florida

/SCHU01/ J.Schubert, A.Klenk, K.Maile: Durchführung und Auswertung von Zeitstandversuchen mit Proben aus Schweißverbindungen; 27.VDEh-Vortragsveranstaltung am 26.11.2004 in Düsseldorf

/SCHU05/ J.Schubert, A.Klenk, K.Maile: Determination of weld strength factors for the creep rupture strength of welded joints, ECCC Conference 2005, IOM London.

/SRH99/ Holdsworth, S.R., 1999, 'Recent developments in the assessment of creep-rupture data', Proc. 8th Intern. Conf. on Creep and Fracture of Engineering Materials and Structures, Tsukuba, November, 1-8.

/STU77/ Stubbe, J. & van Melsen, C., 1977, 'Practical applications of a short-term creep test method for evaluation of the restlife', Proc. NIL-Int. Symp. Predictions of Residual Lifetime of Constructions Operating at High Temperature, The Hague, 95-140.

/THE88/ Theofel,H. and K. Maile: Investigation of the structural formation, toughness and strength of the heat affected zone by means of weld simulated specimens of 1% CrMoV-steel, Final Report COST 505 Project D17, December 1988

ANNEX C

PROPOSED METHOD FOR THE DETERMINATION OF WELD STRENGTH FACTORS

J Schubert, A Klenk, K Maile

Abstract

Based on the experience described in Annexes B and D procedures for the determination of reliable weld strength reduction factors are proposed. Especially the problem of assessing welded joints exhibiting a change in fracture location and the derivation of weld strength (time) factors is addressed.

1 Introduction

Welded joints are important constituents of plant components. Especially in case of the design of high temperature components welds are often the critical locations since they have lower strength due to the metallurgical changes after welding. Therefore it is important to know the longterm characteristics. It is necessary to reliably measure and analyse them. Crossweld tests are a common method to determine longterm creep rupture strength values for a welded joint. The reduction in strength in relation to the to the appropriate parent metal is described by weld strength factors or weld time factors as given in /1/ and the main document. In this paper reference will only be made to the weld strength factor WSF. As far as principles of determination are concerned these are applicable to the other parameters in an analogous way.

2 Determination of creep rupture strength for welded joints

Usually designers are interested in the time and temperature dependent mean and minimum of the creep rupture strength and the mean weld strength factor, respectively. Usually the weld strength factor for 100.000 h and 200.000 h is needed. To determine the weld strength factors the procedures depicted in Figure 1 may be applied.

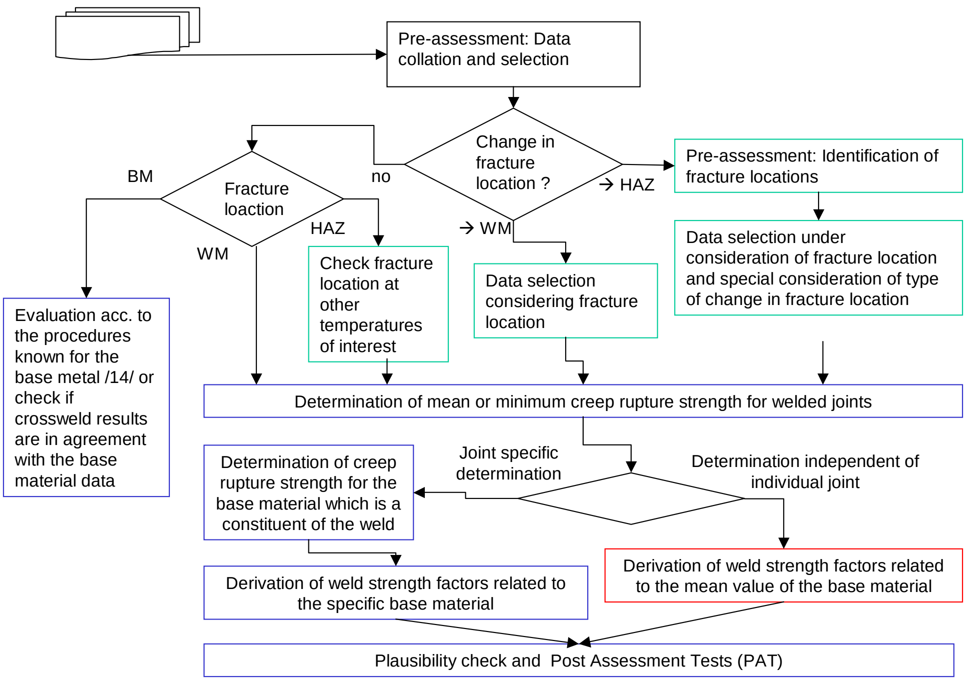


Fig. 1: Schematic representation of determination of weld strength factors

2.1 Pre-assessment

In addition to the pre-assessments concerning material pedigrees and data as described in the main document the following is applied. If there is no change in fracture location within the temperature range of interest the procedures known for base materials /3,4/ can be applied. A change in fracture location is to be regarded in a special way. Hence in the pre-assessment it has to be proven that a proper evaluation of fracture location is available for the tests. In the following the procedure is described step by step.

Crossweld-creep test results are pre-assessed with special attention to the welding process, the filler material and the heat treatment after welding according to the guidelines given for pre-assessments /3/. Similar and dissimilar welded joints can be evaluated together, if the rupture is located in the same weldment microstructure. Assessments can be conducted using the procedures given in /3-5/. The graphical assessment method described in /4/ may have advantages for the assessment of crossweld results.

Plots of isothermal creep strength curves and if available of the appropriate parent metal melt are the base of further evaluation. The fracture location should be depicted in the isothermal creep strength curves. The change in fracture location is illustrated in Appendix D and by example in Figures 2 and 3.

