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ECCC RECOMMENDATIONS - VOLUME 3 Part II [Issue 3]

DATA ACCEPTABILITY CRITERIA AND DATA GENERATION:

CREEP DATA FOR WELDS

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DATA ACCEPTABILITY CRITERIA AND DATA GENERATION: CREEP DATA FOR WELDS

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ABSTRACT

ECCC Recommendations - Volume 3 Part II defines the material pedigree and testing practice information required to accompany (i) existing and (ii) new creep rupture data for welds. The acceptability criteria for existing test results have been set to make full use of the available data. Those defined for new results are the consequence of a comprehensive review of current practices for testing actual welds and simulated HAZ materials (Appendices 1 and 2).

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Contents of Volume 3 Part II

1 OVERVIEW

In general, weldment creep data are needed for two main reasons. The first is to determine the creep characteristics for a welded joint representing all zones of the weld of interest. In this case the test result is the rupture time of the cross-weld testpiece and the fracture location. Secondly, tests are carried out to determine the specific behaviour of a distinct zone (e.g. the intercritical region of the heat affected zone) to use the determined parameters as an input for calculations such as those involving finite element methods in which each zone is modelled using different material characteristics. In this case the specific behaviour of a single zone is of interest. Alternatively, if the weakest part of a weldment is known, the data obtained for this zone may be used for characterisation of weldment creep properties.

Different testing techniques have to be applied for the two approaches. In this document, a distinction is drawn between

- obtaining data for the whole weldment by means of cross-weld specimen testing

- obtaining data for a distinct part of the weldment:

  • parent metal or weld metal by means of conventional creep specimens (sampled in a longitudinal direction, see Figure 1 in Appendix 1)

  • heat affected zones by means of miniature specimens

  • heat affected zones by means of simulation techniques

Part II of Volume 3, with reference to Part I [1], gives specific recommendations for creep testing of welds. With regard to the creep testing of welds special considerations are needed for specimen shape and dimensions, sampling of testpieces from the weldment and pre-assessment of the results. Hence, Volume 3 (Part II) is prepared in order to:

• give minimum information requirements for the weld description and the material pedigrees of parent metal(s) and weld metal

• describe testpiece sampling strategies considering experiences on the effect of specimen size, shape and sampling location

• define the information required for recording of failure location, failure mechanism

• ensure a representative property characterisation of the overall weldment behaviour

• describe heat affected zone simulation techniques to gain data for the characterisation of parts of welds particularly of the heat affected zone (HAZ) for finite element calculations and for the description of the creep behaviour of a weldment using its weakest part .

The recommendations are a consequence of a review of current testing practices (Appendix 1) and HAZ-simulation techniques (Appendix 2).

2 WELD DESCRIPTION

The data acceptability criteria covering the description of weldment and material pedigrees are an integral part of the ECCC-Terms and Terminology documents [2,3,4]. The minimum information requirements are summarised in Table 1.

2.1 Material Pedigree

Parent metal should be characterised according to the minimum information requirements given in Tables 1 and 2 of Volume 3 Part I [1]. In the case of a dissimilar weldment both parent metals should be described.

2.2 Weld Geometry and Sequence, Welding procedure

The minimum information required to describe the weld geometry and welding sequence relating to existing weld creep data, as given in the Terminology document [3] is summarised in Table 1. The mandatory and recommended information required is given in Table 2.

Table 1   Minimum Weld Description Information Required for EXISTING Weld Creep Data

CATEGORY	MINIMUM INFORMATION REQUIRED[a]
Material codes and pedigree for parent metal(s)	- see Table 1 of Part I
Weld geometry and sequence	- Joint type[b]
Welding procedure	**- Welding consumable[c]** **- Preheat and interpass heating[d]** **- Intermediate heat treatment (after buttering)[d]** **- Post weld heat treatment[d]**
Weldment characteristics	**- Approved for creep testing**

Table 2   Minimum Weld Description Information Required for NEW Weld Creep Data

CATEGORY	MINIMUM INFORMATION REQUIRED[a]
Material codes and pedigree for parent metal(s)	**- see Table 1 of Part I[e]**
Weld geometry and sequence	**- Joint type[b,e]** - Joint preparation[f] - Backing material and type **- Total weld thickness**
Welding procedure	- Welding process details (type, technique, position)[g] **- Welding consumable[c,e]**, deposit analysis[h], flux details[i] - gas details (shielding, backing, plasma)[j] **- Preheat and interpass heating[d,e]**, details - Heat input **- Intermediate heat treatment (after buttering)[d,e]**, details **- Post weld heat treatment[d,e]**, details
Characteristics of the weldment	**- Approved for creep testing** - Welding qualification standard used - Non-destructive testing (types of examination, imperfection) - Destructive testing (tensile, impact, macro[k])

NOTES: (a) the reporting of additional information is not precluded, see [2]
(b) specify reference number according to Table 2.1 of [3]
(c) at least one of Alloy name, Specification and Grade name, Trade name shall be supplied to identify the filler metal
(d) simple acknowledgement of whether applied
(e) mandatory requirements from Table 1
(f) specify the parameters indicated in Table 2.1 of [3]
(g) select options from Tables 3.1.1, 3.1.2 & 3.1.3 of [3]
(h) at least one of typical or actual to identify the filler metal
(i) at least (if appropriate) one of flux classification or flux trade name to identify the flux
(j) select options from Table 3.3 of [3]
(k) widths of weld zone, HAZ, and (if appropriate) buttered layer(s)

3 CREEP AND RUPTURE TESTING OF WELDS

Creep rupture testing of weldments is much more complex than testing to gain creep and rupture data for a single material. Therefore special considerations should be made. It has to be borne in mind, that the weldment consists of zones with different material behaviour. The different deformation behaviour of these zones may yield stress redistributions or stress enhancement which may cause size and shape dependence of the test result. Therefore before designing a testpiece and the sampling strategy, the aim of the test should be clearly defined. With respect to the aim of test, the influencing parameters discussed in Appendix 1 should be considered.

3.1 Creep and Rupture Testing of Parent metal and Weld Metal

Conventional creep tests can be performed on parent material (PM) and weld metal (WM). The recommendations on testing and pre-assessment of data, as well as the minimum information requirements given in [1] are applicable. Testpieces from all weld metal are sampled as longitudinal weld metal specimens (see Figure 1 of Appendix 1), i.e. in the parallel direction with respect to the weld seam. In order to describe the location of these testpieces, in addition to the information given in [1], the depth below the weld surface, k, as given in Figure 1 of [4] is required.

3.2 Stress Rupture Testing with Cross Weld Specimen

The gauge length (parallel length) of a cross weld specimen may contain one or two regions of parent metal, part or a complete section of weld metal, and one or two heat affected zones. Usually tests with such testpieces are conducted to obtain time to rupture only. Strain measurement may be recorded in order to obtain useful information for the testing procedure or provide results for comparison when determined using similar testpieces (with regard to geometry and type, number and size of weld zones incorporated).

In general the recommended minimum requirements for future creep rupture testing as given in Table 5b of reference [1] are applicable with the exception of a different minimum gauge length (see 3.2.2).

3.2.1 Testpiece sampling

The testpiece should be sampled in a way, that at least one half of the joint is included in the gauge length. This means it contains weld metal and heat affected zones on one side of the joint. In the case of dissimilar welds, heat affected zones may be different. If it is known which side of the joint is the weaker part it is sufficient for the testpiece to contain this side of the joint in the gauge length. Otherwise the whole joint with weld metal and both heat affected zones as well as both parent materials should be included in the gauge length. In special cases a test piece may contain not all zones of a joint. If such tests are carried out, special reporting is required, in particular the metallurgical zones incorporated and the position of these should be reported (see section 3.2 in [4]).

Usually testpieces are sampled with the axes perpendicular to the weld axis (sampling method (a) in Figure 3 of Appendix 1). Another method is to cut the testpiece perpendicular to the fusion line. This is discussed in more detail in Appendix 1.

3.2.2 Shape and size of testpieces

Examples for testpieces applicable for crossweld testing are given in Figure 5 and 6 of Appendix 1. Usually testpieces with a smooth cylindrical shape are used. Others may be applied if necessary.

A minimum diameter of 8 mm is necessary to ensure that crossweld specimen deformation behaviour is representative of the welded joint. If the minimum diameter requirement of 8 mm

cannot be achieved due to limited material thickness and the consequent ratio of fine grained HAZ-width to diameter is large, different necking effects may cause different stress enhancement or stress redistribution and hence influence the rupture time.

A minimum gauge length (parallel length) of at least $5\,d_0$ ensures that there is no influence on stress rupture time (see Appendix 1).

For rupture testing on similar welds a parallel gauge length of

$$L_C = 5\,d_0 + L_s'$$

is recommended (see Figure 4a in Appendix 1).

For a small testpiece diameter or large width of welded zone, exceeding a maximum reference length of $10\,d_0$ should be avoided. In this case, if a symmetrical weld is tested, half of the weld zone should be included in the gauge length (see Figure 4d in Appendix 1).

In order to cater for the possibility of failure in the PM, the testpiece gauge length must contain a considerable length of parent metal. High deformation in the fine grained HAZ may cause stress redistribution in the PM in the direct vicinity of the HAZ. It is therefore recommended that the length of the unaffected PM should not be smaller than $2{,}5\,d_0$. This can be reached, for example, by having the fusion line at mid-length (see Figure 4c).

For special purposes other specimen types may be used (e.g. waisted specimens, see Figure 5 in Appendix 1).

3.2.3   Testing procedure

Uninterrupted or interrupted creep rupture tests can be carried out. The type of test should be noted. The measurement of overall elongation may be advantageous for estimating the rupture time. For large scale specimens the influence of interruptions on the inhomogeneous stress and strain field should be taken into account. From experience it is evident that there is no influence for conventional specimens with diameters up to 12 mm.

3.2.4   Test results and assessment of data

Test results are

- Time to rupture at a given stress and temperature

- Fracture location

- Fracture mechanism

Assessed results are

- Rupture Strength of weldment at given temperature and duration

- Strength reduction factor at temperature for duration, t, relative to that of parent metal

- Time reduction factor for given stress and temperature

Fracture locations should be given according to the designations in Section 4.2 in [4]. In the literature a classification as given in Figure 6 of Appendix 1 is often used.

Fracture mechanism may be obtained by visual or metallographic examination.

Overall elongation with respect to the reference length may be evaluated according to [1] for the purpose of comparison, if tests with testpieces of same size, shape and partitions of HAZ, weld metal and base metal are carried out.

Additional test results which can be assessed are ductility measures and elongation of distinct zones.

If elongation and reduction of area after fracture are recorded as test results, it should be noted that these values are only able to provide a qualitative indication which may be used, for example for the comparison of data determined using similar specimens (with regard to size, shape and number and types of weld zones incorporated).

In order to obtain the elongation of various weld zones, it is recommended to place indentations at a regular distance over the gauge length. If in parallel, a metallographic investigation to determine microstructural zones is prepared, the deformation of these zones can be determined by measuring distances between indentations at the beginning and the end of test.

3.2.5 Minimum Information Requirements

The minimum information requirements as given in Table 4 of Reference [1] are recommended except those which are not applicable (information on strain and rupture ductilities).

In addition to that, information on testpiece location and sampling (as given in Table 2) should be reported in terms given in Section 3 of reference [3]. The information on test results as summarised in Table 3 should be given in terms of Section 4 of reference [4].

Table 3   Additional Minimum and Recommended Welding Testing Information Requirements[a]

CATEGORY	MINIMUM INFORMATION REQUIRED[a]	COMMENTS
Testpiece location	- Depth of testpiece centre line below weld surface - Weld width at centre line of testpiece - **Orientation of testpiece centre line with respect to axes of weldment**[b] - Weld zones in gauge length	 - presence and extent of various metallurgical zones in testpiece gauge length
Test Results	- location	- within/at XXHAZ, WM, FL

NOTES: (a) the reporting of additional information is not precluded, see [2]
        (b) mandatory requirement [3]

4 HAZ SIMULATION

In order to characterise the creep behaviour of individual zones within the heat affected zone, HAZ simulation procedures are applied to base materials. It is generally intended to apply a temperature-time-history as experienced in a distinct sub-region of the HAZ. This can be either measured by inserted thermocouples or predicted numerically, as described in the German code SEW-088. A detailed description of the creep testing of HAZ simulated structures is given in appendix 2.

There are different methods in industrial use to apply the weld thermal cycle, like

a) induction heating and hold at peak temperature with subsequent cooling in an oil bath

b) heating in a hot salt bath until the peak temperature is reached, immediately followed by cooling in a salt bath at about 100°C and

c) HAZ simulation using a Gleeble machine

Method c) gives the best agreement with the actual weld thermal cycle and it is more flexible with the capacity for a larger range of heat inputs. The length of constant microstructure is however limited (about 10mm), which has consequences with respect to the gauge length. Methods a) and b) provide a uniform microstructure along the whole specimen length, the heating rate is however much slower and the applicable cooling time is quite restricted.

4.1 Information requirements for HAZ simulated creep samples

In addition to the information on the base material (see Tables 1 and 2 of Volume 3 Part I), additional information is required for the applied weld thermal cycle, as shown in Table 4.