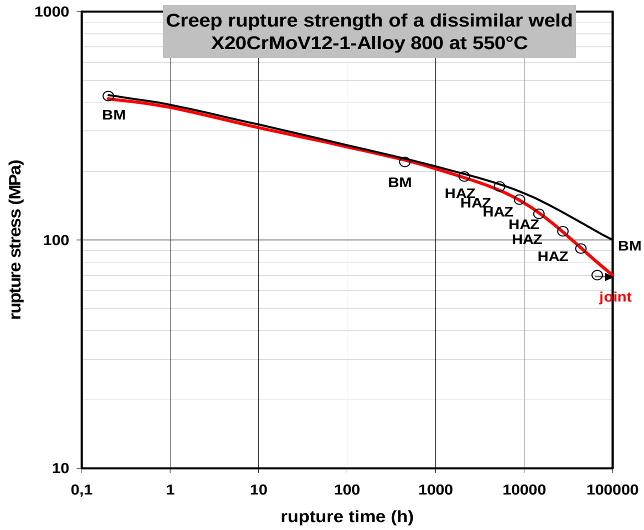


Fig. 2: Creep rupture strength of a dissimilar weld 12Cr-Alloy800 at 550°C

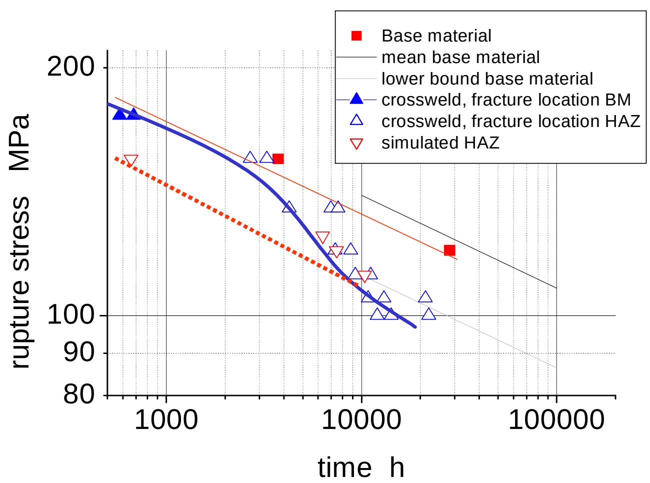


Fig. 3: Change in fracture location illustrated by the depiction of the creep rupture curve for E911 at 600°C

Different behaviour is shown, which is also dependent on the observed time range. In case of the behaviour shown in Fig.2 the creep rupture curve can be drawn or determined using all data for which fracture is located in the heat affected zone. In every case this procedure delivers more conservative descriptions in the longterm range. In case of Fig. 3 the drop in creep rupture strength is complete when the damage is primarily concentrated in the heat affected zone. In order to avoid too conservative results of an assessment at longer times data obtained for the transformation zone where the fracture location changes from base or weld metal, respectively, to the heat affected zone may be disregarded, Fig. 4.

A sufficient number of remaining data at times of at least 30,000 h should be available for further assessment. If reliable data on simulated heat affected zone material are available they can support these evaluations especially in the short term range. However, it has to be noted that the heat affected zone simulation procedure must be done carefully using appropriate parameters which are material dependent, see Annex B in /2/. If available unbroken specimens can be included in the assessments acc. to /5/ or by using creep strain curves for extrapolation of creep rupture strain. These data must be weighted differently. For all assessments, a maximum time extrapolation factor of 3 must be regarded.

2.2 Determination of creep rupture curves for the welded joint and derivation of weld strength factors

The data set prepared by special data selection in the pre-assessment is assessed using numerical assessment methods or the graphical cross plotting method as described in /3/ considering the recommendations for small datasets.

From these assessments mean creep rupture curves and in case of graphical cross plotting /4/ a minimum creep rupture curve can be derived. The weld strength factors for 100.000 h and if necessary 200.000 h for the welded joint are derived. If sufficient data for parent material and the welded joint are available weld and joint specific WSFs can be determined as shown in Fig. 5. A mean and a minimum value can be derived by averaging the individually obtained values as shown in Fig. 6. As shown in Fig. 5 and 6 for the derivation outliers which result for example from deviating post weld heat treatment parameters are disregarded.

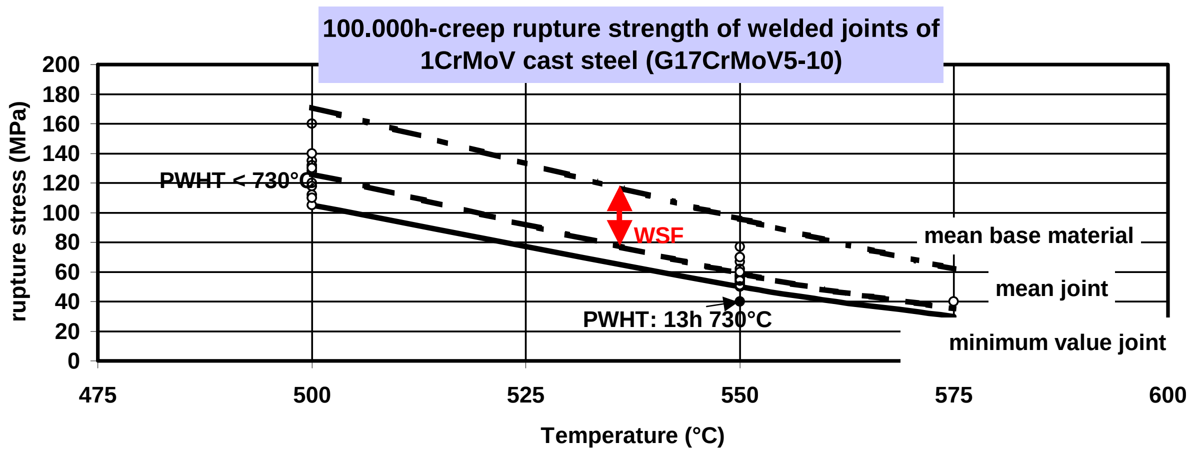


Fig. 5: Derivation of weld strength factor for 100,000 h creep rupture strength

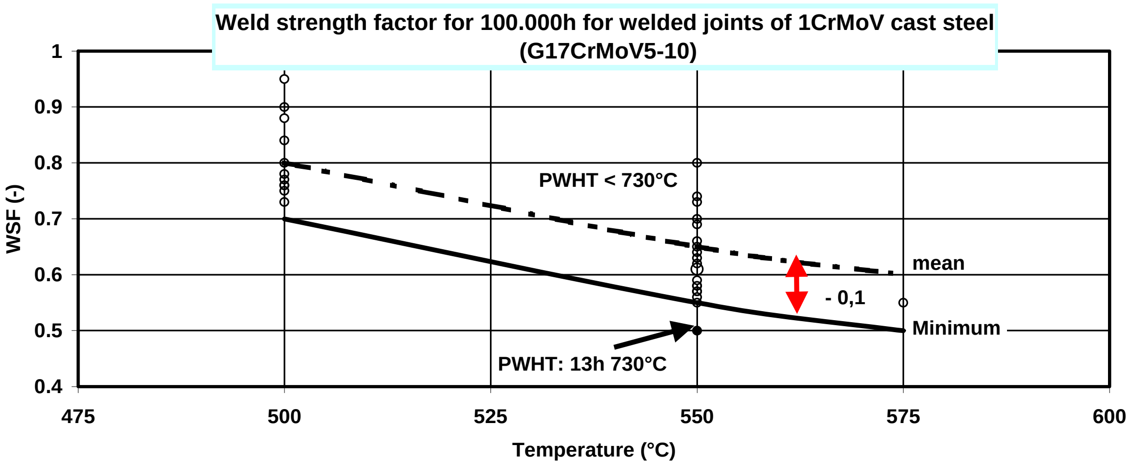


Fig. 6: Derivation of mean and minimum weld strength factors for 1CrMoV-cast steel

Mean weld strength factors are factors derived as the quotient of mean weld creep rupture strength for crosswelds and the base material mean values given e.g. in a standard or in ECCC data sheets. Table 1 summarises the derivation of WSF from creep rupture strength values.

Table 1: Derivation of weld strength factors for individual cases based on data availability

case	WSF (mean)	Mean value of creep rupture strength of a welded joint	Minimum value of creep rupture strength of a welded joint
1: one joint without corresponding parent metal melt	WSF = creep rupture strength of joint / mean value of parent metal (ECCC, standard)	Mean creep rupture strength of joint = WSF (mean) x mean creep rupture strength of PM	Minimum creep rupture strength of joint = WSF(mean) x minimum creep rupture strength of parent metal ZSF
2: one joint with corresponding parent metal melt	WSF = creep rupture strength of joint / creep rupture strength of corresponding parent metal melt		
3: several joints without corresponding parent metal melts	WSF = mean value of creep rupture strength of joints / mean value of parent metal (ECCC, standard)		Minimum creep rupture strength of joint = Minimum value of: • WSF (mean) x minimum creep rupture strength of parent metal • = minimum WSF
4: several jonts with corresponding parent metal melts	WSF (mean) = mean value of WSF of the individual joints		
5: combination of cases 3+4	WSF_l = weightet mean value of cases 3 and 4		

2.3 Post assessment

Finally the preliminary mean and minimum curves for the creep rupture strength and for the weld strength reduction factors are compared and – if necessary – adapted whereby the following conditions have to be conserved: The distance between the mean curve of the parent metal and the welded joint in Fig. 5 has to fit to the WSF mean curve in Fig. 6. The product of the minimum creep rupture strength of the parent metal and the mean value of WSF (see Fig. 6) has to fit to the minimum value of the creep rupture strength of the welded joint (in fig. 5). If numerical assessment methods as decribed are used the Post assessment tests as given in the main document are applied.

Extrapolation of weld strength factors is generally not recommended. It is only possible in a very limited time range as described in the main document. Generally it is recommended to determine weld strength factors assessed creep rupture strength curves of parent metal and welds.

References

/1/ ECCC Recommendations Vol. 2, 2001, Terms and Terminology for use with stress rupture, creep rupture, creep and stress relaxation : Testing, data collation and assessment, e. Morris, P.F., Orr, J., Servetto, C. & Seliger, P., publ. *ERA Technology Ltd, Leatherhead*, (a) Part I General terms and terminology and items specific to parent material, (B) Part IIa Terms and terminology for welding processes and weld configurations, (c) Part IIb Terms and terminology for weld creep testing, (d) Part III: Terms and terminology for post service exposed creep data.

/2/ ECCC Recommendations Vol. 3 Part II, 2001, Data acceptability criteria and data generation: creep data for welds eds. A. Klenk and B Buchmayr, published ECCC,2001

/3/ ECCC Recommendations Vol. 5, 2001, Guidance for the assessment of creep rupture creep strain and stress relaxation data, e. Holdsworth, S.R., Merckling, G., publ*. ERA Technology Ltd, Leatherhead*, (a) Part I Generic recommendations and guidance for full-size datasets, (b) Part IIa: Recommendations for the assessment of sub-size creep rupture data, (c) Part IIb: Recommendations for the assessment of weld creep-rupture datasets, (d) Part III Recommendations for the assessment of post exposure (ex-service) creep data.

/4/ J.Granacher, M.Schwienheer: Graphical Multi-Heat Averaging and Cross Plotting Method, Appendix D4 in /3/.

/5/ ISO 6303

ANNEX D

EXPERIENCE FROM THE ASSESSMENT OF VARIOUS WELDED JOINTS

J Schubert, A Klenk, K Maile

Abstract

In this annex general observations on weld creep behaviour of ferritic and martensitic forged, cast and piping steels as well as Ni-based alloys are described. Data of longterm crossweld tests on similar and dissimilar welds with test durations up to 100,000 h are used for a systematic description of weld creep behaviour.

Keywords: Weld strength factor, creep rupture strength of welded joints, crossweld testing.

1 Introduction

Welded joints are important constituents of plant components. Especially in case of the design of high temperature components welds are often the critical locations since they have lower strength due to the metallurgical changes after welding. Therefore it is important to know the longterm characteristics. It is necessary to reliably measure and analyse them. Guidance on nomenclature /1/ and for tests using crossweld specimens /2/ are given in ECCC-Recommendations. Some additional remarks on the planning of tests aimed to determine weld strength factors are given in section 2.

The determination of welded joint factors is especially necessary for the fully loaded production, construction and maintenance of welds in components designed against creep strength. These are:

- Longitudinally welded pipes under internal pressure
- Circumferentially welded pipes under internal pressure and axial load (e.g. pipe gaskets or pipe bottoms)
- Manufacturing welds in cast pieces under internal pressure
- Pressure vessels

Up to now, a time and temperature independent weld strength reduction factor for the long term rupture strength of 0.8 is assumed according to /3/. Recent investigations as for example in /4,5/ and the compilations in /6,7/ demonstrate that this factor is dependent on material, temperature and time and can be either higher or lower than 0.8. In the following experiences on the determination of weld strength factors are given illustrated by examples for various similar and dissimilar welded joints.

2 Tests to determine creep rupture strength of welded joints

Usually interrupted or uninterrupted creep tests according to [8] are carried out in single or multiple specimen furnaces. The specimens are made from base material melts (without heat treatment after welding) and from the welded joint produced from them. The following should be obeyed.

- The *test stresses* of the crossweld specimens should be graded according to the strength reduction which is expected for the weld to obtain fracture times of 300, 1000, 3000, 10,000, 30,000 hrs and 70,000 hrs. Thus, it is possible to evaluate weld strength factors both for 100,000 as well as for 200,000 hrs.

- Test durations exceeding 10,000 hrs are of utmost importance because a change in the fracture location from the base material in the heat affected zone (HAZ) can occur at long times. The change in fracture location usually occurs earlier at higher testing temperatures. Due to this, tests at increased temperature (25 – 50 °C above the normal operating temperature) can be used to obtain information about a change in fracture location, as shown in Fig. 1. Derivations or extrapolation methods to determine the time of change in fracture location as shown in /9/ need further confirmation for general application especially for long times.