Table 4: Additional Minimum Information Required for HAZ Simulation

CATEGORY	MINIMUM INFORMATION REQUIRED[a]	COMMENTS
HAZ simulation	- **Method used** [b]	- e.g. induction heating and oil cooling, or salt bath heating and cooling, or Gleeble HAZ simulation
Weld thermal cycle	- **Peak temperature** [b] - Heating rate or heating time to peak temperature - Holding time at peak temperature - **Cooling time between 800 and 500°C** [b] - **Details of multipass HAZ simulation** [b]	- (second peak temperature and cooling time, $t_{8/5}$)
Homogeneity of simulated sample	- Length of uniform microstructure	
Shape and size of testpieces	- See point 3.2.2 and specify gauge length	
Heat treatment	- **Postweld heat treatment used (yes/no)** [b]**,** details	

NOTES: (a) the reporting of additional information is not precluded
(b) mandatory requirement

4.2 Creep and Rupture Testing of HAZ Simulated Specimens

Both creep and creep rupture tests (interrupted and non-interrupted) as well as constant strain rate tests can be used to characterise the creep behaviour of the individual HAZ sub-zones. Especially for Gleeble simulated specimens, it is important to check whether the creep fracture occurred in the homogeneous microstructural length of the sample.

The test results should be reported as specified in Volume 3 Part I.

4.3 Determination of Weak Sub-zones in the Heat Affected Zone

One of the main objectives of creep testing simulated HAZ specimens is to find out the weakest sub-region (="soft zone"). It is therefore recommended to apply a series of different peak temperatures and to draw a plot of hardness or any creep test result as a function of the peak temperature and to compare it with the data of the base material.

It should be noted, that there might be a small influence in the value of the peak temperature of the soft zone, depending on the type of HAZ simulation.

References:

[1]   ECCC Recommendations Volume 3, 2001, 'Recommendations for data acceptability criteria and the generation of creep, creep rupture, stress rupture and stress relaxation data', Part I 'Data acceptability criteria and data generation: Generic recommendations for creep, creep rupture, stress rupture and stress relaxation data', ECCC Document 5224/MC/30 [Issue 5], Edited: J Granacher and S R Holdsworth

[2]   ECCC Recommendations Volume 2, 2001, 'Terms and terminology for use with stress rupture, creep and stress relaxation: Testing, data collation and assessment', Part I 'General terms and terminology and items specific to parent material', ECCC Document 5524/MC/23 [Issue 7], Edited: P F Morris.

[3]   ECCC Recommendations Volume 2, 2001, 'Terms and terminology for use with stress rupture, creep and stress relaxation: Testing, data collation and assessment', Part IIa 'Terms and terminology for welding processes and weld configurations', ECCC Document 0509/MC/39 [Issue 2] Edited: C Servetto

[4]   ECCC Recommendations Volume 2, 2001, 'Terms and terminology for use with stress rupture, creep and stress relaxation: Testing, data collation and assessment', Part IIb 'Terms and terminology for weld creep testing', ECCC Document 0509/MC/40 [Issue 2], Edited: P F Morris

APPENDIX 1

CREEP TESTING OF WELDMENTS: PRACTICES AND INVESTIGATIONS ON THE EFFECTS OF SAMPLING AND SIZE ON CREEP TEST RESULTS FOR WELDMENTS

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Appendix 1

Creep Testing of Weldments: Practices and Investigations into the Effects of Sampling and Size on Creep test results for Weldments

A Klenk, MPA Stuttgart

Content

Abstract

To estimate the life time of components for high temperature application it is important to know the creep behaviour not only of parent metals, but also of weldments. The aim of this work is to provide guidelines which help to determine these data. Investigations are considered to obtain creep behaviour for the whole welded joint (e.g. by means of crossweld specimens) and to determine the specific behaviour of a distinct zone (e.g. heat affected zone). This requires different testing techniques. Creep testing of weldments needs special considerations as to the specimen shape and dimensions, sampling of testpieces from a weldment, and pre-assessment of results.

This Appendix deals with a review of methods and practices for the determination of weldment creep rupture data with standard specimens. Related to this topic are extensive investigations on the applicability and relevance of laboratory data particularly on the description of specimen size and shape effects.

1 Introduction

In general there is a need for creep rupture data for weldments for two different reasons. The first is to characterise the creep behaviour for a welded joint representing all zones of a weld. In this case the test result is the rupture time of the weldment testpiece and the fracture location. Secondly, tests are carried out to determine the specific characteristics of a distinct zone (e.g. the intercritical region of the heat affected zone) to use the determined parameters as input for calculations such as those involving finite element methods in which each zone is modelled using different material characteristics. In this case the specific behaviour of a single zone is of interest.

The sampling locations are given in Figure 1. The specific behaviour of a part of the weldment can be determined with a specimen machined from a single part. Longitudinal weld metal specimens are used to determine the creep behaviour of the weld metal. Testing

procedures for uniaxial creep testing can be applied for the longitudinal weld metal specimens [1].
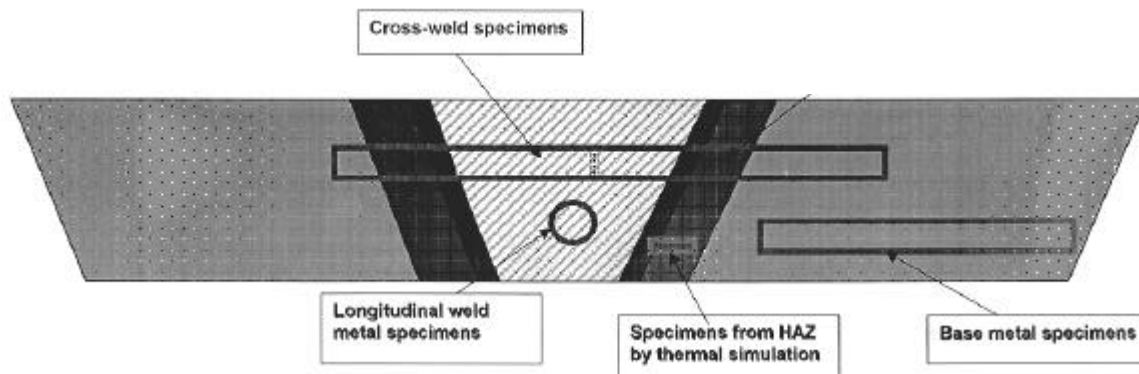

Fig.1 : Locations and specimen sampling in a weld

Cross weld specimens containing all parts of the weldment are used to determine the overall behaviour of a weld.

Often heat affected zones are the most critical metallurgical regions in welded joints. Since these zones are comparatively small one of the following methods must be used to determine the material characteristics
-    miniature specimens like disc creep test specimens or impression creep test specimens
-    specimens machined from simulated material

Miniature specimens are used to determine material constants for the part of the heat affected zone they are machined from. Examples are given in Fig.2 [2]. Special testing techniques, e.g. small punch tests [3] are being developed. These techniques are often aimed at delivering results for life assessment [4]. Investigations on this technique are still under way. A draft code of practise for small punch testing was developed in [3].

HAZ-simulation techniques and needs are discussed in Appendix 2.

In the following, the scope is focussed on sampling, manufacturing and testing of cross weld specimens, and analyses to ensure the relevance of data determined by tests with cross weld specimens. Sampling, shape and size influence the test result obtained with a cross weld specimen.   In this document, experiences mostly based on experimental data combined with numerical analyses are summarised in order to provide a basis for recommendations for shape and size of crossweld specimens and testing procedures. The most important question in this context is whether the stress redistribution in a specimen during creep is similar to that in a component.

H=2.5 W=10

(i): for base and weld

W=10 H=2.5
W=10

(ii): for HAZ

(b): Typical impression creep test specimens
impression creep test specimens

H=0.5 W=9.5

(c): Disc creep test specimen
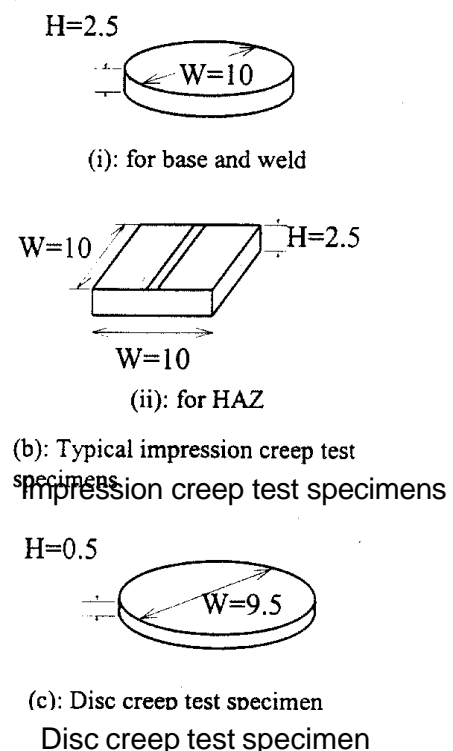Disc creep test specimen

Figure 2: Miniature specimens after Hyde et.al [2]

This means that the influencing effects on the behaviour of a weld in a component should be considered with regard to representation by a testpiece. These effects are
- Differences in strength between base and weld material
- Different microstructures in the HAZ
- Development of zones near the fusion line with change in chemical composition due to diffusion
- Additional thermal stresses due to different dilatation coefficients
- Stress enhancement due to different creep rates in constituent materials
- Residual stresses due to the welding and manufacturing process.

In particular the last three effects can be quite different in a testpiece.

2 Crossweld specimens

2.1 Specimen sampling

In principle, the testpiece can be machined from a weld perpendicular to the symmetry line of the weld (a), or perpendicular to the fusion line (b), Figure 3.
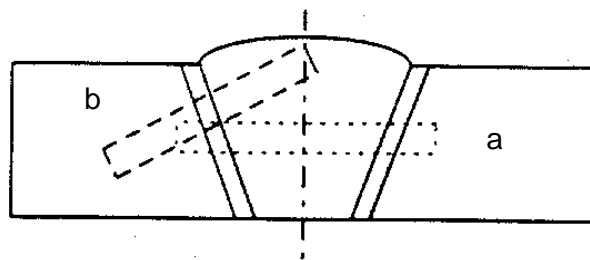
Figure 3: Sampling of cross weld specimens (after [2])

Sampling technique (a) is most common and sampling is comparatively easy. However, this sampling technique raises the following problems:
- The specimen is not symmetrical.
- Weld metal zone and heat affected zone (HAZ) have different relative lengths to the gauge length.
- The differences in material behaviour, in particular different steady state creep rates cause stress enhancement in the specimen which may be different from that in a component.
- It is likely that there are cross-sections in the specimen consisting of different material types (e.g. fine grained + coarse grained heat affected zone material or weld metal + coarse grained heat affected zone). This exacerbates any problems associated with differential creep rates.
Obviously while sampling technique (b) is able to avoid some of these problems, machining is much more complex. For distinct geometries it is not possible to sample the testpiece in this way.
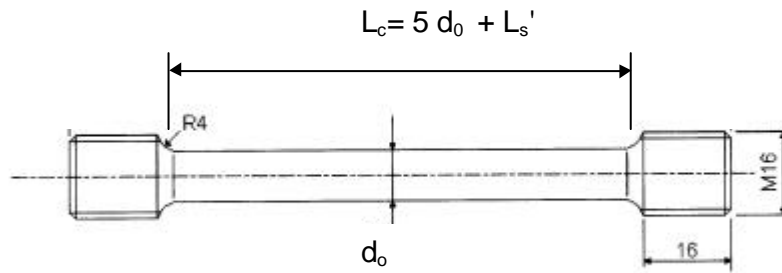
Dependent on the size of welded parts and the specimen size, in particular for sample technique (a), the following configurations may be employed:
- The specimen contains all zones of a weld (weld metal, heat affected zones and base metal. For similar welds it is usually assumed that the weld is symmetrical with respect to the centre-line in the weld metal. For dissimilar welds there are two base metals and two different heat affected zones.
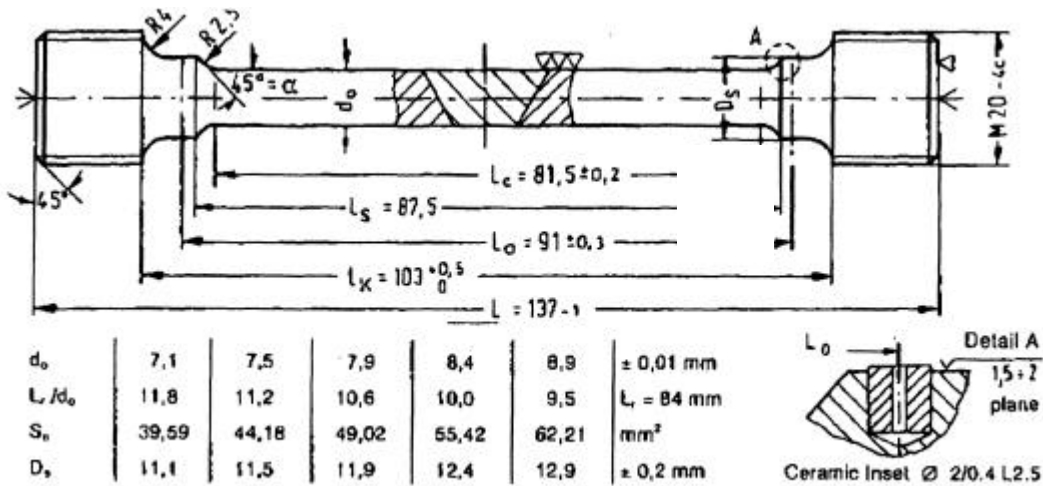- The specimen contains only parts of the weld.
Dependent on these, different stress distributions and creep behaviour will be experienced.