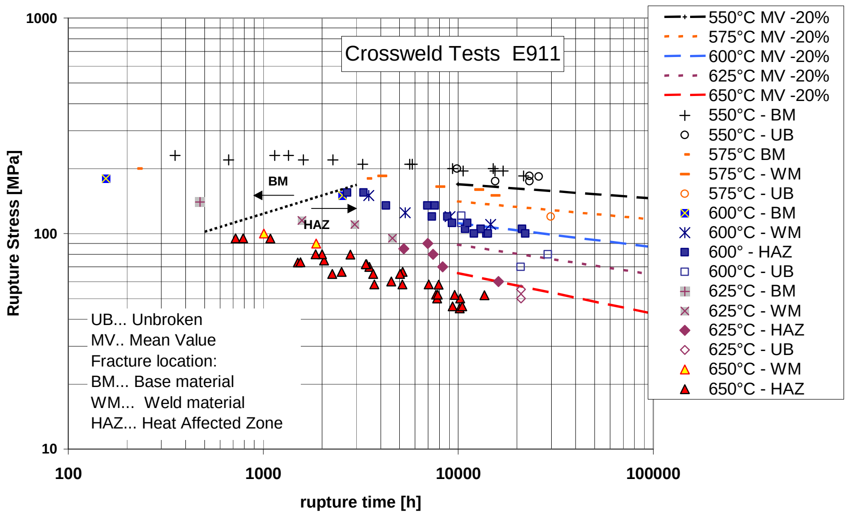


Fig. 1: Change in fracture location, E911-crossweld specimens /10-12/

- Especially at low stress levels the tests should be run twice to avoid influence of scattering due to specimen manufacturing, small allowable weld failures and inhomogeneities of microstructure in the weld.
- To determine the weld strength factors independent of melt and joint for a steel (cast) type, at least 3 welded joints of different producers have to be tested together with the relevant base materials.
- To determine systematically creep minimum values, a welded joint of maximum allowable annealing temperature and duration should be tested. The same can be obtained by testing many welded joints (also without the appertaining base materials).

3 Creep behaviour of crossweld specimens

In the following, experience from investigations on various welded joints are represented. This is based on long term tests on crossweld specimens.

In case of similar joints of ferritic and martensitic steels, the fracture position generally moves with increasing temperature and test duration from the base material in the fine-grained area of the heat affected zone (HAZ). The microstructure of this area is given by recrystallisation due to the heat input during welding. Dependent on the welding process it can be found at a distance of 1-2 mm from the fusion line. The peak temperature during welding in this area is between A_{C3} and A_{C1}. For modern martensitic steels the distance may be considerably greater.

With the change in fracture location the type of fracture also changes from the transgranular base material fracture to the intergranular low ductility creep fracture of the HAZ. When there is a significant difference between the creep rupture strengths of the base material and the HAZ, there is a transition associated with the change in fracture location (Fig. 5a). In this regime the creep rupture strength drops from the higher level of the base material to the lower level of the HAZ. This drop can be less distinct in the case of an early change in fracture location (Fig. 2).

On weld-simulated P91-HAZ-specimens /6, 7/ it could be demonstrated that creep rupture of HAZ material in the high stress region where base metal fracture occurs in welded joints is lower than that of the base material. Consequently, the small HAZ is prevented from deforming (mainly yield and creep of dislocations) and especially from necking by adjacent higher-strength areas. This constraint effect disappears under low stresses and longer loading times (i.e. during creep by grain boundary sliding).

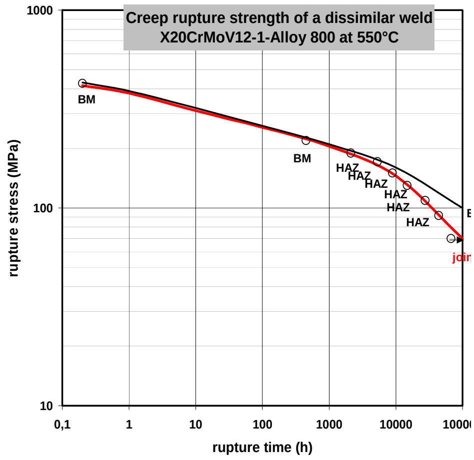


Fig. 2: Creep rupture strength of a dissimilar weld 12Cr-Alloy800

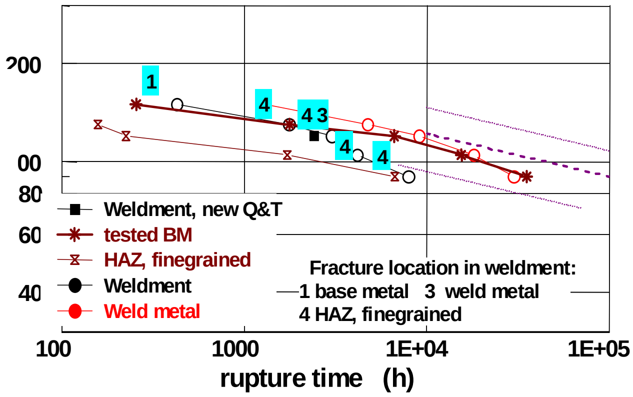


Fig. 3: Creep rupture curve of HAZ simulated material compared to the creep rupture curve of welded joints for P91

A S-shaped curve could be determined in case of alloys with age hardening during creep tests as for example Alloy 617 at 650 °C, Fig. 4. This is also observed in austenitic steels.