2.2 Specimen forms

Examples for specimens are given in Figures 4 and 5. Beside different sampling techniques the following differences in specimen form can be found.

$$L_c = 5\, d_0 + L_s'$$

a) Smooth specimen for stress rupture tests

d_o	7,1	7,5	7,9	8,4	8,9	± 0,01 mm
L_t/d_o	11,8	11,2	10,6	10,0	9,5	L_t = 84 mm
S_o	39,59	44,18	49,02	55,42	62,21	mm²
D_s	11,1	11,5	11,9	12,4	12,9	± 0,2 mm

Detail A
1,5÷2
plane

Ceramic Inset Ø 2/0.4 L2.5

b) Smooth specimen for stress or creep rupture test (German Arbeitsgemeinschaft Warmfeste Stähle und Hochtemperaturwerkstoffe and IfW Darmstadt)
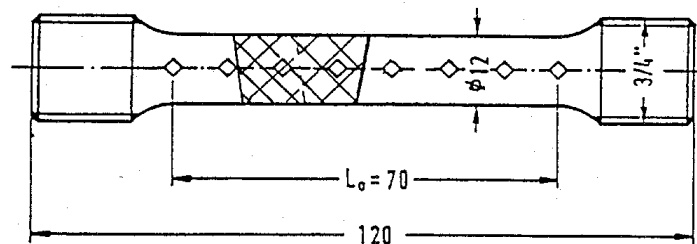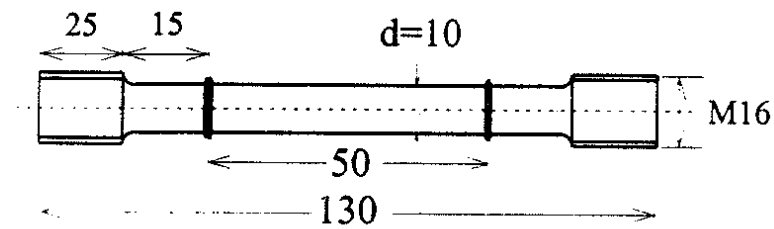

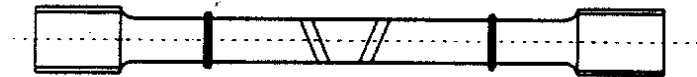c) Smooth specimen with a fusion line exactly mid-length [7,9]
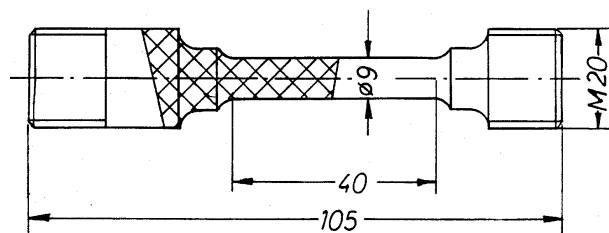
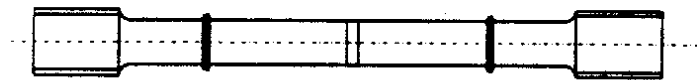d) Smooth specimen containing only one side of symmetrical weld [7,9]

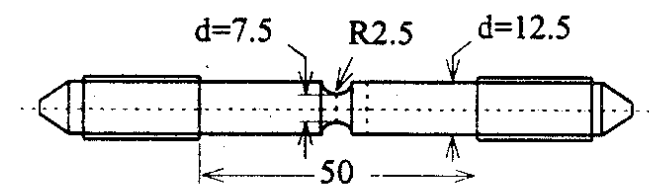Figure 4: Cross weld specimens used in several investigations

25   15   d=10

M16

50

130

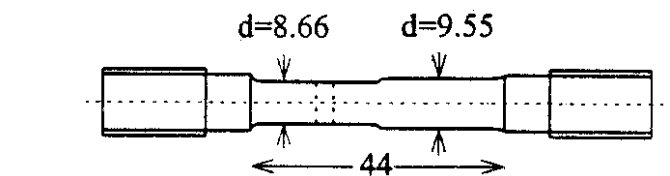(a): A typical uniaxial creep test specimen

(i) specimen axis is at an oblique angle to HAZ

(ii) specimen axis is perpendicular to HAZ

d=7.5   R2.5   d=12.5

50

(iii) notched specimen, with BM to HAZ
interface at centre of notch

d=8.66   d=9.55

44

(iv) Waisted specimen, with BM to HAZ
interface at centre of waisted section

Figure 5: Cross weld specimen types (after [2])

- Different gauge length to diameter ratios
- Different absolute diameters
- Different constituent material volume ratios (HAZ/weld metal/base metal)
- Locations of heat affected zone and weld metal zone in the gauge length.

Unfortunately in publications there are often no details on specimen forms. However, the principal forms given in Figure 4 are most common. A gauge length to diameter ratio of approximately 10 as given in Figure 4 b) was found for example in [5] a gauge length to diameter ratio of approximately 5 was found for example in [6,7,8] for investigations on similar and dissimilar welds.

2.3 Designation of crack location (Types of cracking)

The designations for the characterisation of crack locations are illustrated in Figure 6. According to [10] and [11] the classification of cracks depending on location and orientation of a crack is given as Type I if the crack location is in the weld metal, Type II if the crack starts at the fusion line, Type III if the crack locates in the coarse grained HAZ (CGHAZ) and Type IV if the crack is in the fine grained HAZ (FGHAZ) or the intercritical zone (ICHAZ).
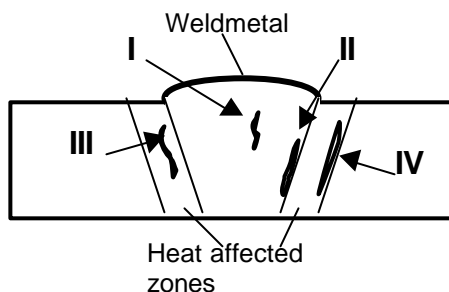

Figure 6: Classification of crack locations

3   Investigations on influencing effects and applicability of uniaxial creep data to weldments in components

The sampling technique has to ensure the applicability of creep data to components. Therefore numerous experimental and numerical investigations have been carried out in order to characterize the effects of size and sampling. Results of large scale tests have been compared to laboratory data. Both investigations have been supported by numerical analyses.

The effect of size and shape on creep test results was discussed in detail in [12]. For a small diameter to gauge length ratio a significant dependence on specimen diameter was found on rupture life, Figure 7. However, if a reasonable gauge length is used this effect is negligible.
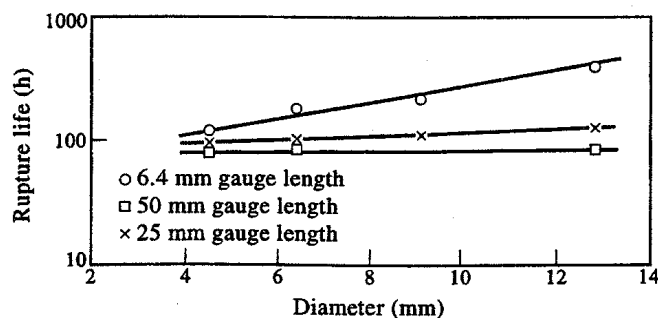

Figure 7: Variations in rupture life with specimen dimensions [12]

The effect of different specimen diameter on elongation and strain, however, was found to be significant, <u>Figure 8</u> for constant load tests for a CrMoV steel. In this case different rupture
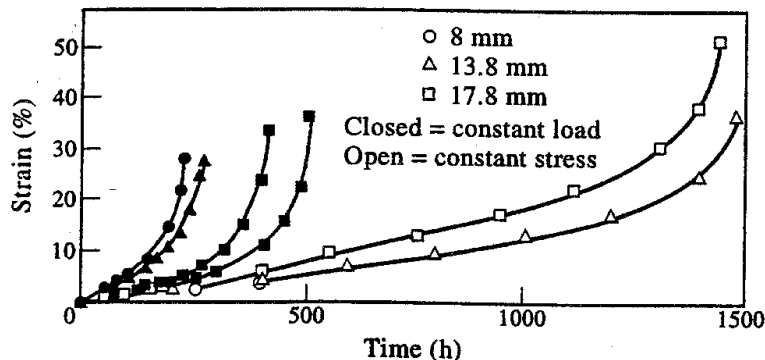

Figure 8: Variation of strain time behaviour with specimen diameter [12]

lives were determined. For stress controlled test the effect was smaller. The difference between stress and load controlled test on rupture lives is larger than the influence of diameter. A comparison of rectangular and cylindrical shape was made, <u>Figure 9</u> Under conditions of a similar area no significant effect of shape has been found.

A summary of cross weld creep data for CrMo, CrMoV and 9 to 12% Cr steels is tabled. A tendency to Type IV cracking for increasing diameter was observed. In general the tendency of increasing rupture life with increasing diameter was confirmed. For P91 material a significant increase of rupture life with increasing cross section area is shown.
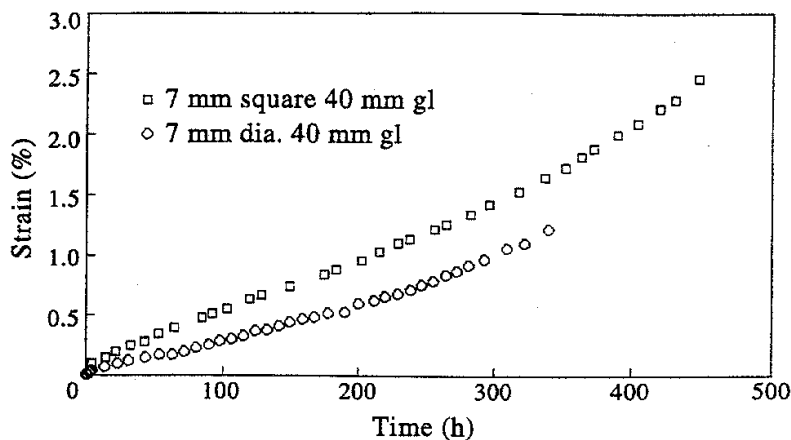

Figure 9: Effect of specimen shape

Parker recommends for the parallel length to add the length of the weld to the normal gauge length of 5 times diameter. This is in accordance to BS 709. An increasing rupture life with increasing cross sectional area of specimen resp. diameter is also found in all other investigations. For an electron beam weldment investigated with standard creep specimens (l=5d), an underestimation of creep strength compared to full thickness specimens was found. A factor of 1.5 to 3 in rupture time was found.

Detailed analyses using a finite element method have been carried out by Storesund and Tu [12]. As a constitutive equation Norton´s law was used applying different constants for each of the four constituents of the weld: parent metal fine grained HAZ, coarse grained HAZ and weld metal. It was found that there is a significant life enhancement with increasing diameter. The location of the maximum stress enhancement in the specimen can also be altered when the diameter is changed. The change of the HAZ width has certain influence on the creep life

of the specimen whereas the change of weld metal width does not show such influence in a practical range. No influence of changing the angle of weld could be seen. This is confirmed in [14] and in agreement with investigations on circumferential welds in pipes [15], Figure 10.

a)   b)
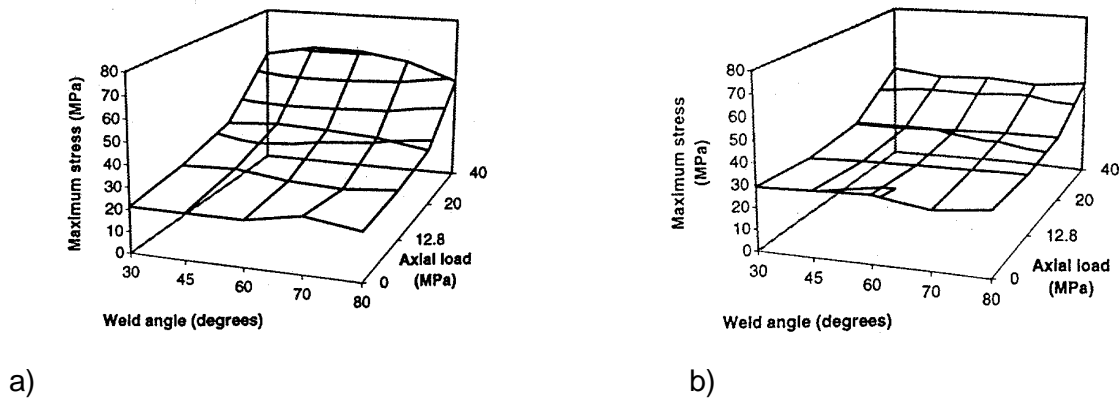
Figure 10: Stresses in HAZ (a) and weld metal zone (b) for different weld angles [15].

In order to provide a method to analyse laboratory data and component data in a similar way and thus make the lab data applicable to components Hyde, Tang and Sun [2] used an analytical method with a reference stress based on limit load solution for determination of stress enhancement in the weld zones. Comparison to finite element calculations showed, that with the analytical method only approximate solutions could be obtained.

Experimental tests with large scale specimens, Figure 11, have been carried out [7] and have been analysed by finite element method, Figure 12, for 12%Cr steel welds and dissimilar welds 12%Cr/1%Cr.

For the similar welds, a migration of the rupture location from base metal into the fine-grained HAZ was observed with decreasing nominal stress. It could be stated, that the creep rupture strength of the welded joint was beyond that of the weakest HAZ microstructure (simulated specimens). For dissimilar welds, the large-scale specimens exhibited longer creep rupture times than the laboratory specimens, Figure 13. Results of the finite element calculations showed that in large-scale specimens the stress- and strain redistribution due to creep is slower than in small scale specimen which is caused by a higher constraint in large-scale specimens, Figure 14.

1 % CrMoV Base Metal   12 % Cr Base Metal

12 % Cr Deposit

30

110

90

M120x4

R15

135

290

12 % Cr Deposit

HAZ 1
HAZ 2
HAZ 3
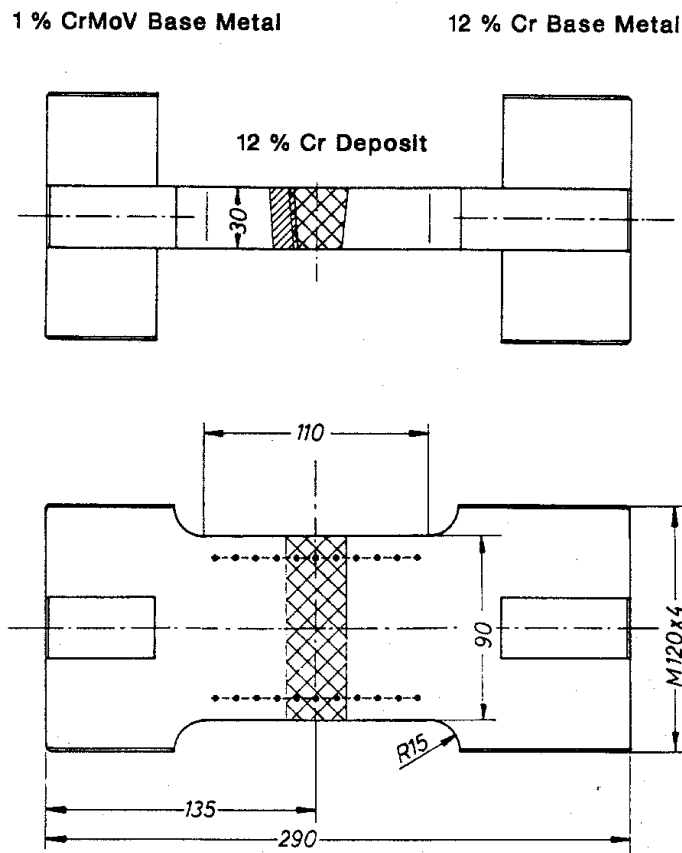
1 % CrMoV Base Metal

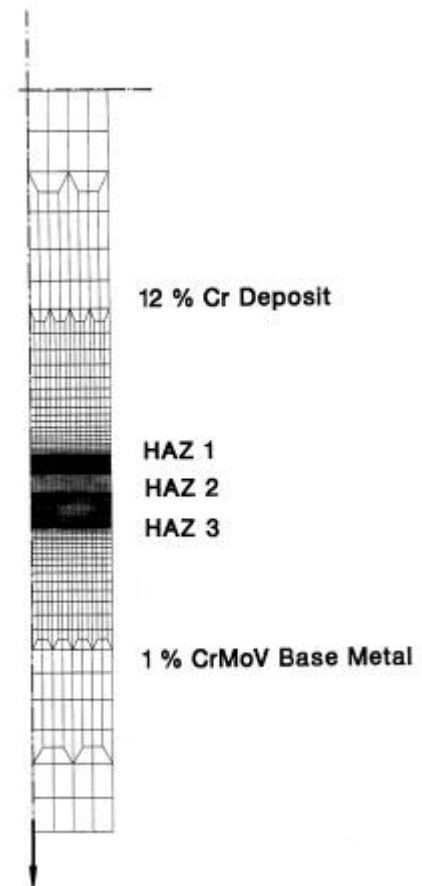Fig.11 Large scale specimens   Fig. 12: Finite element model.
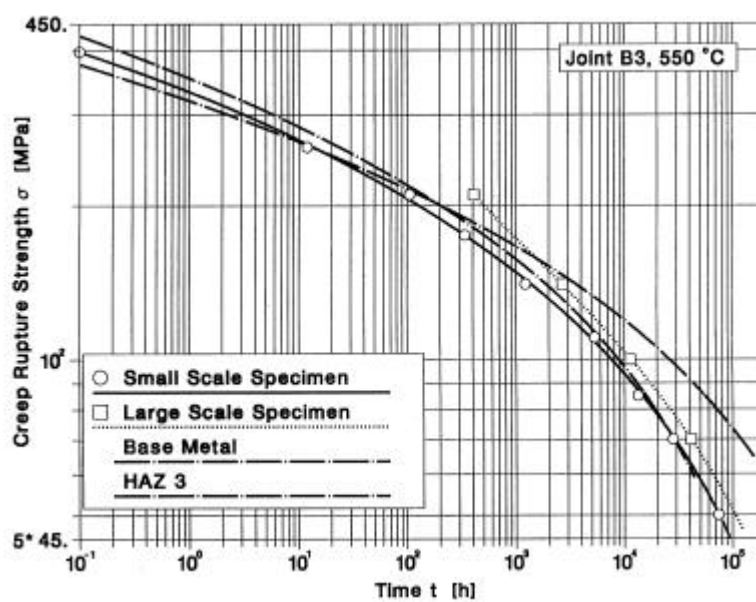
Figure 13: Influence of specimen size on creep rupture time of dissimilar welds [7]
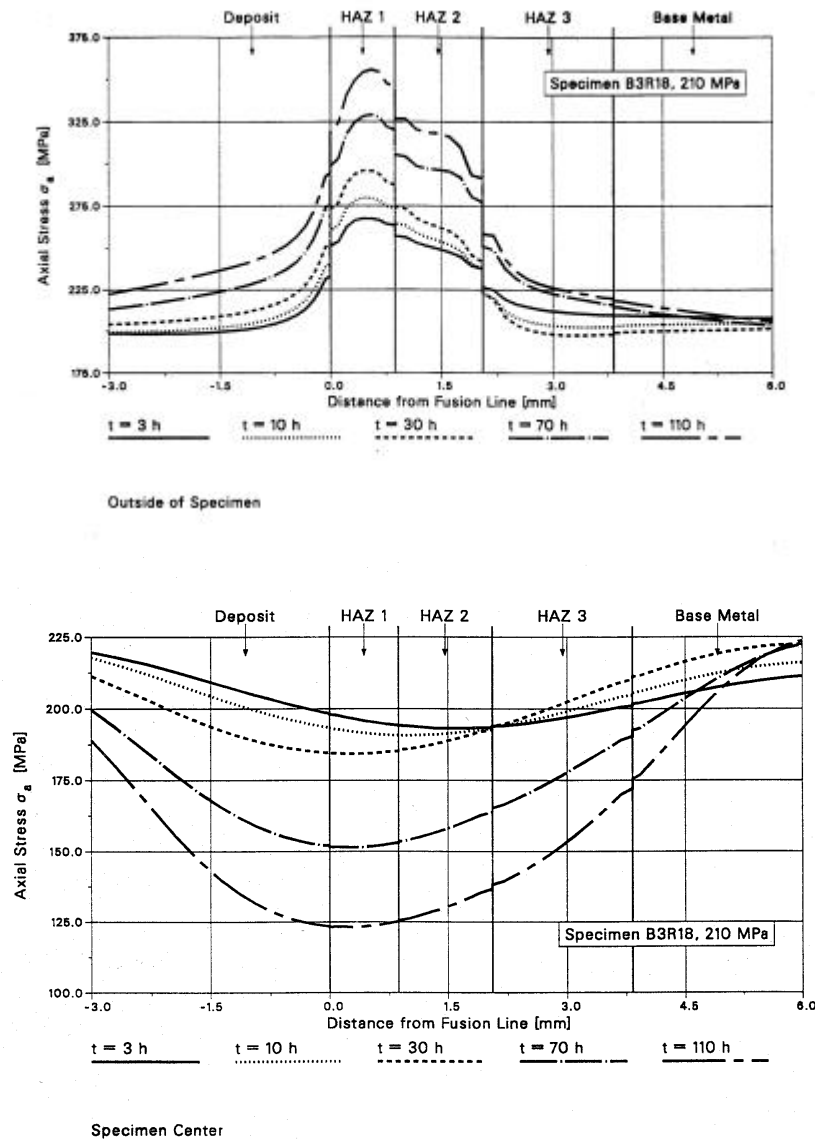
Outside of Specimen

Specimen Center

Figure 14: Axial stress distribution in large scale specimen at specimen centre and near outer surface

4 Concluding remarks

The needs and difficulties in weld creep testing are discussed. Currently used specimen forms are given. Investigations on the influence of specimen shape and size have been reviewed. There is a tendency for increasing rupture life with increasing diameter respectively cross sectional area. The size of heat affected zone influences creep test results as well as the partitions of the different weld zones in the parallel length of the sampled specimens. Detailed numerical and experimental analyses with large scale testpieces show that large geometries normally have longer rupture lives and a slower redistribution of stresses. Based on these findings the recommendations given in the main part of this document have been derived.

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12

APPENDIX 2

CHARACTERISATION OF THE CREEP BEHAVIOUR OF WELDMENTS BY HAZ-SIMULATION

B Buchmayr [TU Graz]

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Appendix 2

Characterisation of the creep behaviour of weldments by HAZ-Simulation

Bruno Buchmayr, TU Graz, Dept. Materials Science, Welding and Forming

CONTENT

Abstract

The behaviour of weldments under creep loading is mainly tested using cylindrical specimens taken from cross welded weldments. As an alternative, creep testing of HAZ-simulated structures is also done in order to characterise the individual subzones within the heat affected zone. The main advantage of this procedure is, that gradual changes in the creep behaviour of the heat affected zone or even soft zones can be determined. Compared to miniature samples, a larger volume is produced, which ensures a lower scatter of the test results. In this report, various HAZ simulation techniques are described and compared, but the main focus will be on Gleeble testing. Details of creep testing of HAZ simulated specimen are shown. The additional gained information is discussed with special emphasis on the comparability with the behaviour of real weldments. The advantages and disadvantages of creep testing of HAZ simulated structures are considered and critically assessed. Creep data on HAZ simulated specimens of 1CrMoV and 9-12% chromium steels are shown as an example. The necessity of such data for FEM calculations is also emphasised.

1. Introduction

The quantification of the creep behaviour of weldments is much more challenging compared to the base material, because of the heterogeneity of the microstructure in the weld metal, in the heat affected zone and the adjacent base material in a rather narrow range. Typically, creep samples are taken from cross welded specimens, where the gauge length includes the weld metal as well as the HAZ and some base metal on both sides of the weld. The determination of any meaningful measurement of the elongation is quite doubtful. In addition to the conventional testing of weldments, 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 transferred to a specimen, so that the testing volume is significantly enlarged, which should reduce the influence of surrounding zones and therefore the scatter. In this report the general procedure of HAZ simulation and creep testing of HAZ-simulated samples is documented, including some remarks on the beneficial and crucial aspects of this kind of testing. By comparison of the creep rupture behaviour of HAZ simulated structures with cross samples taken from weldments, the possibilities for data transfers are considered. Furthermore, the available information in the open literature is referred to. Some case studies of some heat resistant steel grades (1CrMoV, P91, P92) are considered in detail. Finally, the use of creep data on HAZ simulated specimens for finite element calculation of the creep behaviour of real components as in power plants is discussed.