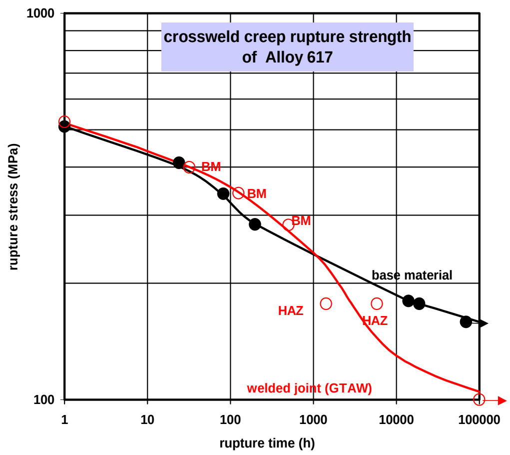


Fig. 4: Crossweld creep rupture strength of Alloy 617 at 650°C

Dissimilar welds behave in the creep test like similar welds of the material showing the lower creep rupture strength, see Fig. 5a. In principle this also applies to dissimilar welds between austenitic and ferritic materials. However, one has to consider that for such joints additional phenomena may occur such as carbon diffusion (decarburised zones) and additional stresses due to different heat expansion. An exception are long-term fractures in weld metal as it may occur for example in P22 (10CrMo9-10) joints welded using similar weld metal with low carbon (Fig. 5b). Consequently, the creep strength of such weld metal has been improved by increasing the average C-content to the present 0.08 %. Something similar happens if unalloyed or Mn-alloyed heat-resistant cast steels are welded using similar weld metal. Improvement is achieved in this case by using a weld metal with approximately 0.5 % Mo. The integral creep strain of a welded joint specimen does not only reflect the creep strain of the HAZ but of all material zones within the cylindrical measuring length. However, the determination of the integral creep deformation curves is useful for improving the estimation of the fracture times of unbroken crossweld specimens. If additionally a grid of indentations is applied on the specimen one can observe approximately the time course of the creep strain of the different material zones in the joint. So it is possible to determine the zone showing the largest strain concentration and derive the creep strain and creep strain rate, Fig. 6a and 6b. The conclusion is that apart from the fine-grained HAZ-zone which was exposed to temperatures between A_{c1} and A_{c3}, the thermally over-aged HAZ zone (exposed to a temperature below A_{c1}) considerably participates in the accumulation of creep strain in spite of the fact that the fractures finally take place in the re-crystallised fine-grained area. In modern martensitic 8-10 % Cr-steels this can affect the HAZ in a width of up to 8 mm (Fig. 6).

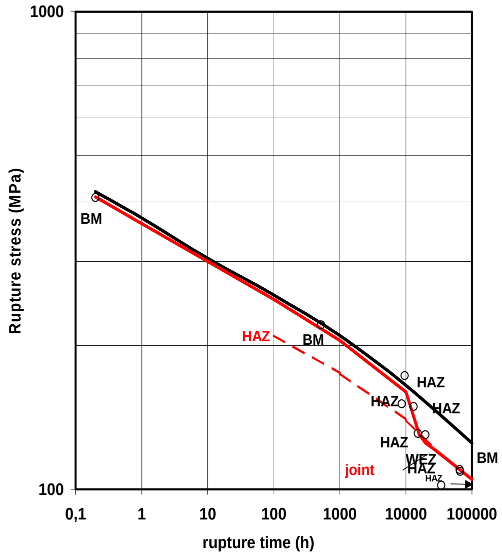


Fig. 5a: Creep rupture strength of a dissimilar weld 12Cr – Alloy 800 at 550°C

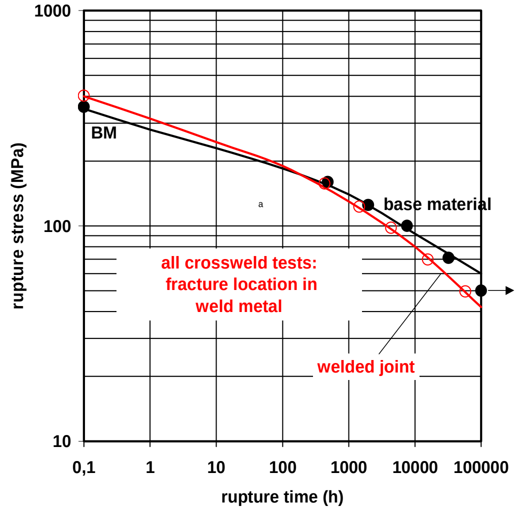
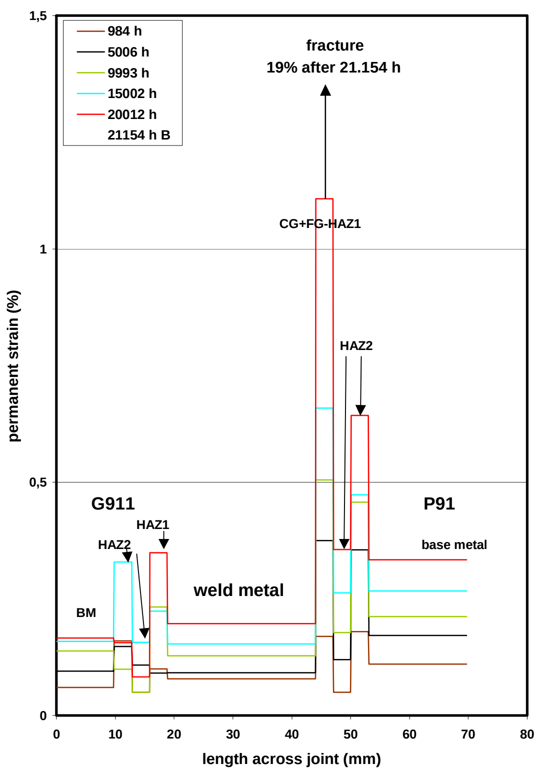


Fig. 5b: Creep rupture strength of a P22 joint welded with similar weld metal with low carbon



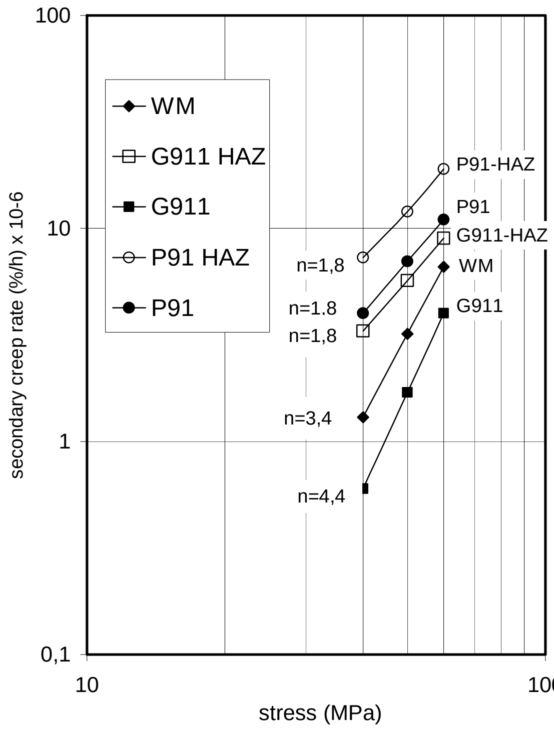


Fig. 6: a) Creep strain distribution and b) creep strain rate in a dissimilar weld P91-G911 at 600°C