2. Principles of HAZ simulation

The mechanical properties including also the creep properties of a weldment depend on manifold influencing parameters, which have to be taken into account. Figure 1 shows a simplified matrix of various weldability aspects, their interactions and influencing parameters.
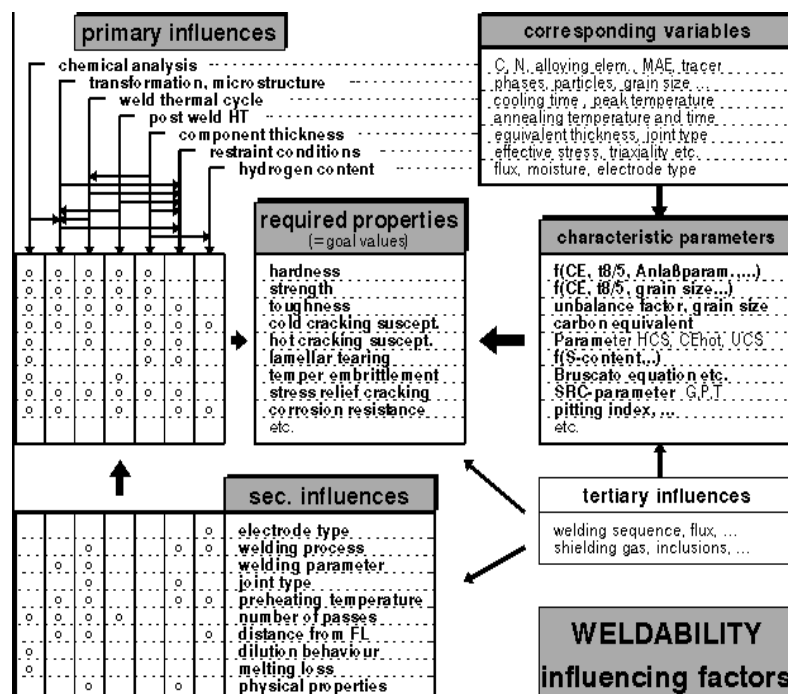

Figure 1: Influencing factors and characteristic parameters regarding the weldability of steels.

As illustrated, there are a variety of influencing and interacting parameters, which are not easy to keep in mind during an assessment, therefore previous attempts have been focussed to combine single influencing factors to so-called „characteristic parameters" for a particular aspect. Most of these parametric equations are based on multiple regression analysis of large experimental data sets.

The basic idea of HAZ simulation is to take into account the most important parameters, whereas disturbing parameters are eliminated as far as possible. In order to investigate the influence of the most important welding parameters on the resulting mechanical properties, the principle route, as shown in figure 2, is applied. 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 itself is influenced by the austenite grain size. The austenite grain size is given 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.
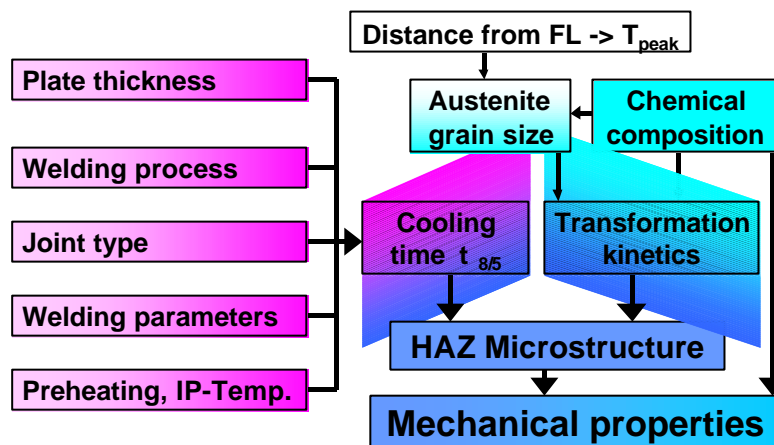
Figure 2: Coupling of the most influencing factors on the HAZ properties in a logical way

3. Determination of the weld thermal cycle

There are many means to calculate the weld thermal cycle, as summarised in figure 3.

1. **Analytical Solution**   (**Rosenthal** , **Rykalin**) $T - T_o = \dfrac{E/v}{2 \cdot p \cdot l \cdot r \cdot t} \cdot \exp(-r/4at)$

2. **Analytical Solution for modified heat sources**

3. **Cooling time concept**   **t8/5 (SEW088)** $t_{8/5} = \dfrac{h \cdot E}{2 \cdot p \cdot l} \cdot \left[\dfrac{1}{500 - T_o} - \dfrac{1}{800 - T_o} \right] \cdot F_3$

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**) $[C] \cdot \left\{ \dot{T} \right\} + [K] \cdot \{T\} = \left\{ \dot{Q} \right\}$
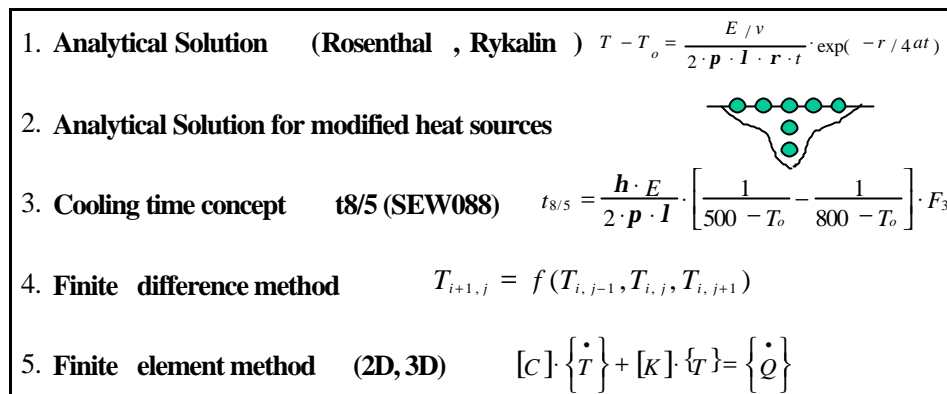
Figure 3: Approaches mainly used for the calculation of the weld thermal cycle

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. There are two principle cases, firstly, when the heat flow is two-dimensional (thin sheet) and secondly, when it is three-dimensional (thick plate). Therefore the first step is to calculate the transition plate thickness for two or three-dimensional heat flow. Further details are given in SEW088. At TU Graz, the author developed a computerised software package to perform the prediction of the weld thermal cycle. The computer package is called "HAZ-calculator" [1], which is available via DVS Düsseldorf. The main menu of this software is shown in figure 4. The thermal cycle is calculated using routine 4, base on the SEW-approach. The input parameters and the final result is shown in figure 5 and 6.


```
Main Menu - HAZ-CALCULATOR  *   M A T - W E L D - S O F T   Graz, Austria

                                                 Mechanical Properties
 1 Transformation Temp.     11 Carbon Equivalents     21 BM /  Pickering
 2 BM Structure / Hardness  12 Preheating Temperature 22 BM /   Gladman
 3 BM Crit. Cooling Rates   13 HAZ-Index /Implant Str. 23 BM /  Masubuchi
 4 Weld Thermal Cycle,t8/5  14 Crit. Hardness / t8/5  24 HAZ / Seyffarth
 5 Peak Temperature vs. HAZ 15 Hot Cracking Severity  25 WM(CMn) / Evans
 6 Electron Beam Welding    16 Lamellar Tearing        26 WM Hardness
 7 HAZ Structure / Hardness 17 SAW Melting Rate        27 SRC Parameter
 8 HAZ Hardness (atanh)     18 Nugget or Fused Area    28 PWHT Parameter
 9 HAZ Hardness (Dueren)    19 Diffusion Data/Calc.    29 Temper Embrittl.
10 Welding CCT Diagram      20 Solubility Products     30 Toughness

41 Thermal Cycle t8/5,tl2/8 44 Delta-Ferrite Determin. 47 Pitting Index
42 Schaeffler Diagram       45 Ms-/Md30-Temperature    48 Sensitiz. Time
43 DeLong Diagram           46 Dilution                49 Mechan. Propert.

60 REFERENCES (List)        70 USER SPECIFIED FILES    80 WELDABILITY
65 MULT.REGRESS.ANALYSIS    75 XY-PLOT (user defined)  85 STANDARDS

<RETURN> ---> input form,              type <99> ---> start menu

     Your Choice :  0
```

Figure 4: Main Menu of software "HAZ-Calculator", developed at TU Graz

Figure 5: Calculation routine 4 "Weld thermal cycle" in the software HAZ-Calculator
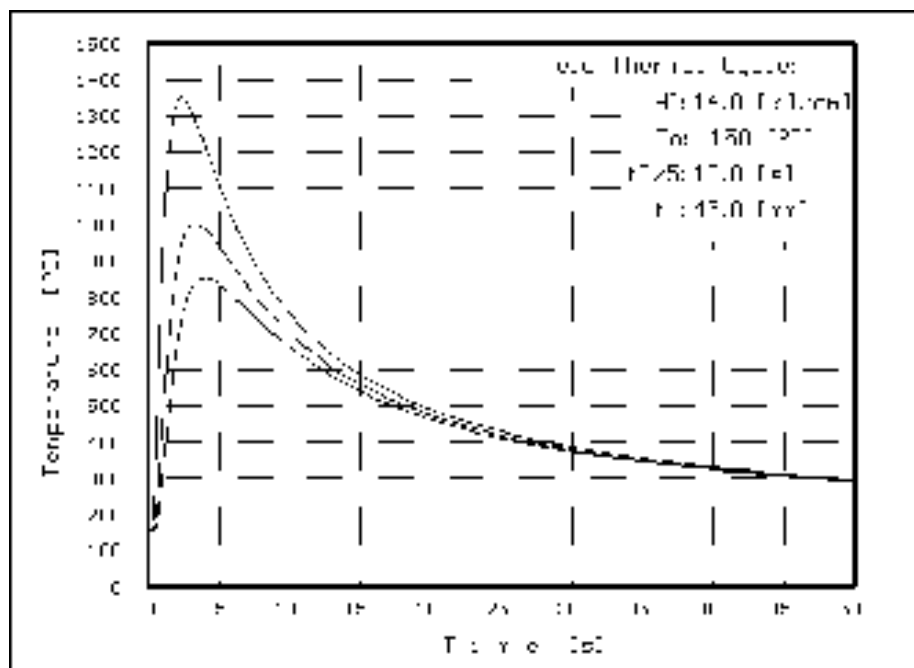

Figure 6: Calculated weld thermal cycles for one cooling time t $_{8/5}$ and three peak temperatures

By definition one can predict the cooling time $t_{8/5}$ from various sets of information, like from
arc voltage, welding current and welding speed, preheating temperature and plate thickness,
heat input, preheating temperature and plate thickness,
electrode diameter and runout ratio and
electrode diameter and fused area.

For the graphic presentation of the whole thermal cycle, the user has to define the peak
temperatures or the distance from the fusion line.

This information about the weld thermal cycle is then used as digitised input parameters for the Gleeble machine. By application of one temperature-time-cycle, one particular subzone in the HAZ under given welding conditions can be simulated. Usually, one needs variations of heat input or cooling time and peak temperature.

In other cases (e.g. for austenitic stainless steels, aluminium etc.), the Rosenthal equation has to be used, whereby some adjustments should be done to improve the accuracy. An example is given in figure 7, using the computer algebra system Mathcad.
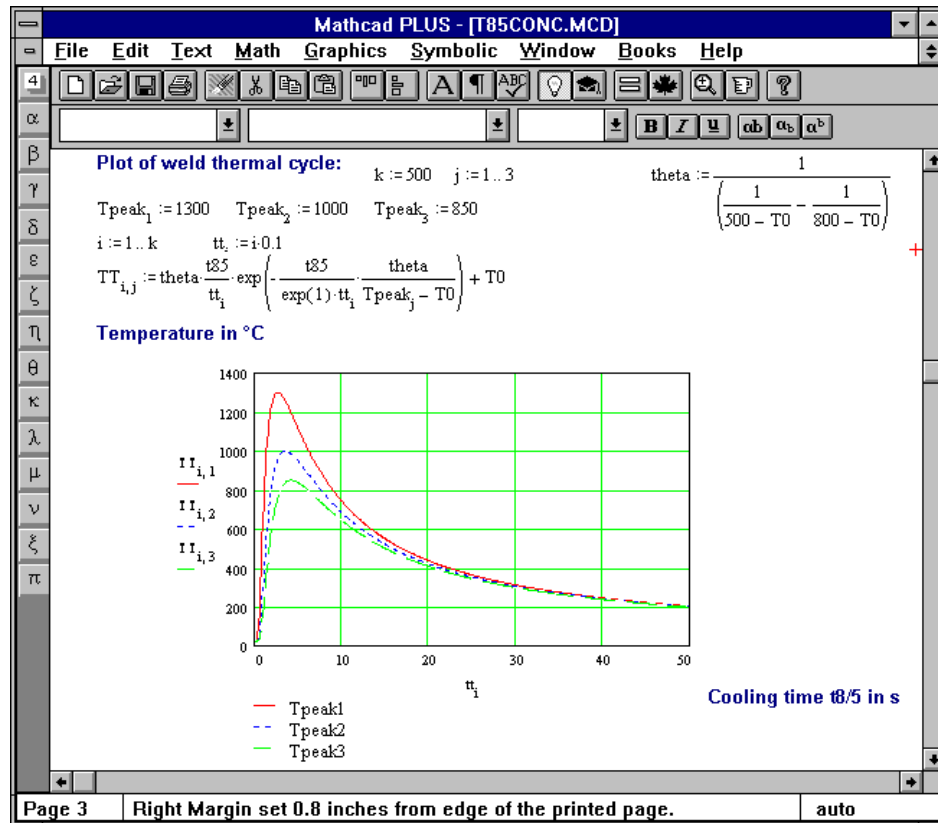

Figure 7: Algebraic calculation of the weld thermal cycle using Mathcad

4. HAZ simulation procedures

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.

The main objective of all these techniques is to apply the weld thermal cycle as measurable in a distinct subregion of the HAZ to a sample with larger testing volume. In the following these methods are described.

4.1 GLEEBLE welding simulation

Gleeble simulation is a very useful tool for the determination of the microstructure in the heat affected zone. By the controlled application of thermal and/or thermomechanical cycles according to a particular weldment geometry and the welding parameters, nearly every position in the weldment can be produced representatively and the microstructure can be investigated using conventional or sophisticated skilful techniques.

The Gleeble system is a fully interfaced system, readily programmed to provide reference signals for closed loop control of both thermal and mechanical operations. Heating is accomplished by the flow of low-frequency alternating current in the specimen with heating rates up to 10000 K/s. The feedback signal necessary for closed-loop control is normally obtained from a fine wire thermocouple percussion welded to the specimen surface.

In order to determine a specific (creep) property of a particular region in the HAZ, the weld thermal cycle (determined as described in chapter 3) is fed in the control computer and a cylindrical samples is heated up very rapidly to the desired peak temperature by direct current flow with up to 6000A. The cooling is provided by the heat flow through the copper jaws. At slow cooling rates, the given T-t-curve is very well controlled, faster cooling rates can be reached by reducing the free span between the jaws or by external gas cooling. Figure 8 shows the weld thermal cycles which were applied for weldability tests of 9-12% Cr-steels regarding the likelihood of „type IV"-cracking.
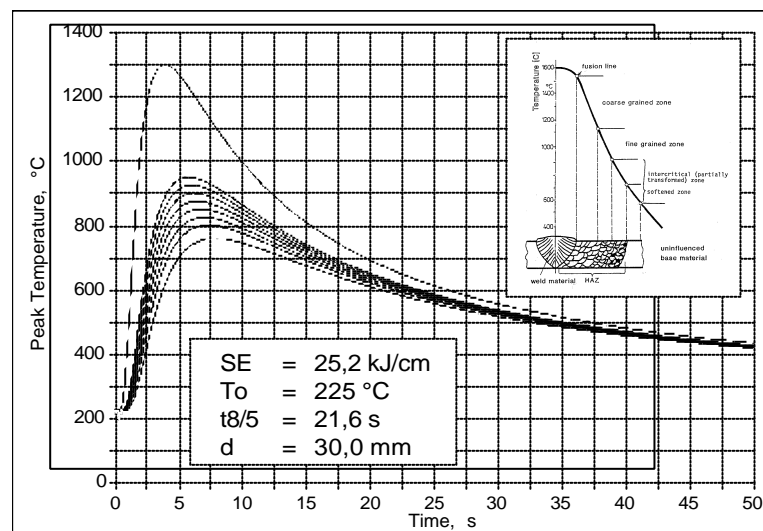

Figure 8: Weld thermal cycles for the coarse-grained zone and in the vicinity of the
intercritical zone for given welding parameters.

The resulting microstructure in the middle of the test specimen, where the thermocouple is located, is then exactly the same as in a real weldment at the considered position.

The advantages of Gleeble weldability testing can be summarised as follows:
- accurate application and measurement of the thermal cycle for a predefined location in the HAZ
- after simulation, an enlarged volume for further metallographic investigations or mechanical tests is available compared to the limited size in a real weldment
- due to the larger volume and higher homogeneity of the simulated microstructures, there is a reduced scatter of the HAZ properties
- phase transformations during welding can be measured by thermal analysis or dilatometric measurement of the C-strain
- in addition, mechanical stresses during the cooling phase can be superimposed in order to simulate any contraction of the surrounding material
- The mechanical material properties during cooling from high temperatures can be directly measured for input in finite element calculations.
- Other combined thermomechanical tests can be applied, like reheating relaxation test, hot ductility test, partly-melting and afterwards cooling to simulated the behaviour of the weld metal.

Some pitfalls are however:
- The temperature profile in longitudinal direction causes some experimental troubles.
- Effects of local gradients in microstructure, properties and residual stresses are not taken into account when using the HAZ simulation technique.
A quite common procedure for weldability Gleeble testing is illustrated in figure 9.

Typical sample geometry for Gleeble testing
Due to the high electric power available (max. current is about 6000A), specimens up to 16mm can be used. At TU Graz, typically round specimens with a diameter of 10mm is used for HAZ simulation. The typical length is about 140mm. Depending on the further testing procedures, there are also other geometries possible (also rectangular geometries). For any thermo-mechanical simulation, the specimen is fixed by a thread of about M10, M12 or M14.

The most important aspect is related with the temperature profile along the Gleeble specimen. Due to heat flow into the jaws there is a considerable temperature profile. The situation can only be changed by using less conducting jaw material and longer free span.

Usually, there is only a range of up to 10mm in the middle, where the temperature is almost constant. That means, that for any further evaluation and further testing (like creep rupture testing), the simulated specimen has to be turned in the middle, to reduce the nominal diameter and to favour that the specimen will brake at a position where the conditions are well controlled. This also means, that a limited gauge length (10mm) has to be used, compared to other standardised specimens.
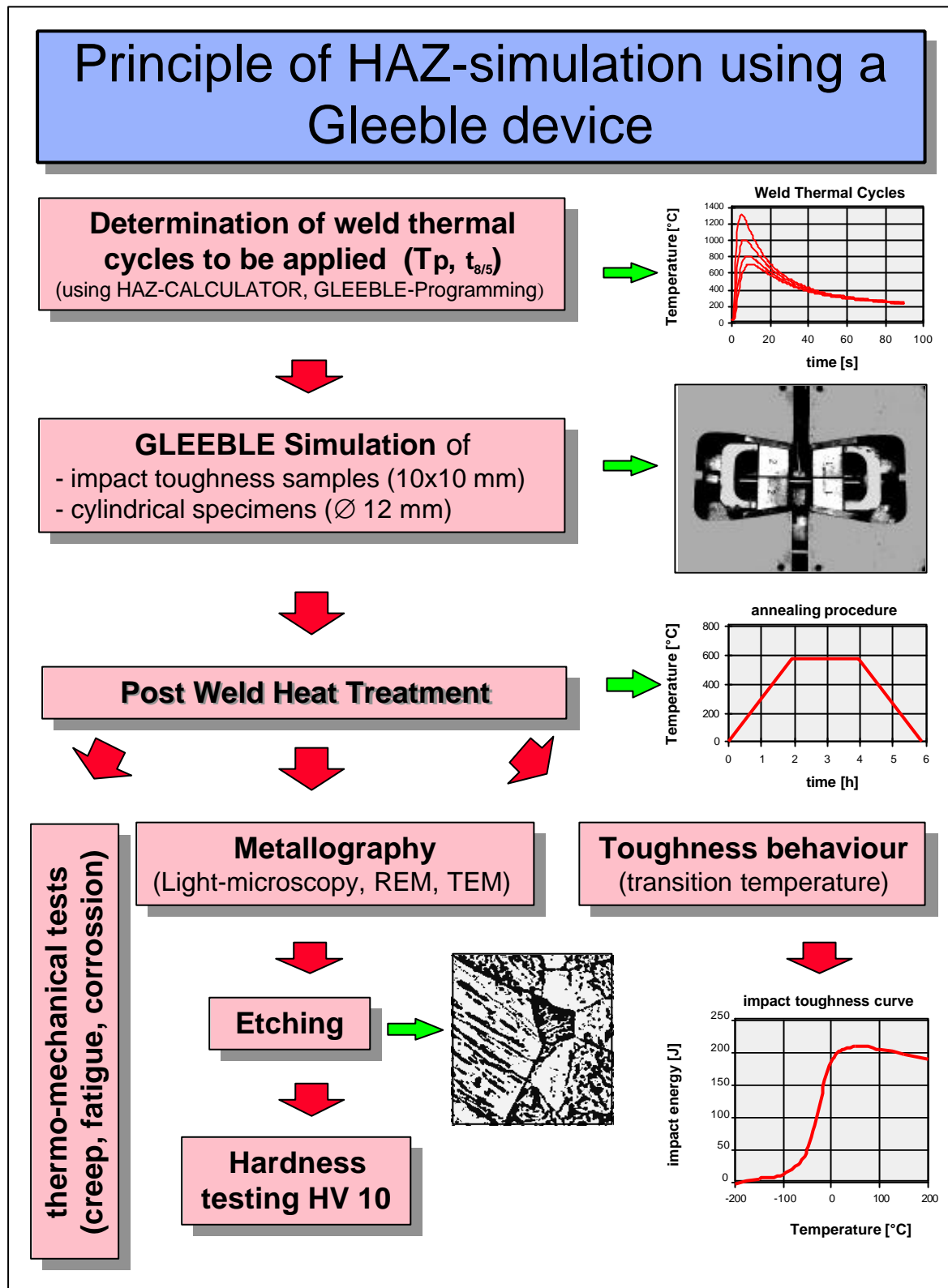
Figure 9: Typical procedure for GLEEBLE weldability testing and subsequent property determinations.

4.2 Induction heating and oil quenching

The HAZ simulation, as applied by MPA Stuttgart, is performed by means of inductive overheating. The used testbars are $\varnothing 20$ mm x 180 mm in length. After heating up in a coil (heating time up to 1300°C is 35 s) and hold at peak temperature for some seconds, they are dropped into an oil bath. Here, the typical cooling time after 1300 °C peak-temperature is 10 s for the range from 800 to 500 °C ($t_{8/5}$). The homogenous structure in the testbars has a length of 70 mm, so that normal tensile specimens can be removed, see figure 10.
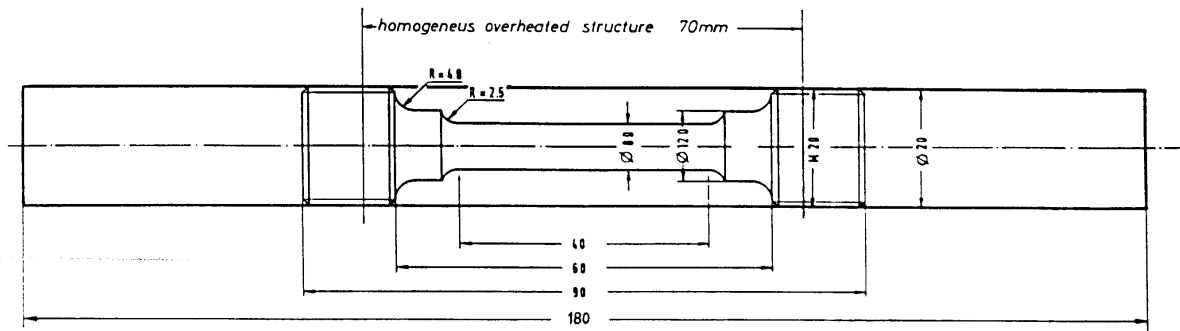

Figure 10 : Shape of overheating testbar and creep specimen

The investigations are mainly concerned with the determination of creep properties. Additional mechanical and technological tests at the same test material can be performed, to characterise the HAZ structures. The case study in chapter 5.1 was done by this manner.

4.3 Salt bath heating and quenching

At the research centre of Mannesmann, a rough machined specimen is heated up by a hot salt bath, corresponding to the desired peak temperature. After the specimen has reached the peak temperature, the specimen is transferred to another salt bath having a much lower temperature (about 100°C). By variation of size and temperature of the second salt bath, different cooling times can be realised. From the simulated sample with uniform microstructure, creep specimen similar as in figure 10 can be machined.

4.4 Comparison of the HAZ simulation techniques

The table 1 points out the main differences in the three considered HAZ simulation techniques.
From this comparison, it can be concluded, that HAZ simulation using a Gleeble machine is most flexible and controllable. The other two methods are mainly used for larger testing samples and series or for first screening tests.
Small deviations may occur in situations, where the time above Ac_1- or Ac_3-temperature has some effect on the resulting creep properties, like in cases of particle dissolution.