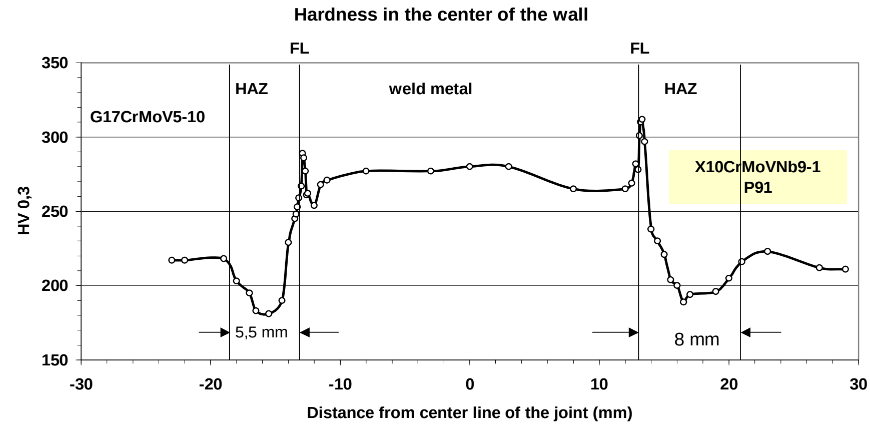


Fig. 7: Hardness in the centre of the wall plotted across a welded joint of P91 and G911

4 Influences on weld strength reduction

As experiences show the weld stress reduction is affected by various parameters. This is shown in table 1. For ferritic and martensitic steels it can be stated, that related to the strength of the base material with increasing ability to precipitation strengthening the heat affected zone is more affected by the heat input due to welding. For high-temperature bainitic steels this leads to a moderate weld strength reduction and for high-temperature martensitic steels to a stronger weld strength reduction, see Fig. 8. Usually a higher weld stress reduction can be determined at high-temperatures, see Fig. 8,9. At lower loading a stronger weld stress reduction can be determined, at least for stresses where failure occurs up to 200.000 h. This tendency can be observed for shorter terms and higher temperature, Fig. 9. These results show, that an extrapolation of weld strength factors is difficult and, hence, the necessity of long-term creep rupture tests for welded joints.

Table 1: Parameters influencing weld strength reduction

Strong impact	Low impact
Base material • Bainitic steel: moderate weld strength reduction • Martens. steels: strong weld strength reduction	Base material For non-alloy and austenitic steels as well as for Ni-based alloys
Temperature (see Fig.9) High temperature → stronger weld strength reduction	Post weld heat treatment and microstructure of base material: Melts with higher creep strength show higher weld strength reduction
Loading Lower stress → stronger weld strength reduction	
Filler Material (Weld material) • For lower creep strength • for austenitic steels and Ni-based alloys using the same type of similar weld material	Welding procedure and heat input for Ni-based alloys, if the weld material is the weakest part with respect to creep strength
Temperature and duration of annealing during post weld heat treatment	Specimen type

The weld material is important if its creep strength is lower than the base material and the heat affected zone. This is the case for e.g. similar weld material with low carbon for P22, Fig. 5b, non-alloyed weld metal for non or Mn-alloyed cast steels. This may also be the case using similar weld metals for 1%- and 9-10%-Cr materials if e.g. the creep rupture strength of the base material is in the upper scatter band. This is shown in Fig. 1 for some melts of

E911. In the case of austenitic steels and Ni-base alloys the weld may also be the weakest point if similar weld metals are used. A clear impact of the temperature and duration of annealing during post weld heat treatment can be determined. This is shown for the cast steel G17CrMoV5-10, see Fig. 10.

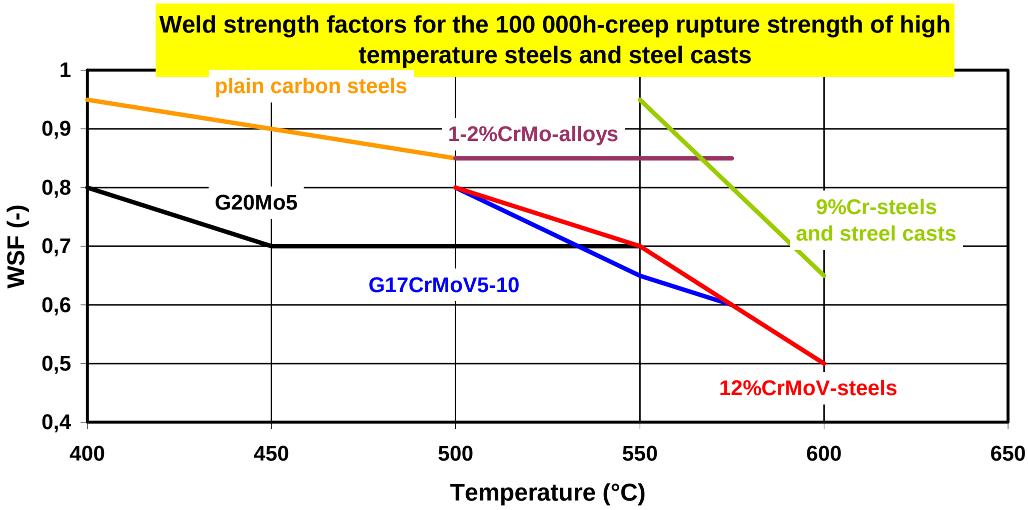


Fig. 8: Weld strength factors for the 100,000 h – creep rupture strength

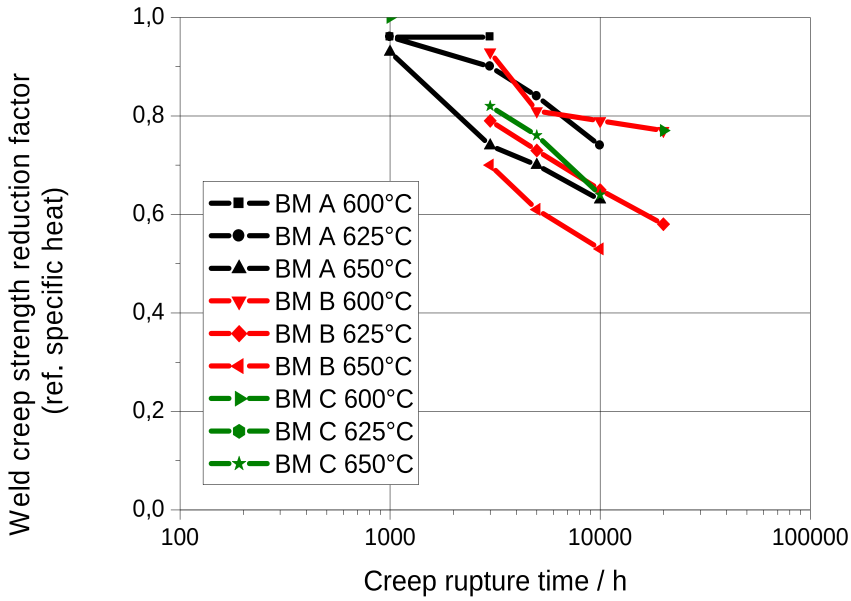


Fig. 9: Melt specific weld strength factors for E911

For ferritic and martensitic steels basically no impact of the welding procedures and heat input can be determined. This is different for e.g. Ni-based alloys and if the weld material is the weakest part with respect to creep strength. For example for Alloy 617 (Fig. 11) the size and orientation of the dendrites in the weld are significant. Detailed investigations performed in /4/ show that a stronger weld stress reduction is determined for smaller specimens. This is particularly important for the transfer to components.