Feature	Gleeble simulation	Induction heating + oil quenching	Salt bath heating + salt bath cooling
heating rate	high, as in HAZ	slower as in HAZ	slower as in HAZ
peak temperature	exact programmable	exact controllable	exact when using TC
holding time at peak temperature	rounded T-t-curve as numerically predicted	some seconds	none
cooling rate	programmable	given by oil temperature and sample size	determined by salt bath temperature and sample size
homogeneity of microstructure	only in a short length of about 10mm	over the whole length constant structure	over the whole length constant structure
gauge length	reduced	as for base material	as for base material
reproducibility	high	moderate	moderate
agreement with distinct HAZ structure	excellent	good	good
consideration of constraint effects	possible by applying of mechanical loading	not done	impossible
additional data measurable	dilation measurement	none	none
simulation costs and duration	high	low	low

Table 1: Comparison of different HAZ simulation techniques

5. Comparison between the behaviour of real weldments and HAZ simulated structures

5.1 Creep behaviour of 1CrMoV HAZ structures

As a case study, investigations on 1CrMoV (cast) steel [2] are described. The creep tests of HAZ simulated samples with different peak temperatures were carried out at 550 °C. In figure 11 the rupture-elongation values are plotted versus rupture time for all structures, while figure 12 shows the creep rupture curves, together with the scatter band for base material 1CrMoV for comparison reasons. The coarse grained microstructure 1300/S shows the worst (< 2 %) rupture elongation, but has the highest creep strength. The fracture curves of refined microstructures (840/S and 900/S) lie below the scatter band, their rupture elongations show the highest values (> 30 %).
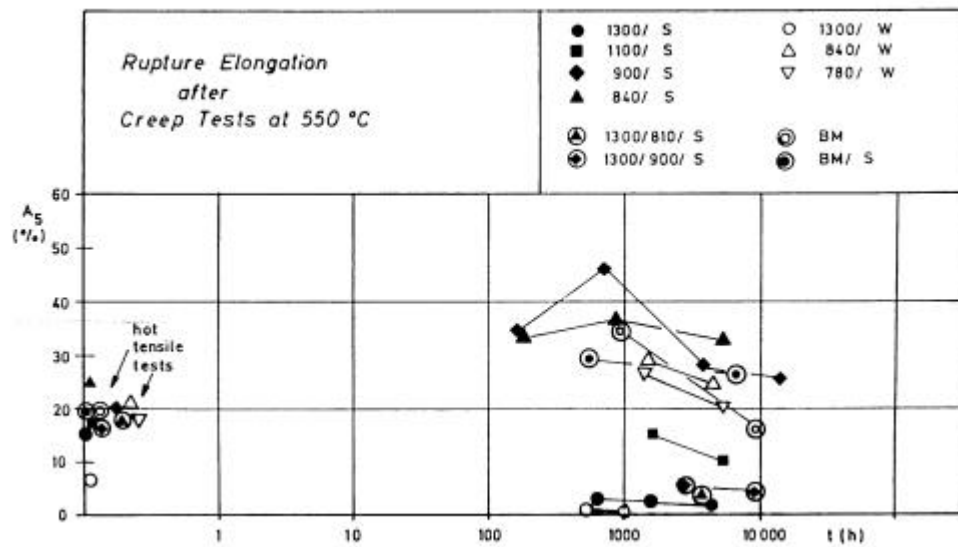
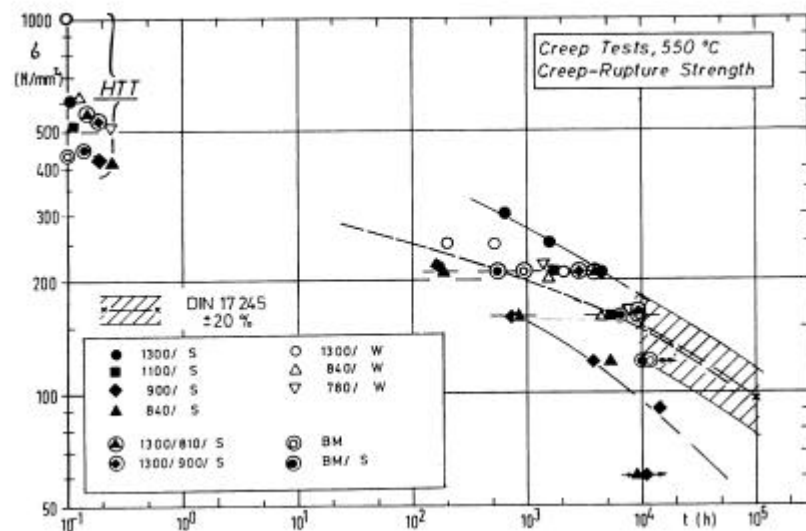Figure 11: Rupture elongation behaviour of a 1CrMoV cast steel

Figure 12: Comparison of creep rupture strength for different microstructures

In figure 13 for various HAZ-structures, having different peak temperatures, the rupture strength for specific times are compared with the lower BM-scatter band values for the same times to failure. For peak temperatures from 800 to nearly 1100 °C the isochrones are lower than the scatter band value. Figure 14 shows the minimum creep rate over the stress for the various structures. This leads to results in a broad scatter band with higher creep rates at the fine grained microstructures and lower creep rates at the coarse grained microstructures, the base material is situated in between. The influence of the different peak temperatures on the creep rate is shown in figure 15. Regarding the band of curves with equivalent stress, the reason for the lowest creep strength of fine grained microstructures ($T_p \leq 900$ °C) becomes obvious.
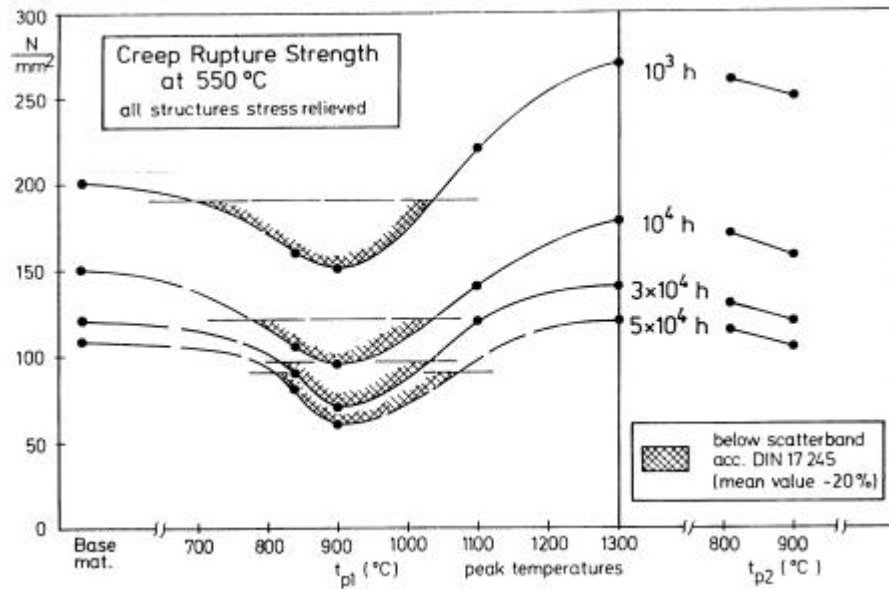
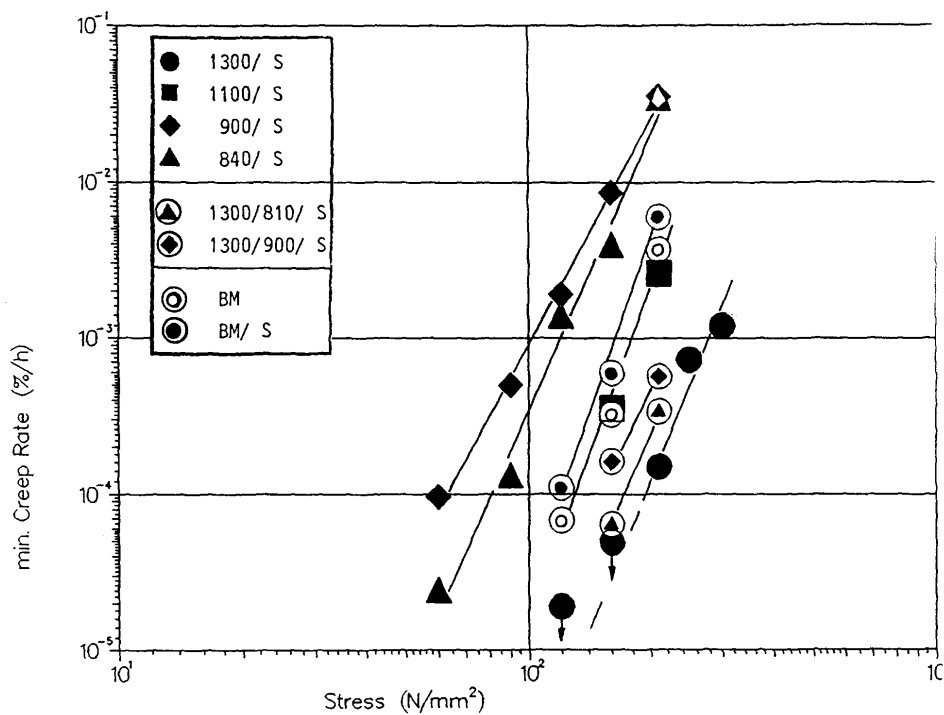Figure 13: Influence of peak temperature on creep rupture strength of 1CrMoV steel

Figure 14:Influence of peak temperature on minimum creep rate

The results show, that the fine grained microstructures have the lowest creep strength, which lies considerably below the one of base material. The coarse grained microstructures show higher creep strength up to the investigated medium rupture time, however the deformation capability is drastically reduced. In the real weld, the particular areas of the HAZ are connected with one another. Due to stress redistribution and multiaxial stress state, the creep deformation capability in the various areas of HAZ may be influenced. A low ductility rupture may occur.
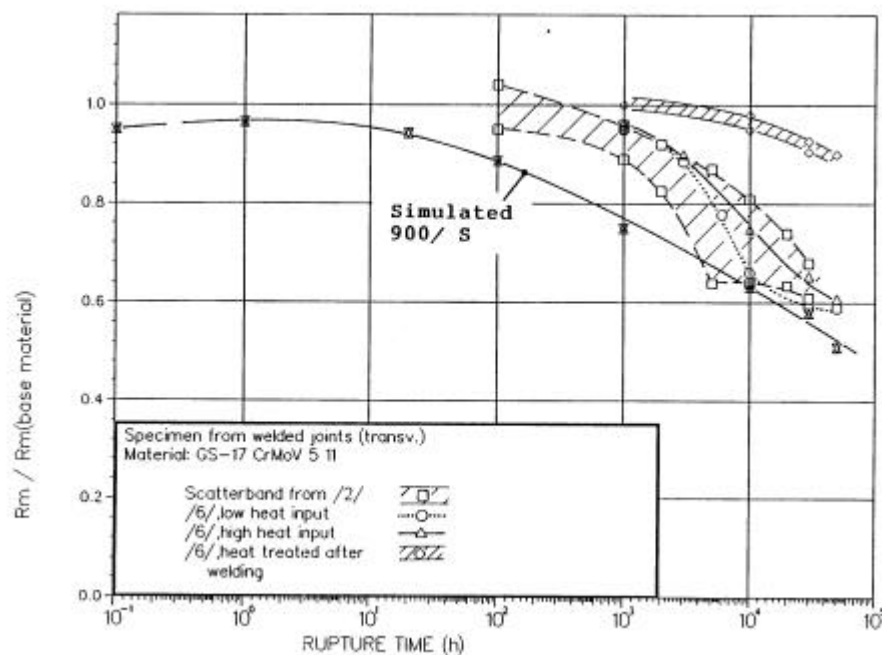
Figure 15: Relative creep rupture strength of welded joints related to
stress relieved base material

With increasing rupture times or lower stresses respectively, the appearing plastic strains at loading and in the primary creep range become smaller. Stress redistribution and consequently a removal of stresses for HAZ-areas with lower creep strength is smaller. The observations at creep specimens and damaged real weldments show, that damage and fracture appear in the fine grained HAZ. With the knowledge of time-dependent deformation and damage history in the various microstructures of the HAZ, it is possible to predict the stress redistribution and the failure location and, consequently, the rupture time in weldments by means of finite element calculations.

Since at longer rupture times rupture occurs in the fine grained HAZ, the creep rupture curve of this zone ought to be the lowest boundary for joint specimens. In figure 15 the ratio of creep strength from joint specimens to the respective base material for different 1CrMoV-materials is plotted. For longer rupture times (>10 000 h) they always lie above the curve of the microstructure which was simulated with a peak temperature of 900°C. To estimate the maximum decrease in creep rupture strength of joints used in the high temperature regime, it is advisable to carry out creep tests with respective overheated simulated base material. The results of these tests complete the usual tests of joints in form of specimens taken from real and sample weldments.

5.2 GLEEBLE weldability tests on advanced 9-12% chromium steels

As part of the European COST-501/III programme „Materials for advanced steam cycles", basic investigations on the weldability and long-time creep behaviour of advanced 9-12%Cr were performed at TU Graz [3]. Welding simulation using a Gleeble device was applied on pipes of P91, E911 and a tungsten containing cast steel G-X12CrMoWVNbN 10 1 1. The creep rupture behaviour of the base material P91 and X20CrMoV 12 1 is compared with the creep rupture strength of crossweld specimens in figure 16 [4]. It is obvious that the creep rupture strength of crossweld samples is significantly lower at higher temperature than that of the base material.