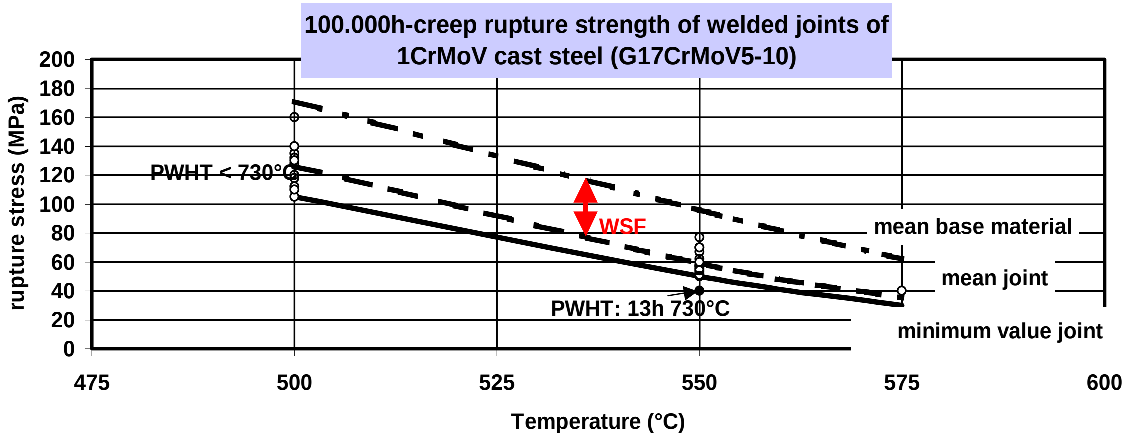


Fig. 10: 100,000 h creep rupture strength of 1CrMoV-cast steel

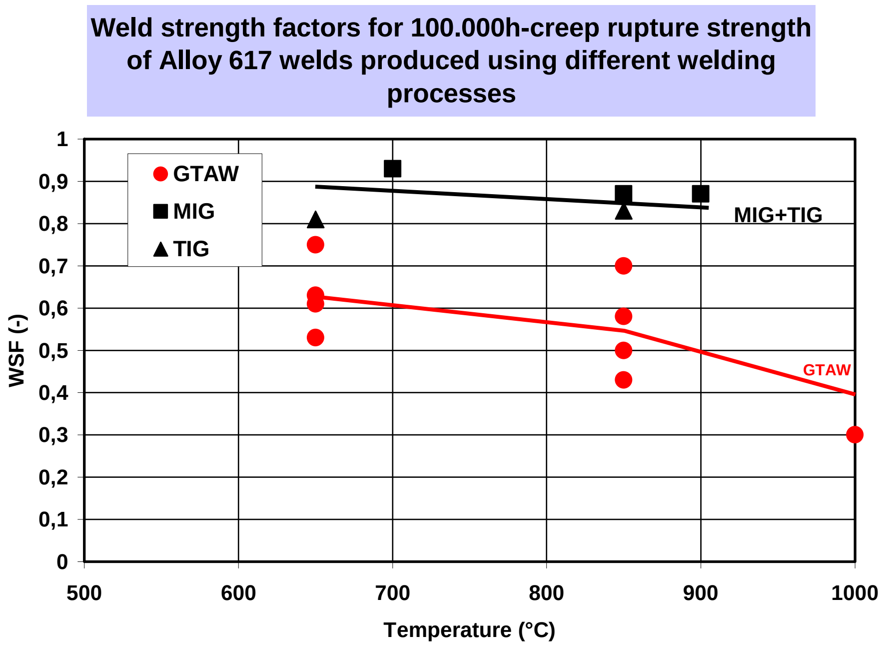


Fig. 11: Weld strength factor for 100,000 h creep rupture strength of Alloy 617 for different welding processes

6 Application of weld strength factors

As described in the previous sections weld strength factors or weld strength reduction factors are usually determined using crossweld specimens. The specimens are taken from a weld and consist of sufficient portions of all parts of the weld: base material, at least one complete heat affected zone and weld metal. The loading is uniaxial and there is nearly no constraint which limits the strain development and the weakest zone which is often the fine grained heat affected zone. Investigations on large scale specimens /17/ having higher constraint show that crossweld specimens with larger cross sections show higher creep rupture strength, Figure 12.

For the application of weld strength factors to components this means that an additional safety margin is given by the fact that usually in components a weld is not subjected to the same uniaxial stress state as a small crossweld specimens. However, in design this can only be considered if a detailed analysis of stresses and stress state is available. Studies on welds and repair welds /18,19/ show, that it is possible to simulate the deformation and damage behaviour of welds using finite element techniques by applying constitutive equations adapted to individual material behaviour to the different zones in a weld i.e. base and weld material, the heat affected zone is modelled as 2 or 3 zones with different behaviour.

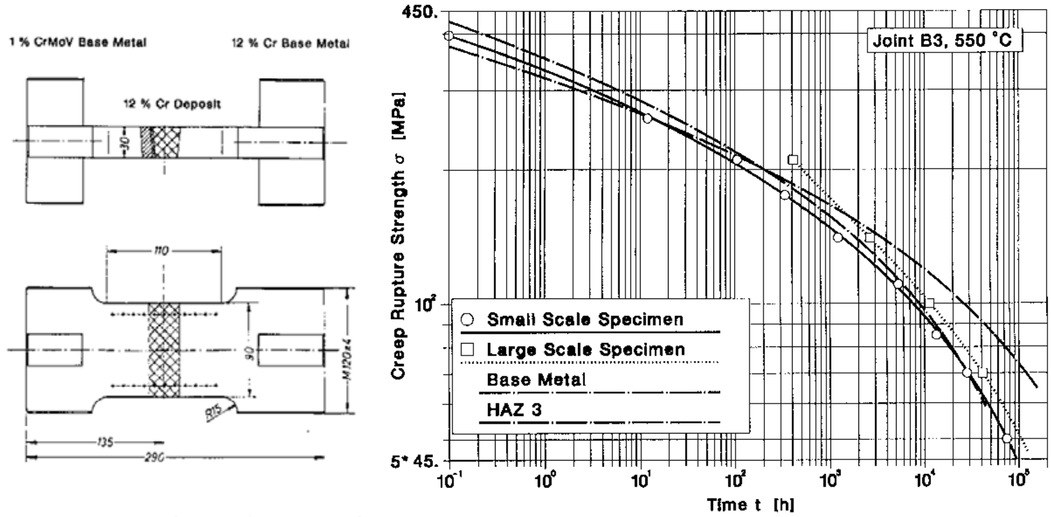


Fig. 12: Comparison of crossweld creep rupture strength and rupture strength of weld specimen with large cross section for a dissimilar weld of 1CrMoV-cast steel and 12CrMoV steel /4,17/

7 Summary and Conclusions

Numerous long term creep tests on cross weld tests of the German Creep Group (AGW) and the plant manufacturers provided the basis for the analyses described in this paper which were aimed to determine reliable creep rupture strength characteristics for welded joints. These analyses showed that long-term tests are inevitable for a safe extrapolation. This need is mainly caused by the change in fracture location which is observed for most of ferritic weldments. Furthermore it can be concluded that the use of extrapolation procedures must be subject to greatest care and usually needs experienced evaluators and that existing methods for the assessment of base materials cannot be used for welded joints without modification and further considerations. Modifications and procedures are proposed to reliably assess the rupture strength of welded joints. As examples a number of weld strength reduction factors were shown and specific influences on weld strength reduction are shown. These results show that the weld strength factors varies with time and temperature and is material dependent. For some materials the weld strength reduction can be as large as nearly 0.5. Applying weld strength factors derived by uniaxial crossweld tests it has to be considered that weld behaviour in a component is dependent on the stress state in the component.

References

/1/ ECCC Recommendations Vol. 2, 2001, Terms and Terminology for use with stress rupture, creep rupture, creep and stress relaxation : Testing, data collation and assessment, e. Morris, P.F., Orr, J., Servetto, C. & Seliger, P., publ. *ERA Technology Ltd, Leatherhead*, (a) Part I General terms and terminology and items specific to parent material, (B) Part IIa Terms and terminology for welding processes and weld configurations, (c) Part IIb Terms and terminology for weld creep testing, (d) Part III: Terms and terminology for post service exposed creep data.

/2/ ECCC Recommendations Vol. 3 Part II, 2001, Data acceptability criteria and data generation: creep data for welds eds. A. Klenk and B Buchmayr, published ECCC,2001

/3/ AD 2000-Merkblatt B 0: Berechnung von Druckbehältern

/4/ G. Maier, K. Maile, H. Theofel: Zeitstandfestigkeit und Kriechverhalten von Schweiß-verbindungen an warmfesten CrMoV-Stählen mit 1% und 12% Chromstahl und Eisen 105 (1985) 21, pp 1105-1110

/5/ K. Maile, A. Klenk, E. Roos, R.U. Husemann, A. Helmrich: Development and Qualification of new Boiler and Piping Materials for High Efficiency USC Plants,
4th Int. Conf. On Advances in Materials Technology for Fossil Power Plants, 26-28 October 2004, Hilton Head Island, SC.

/6/ C.F. Etienne and J.H. Heerings: Evaluation of the influence of welding on creep resistance, Steel Research, 65(1994), 5, 187.

/7/ J.Schubert, A.Klenk, K.Maile: Durchführung und Auswertung von Zeitstandversuchen mit Proben aus Schweißverbindungen; 27.VDEh-Vortragsveranstaltung am 26.11.2004 in Düsseldorf

/8/ EN 10291

/9/ J M Brear, A Fleming : Prediction of P91 life under plant operating conditions, Proc. of Int. Conf. On High Temperature Plant Integrity and Live extension, Robinson College, Cambridge, 14-16 April 2004, European Technology Ltd (ETD), 2 Warwick Gdns, Ashtead, Surrey

/10/ Husemann, R. U., H. Theofel, A. Klenk and K. Maile, „ Langzeiteigenschaften von Schweißverbindungen moderner Stähle für Dampferzeuger“, 23. Vortragsveranstaltung AGW/AGHT. Düsseldorf, 2000.

/11/ Bendick, W., K. Haarmann und M. Zschau, „ E911 - Ein neuer Werkstoff für Dampfleitungen im Kraftwerksbau“, VGB Kraftwerks Technik 5/2000, pp. 114-118

/12/ Forschungsvorhaben AVIF A 129: Nachweis der Langzeiteigenschaften von Schweißverbindungen moderner Stähle für den Einsatz in Dampferzeugern im Bereich bis 620 °C, MPA Stuttgart

/13/ Forschungsvorhaben AVIF A 77: Qualifizierung von Werkstoffen zum Einsatz in Dampferzeugeranlagen mit erhöhten Temperaturen, Wirtschaftsverband Stahlbau und Energietechnik e.V., Düsseldorf; 1999 VGB Kraftwerkstechnik No. 7/2000; pp. 86-88 and No. 8/2000; pp. 97-101

/14/ ECCC Recommendations Vol. 5, 2001, Guidance for the assessment of creep rupture creep strain and stress relaxation data, e. Holdsworth, S.R., Merckling, G., publ*. ERA Technology Ltd, Leatherhead*, (a) Part I Generic recommendations and guidance for full-size datasets, (b) Part IIa: Recommendations for the assessment of sub-size creep rupture data, (c) Part IIb: Recommendations for the assessment of weld creep-rupture datasets, (d) Part III Recommendations for the assessment of post exposure (ex-service) creep data.

/15/ J.Granacher, M.Schwienheer: Graphical Multi-Heat Averaging and Cross Plotting Method, Appendix D4 in /14/.

/16/ ISO 6303. Pressure Vessel Steels Not Included in ISO 2604, Parts 1 to 6 - Derivation of Long-Time Stress Rupture Properties First Edition, 1981

/17/ K. Kußmaul, K. Maile and W. Eckert: Influence of Stress State and Specimen Size on Creep Fracture of Similar and Dissimilar Welds. ASTM-Symposium on Constraint Effects in Fracture May 8-9, 1991, Indianapolis, Indiana

/18/ T H Hyde, W Sun and J A Williams: Creep analysis of pressurised circumferential pipe weldments – a review, J. Stain Analysis, 38 (2003) No 1

/19/ A Klenk, K Karpat, C R Das: Feature tests and Finite Element simulations to assess structural integrity of weld repairs. 2nd Int. Conf. On Integrity of High Temperature