Gleeble simulations representing the manual metal arc welding process were applied to produce HAZ simulated microstructures. The cooling time between 800°C and 500°C was 21.6 s, see figure 8. Special attention was laid on the evaluation of the soft zone in the HAZ by metallographic investigations, using light microscopy and TEM, hardness tests, and constant strain rate tests. In addition, long-time creep rupture tests were performed to study the effect of the soft zone, which usually determines the locus of creep fracture.
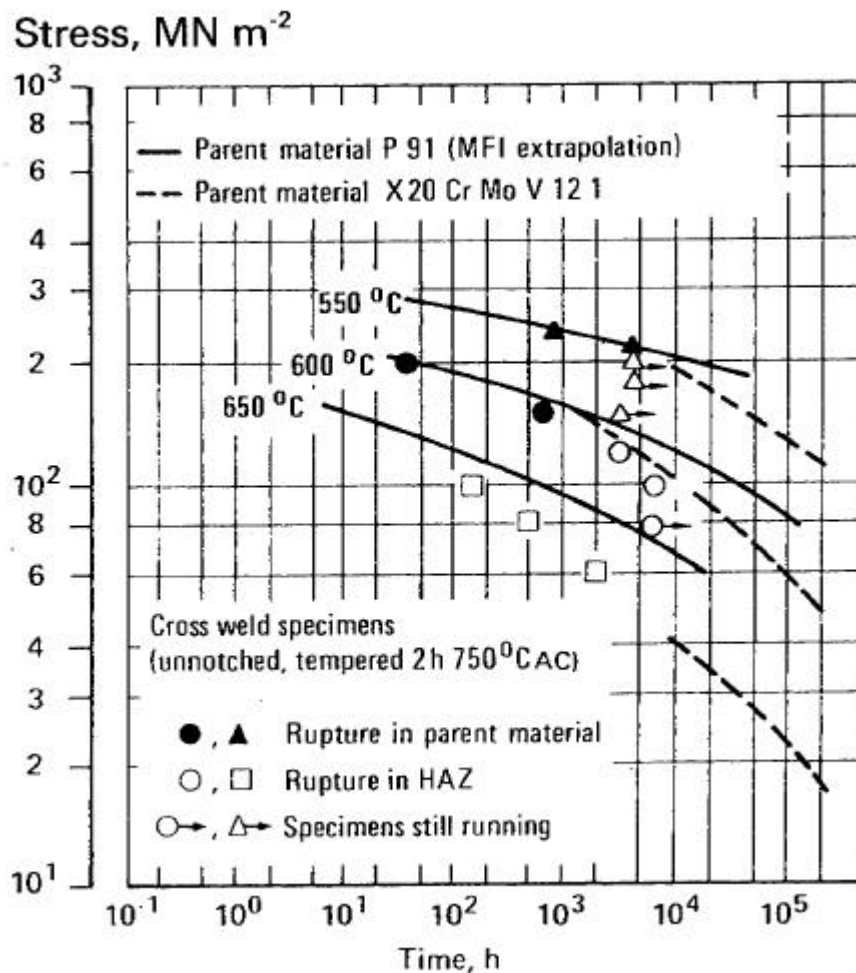

Figure 16: Creep rupture strength of base material and crossweld specimens of pipe steel P91 and X20CrMoV 12 1 [4].

The experiments revealed clearly that the creep strength drop in tungsten modified steel grades is less pronounced than in steel grade P91. This result was found in simulated samples as well as in real weldments.

5.2.1 Hardness profile

Hardness profiles across a weld seam of material P91 show clearly a tendency to form a soft zone in the fine grained HAZ after post-weld heat treatment (PWHT), see figure 17. The hardness in this particular zone is about 20 HV lower than in the unaffected base material. The hardness profiles of steel grades E911 and G-X12CrMoWVNbN 10 1 1 show a similar curve to that of P91. To define the zone in which maximum softening occurs, specimens were subjected to a HAZ simulation at different peak temperatures in the range between 760 and 950°C. The hardness was tested in the as-welded, simulated, and in the simulated and tempered condition. The tempering conditions after welding were 760°C/2 h air cooled for P91, 760°C/2 h for E911, and 730°C/12 h for G-X12CrMoWVNbN 10 1 1.
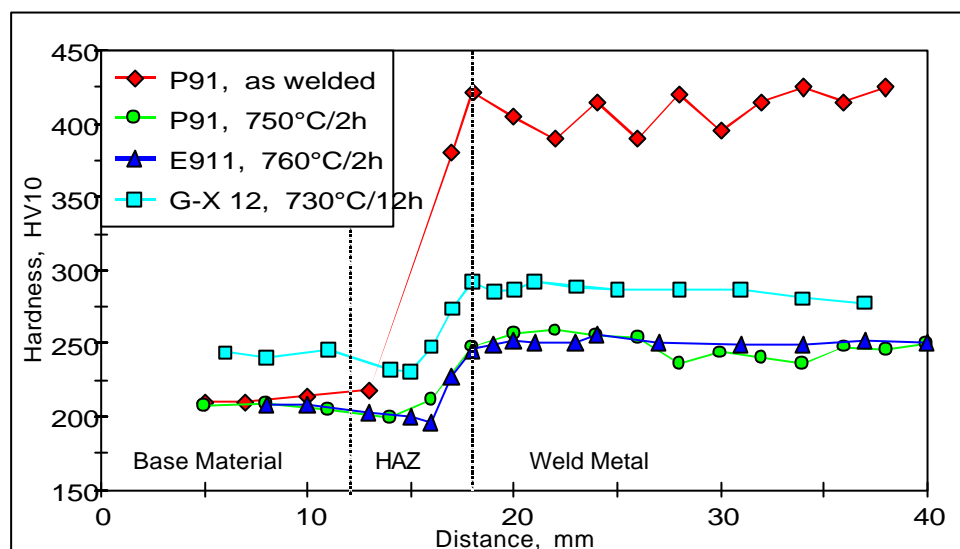

Figure 17: Hardness of weld seam in as-welded condition and after various post-weld heat treatments of P91, E911, and G-X12CrMoWVNbN 10 1 1[3].

The results of the hardness tests performed on the weld simulated microstructures of the three materials are presented in figure 18 as a function of the peak temperature for both the tempered and as-welded condition. The hardness of the base materials tested is shown on the left side of figure 18. It is not influenced by thermal cycles with peak temperatures up to about 850°C. The beginning α/γ-transformation as a function of heat cycles can be observed by the increase of hardness in the as-welded condition. After stress relieving, the hardening effect disappears and a small hardness drop of about 10 HV can be detected for peak temperatures between 850 and 950°C.
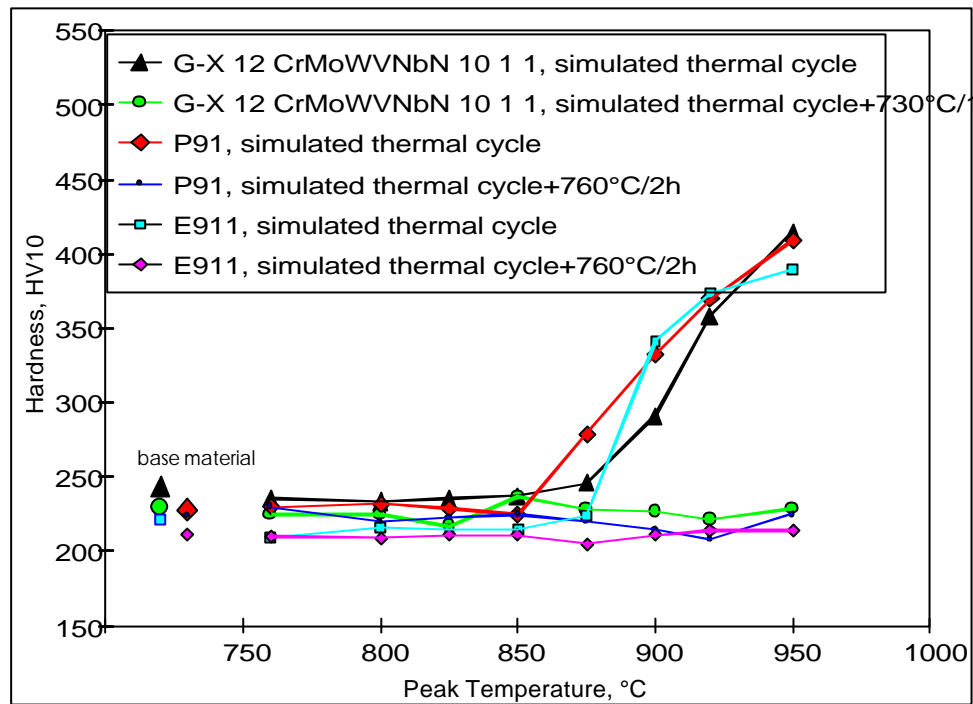
Figure 18: Results of hardness measurements on specimens of P91, E911, and G-X 12 CrMoWVNbN 10 1 1 subjected to weld thermal cycle simulations (determination of soft, intercritical zone) [3].

5.2.2 Constant strain rate tests on HAZ simulated materials

Constant strain rate tests at 600°C with $\dot{e} = 10^{-5}$ s^{-1} were applied on specimens which have been subjected to HAZ simulation and subsequent tempering to investigate the principal influence of the HAZ softening effect on the creep resistance. This test method was first applied on this type of steel in [5]. The maximum stress gives an indication of the creep resistance of the micro-structures tested. The results of these tests, performed at 600°C on microstructures produced by weld simulation with different peak temperatures, are shown in figure 19. For the unaffected base material P91 a maximum stress of 280 N/mm^2 and for G-X12CrMoWVNbN 10 1 1 a stress of 260 N/mm^2 was measured. For peak temperatures in the range of 875-920°C, there is a significant decrease in the maximum stress, analogous with the decrease in hardness. The minimum in the stress versus peak temperature curve is for P91 at 250 MNm^{-2} and 920°C, and for G-X12CrMoWVNbN 10 1 1 at 240 MNm^{-2} and 875°C. The measured minimum of stress is about 10% lower than that measured for the unaffected base material. The investigation of material E911 is still in progress.
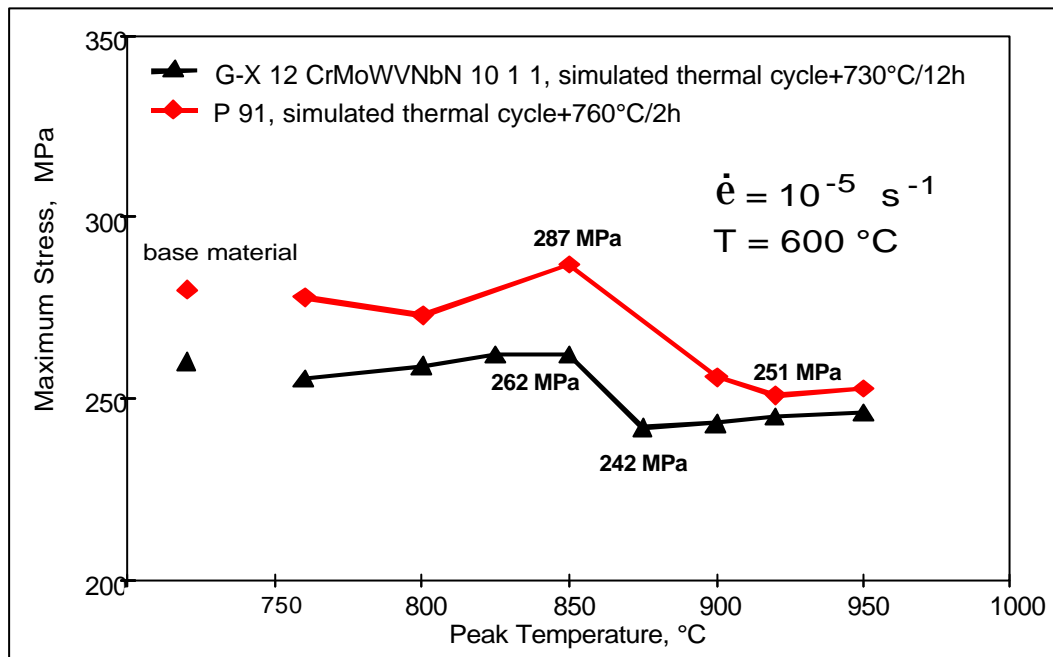
Figure 19: Results of constant strain rate tests on specimens of P91 and
G-X12CrMoWVNbN 10 11 subjected to weld thermal cycle simulation followed by tempering.

5.2.3 Microstructural aspects

As described in [6], the microstructure of the normalised and tempered P91 steel consists of tempered martensite with a large amount of $M_{23}C_6$ and MX precipitates. Microscopic examination of the specimens subjected to HAZ simulation thermal cycles revealed no significant change in the microstructures when the peak temperature did not exceed 850°C. When the peak temperature becomes higher than the AC_1 temperature, depending on the shape of the thermal cycle, more and more austenite will be formed and transformed into martensite during cooling to room or preheating temperature. When heating up to 920°C, the amount of martensite which was found under given conditions of our tests is about 70-90%. At this temperature, slightly above AC_1, and the short times caused by the weld thermal cycle, no significant amount of precipitates and hence carbon and nitrogen go into solution. Therefore, the martensite formed under these conditions lacks carbon. This is confirmed by the increase in hardness caused by higher peak temperatures. Since very small amounts of carbon go into solution at these peak temperatures, the reprecipitation of $M_{23}C_6$ carbides and MX carbonitrides during the subsequent tempering treatment is very limited. In addition, the coherent MX particles coarsen and coagulate and lose their strengthening effect to a large extent. These effects also create a higher tendency towards recrystallisation in this area which, in connection with the overaging of the precipitates, results in a significant softening of these fine grained zones of the HAZ which were heated up to 900-950°C during the weld thermal cycle after PWHT.

5.2.4 Creep rupture tests on HAZ simulated materials

Creep rupture tests were performed on samples which were designed to represent material containing micro-structures caused by a peak temperature of 920°C (HAZ simulated). The results are shown in figure 20 and are compared with results obtained on creep samples made from uninfluenced base material and welded joints. As can be seen, the creep resistance of plain HAZ

simulated materials falls for all investigated materials at high stress levels, significantly below the creep resistance of that of the uninfluenced base material and of welded joints.
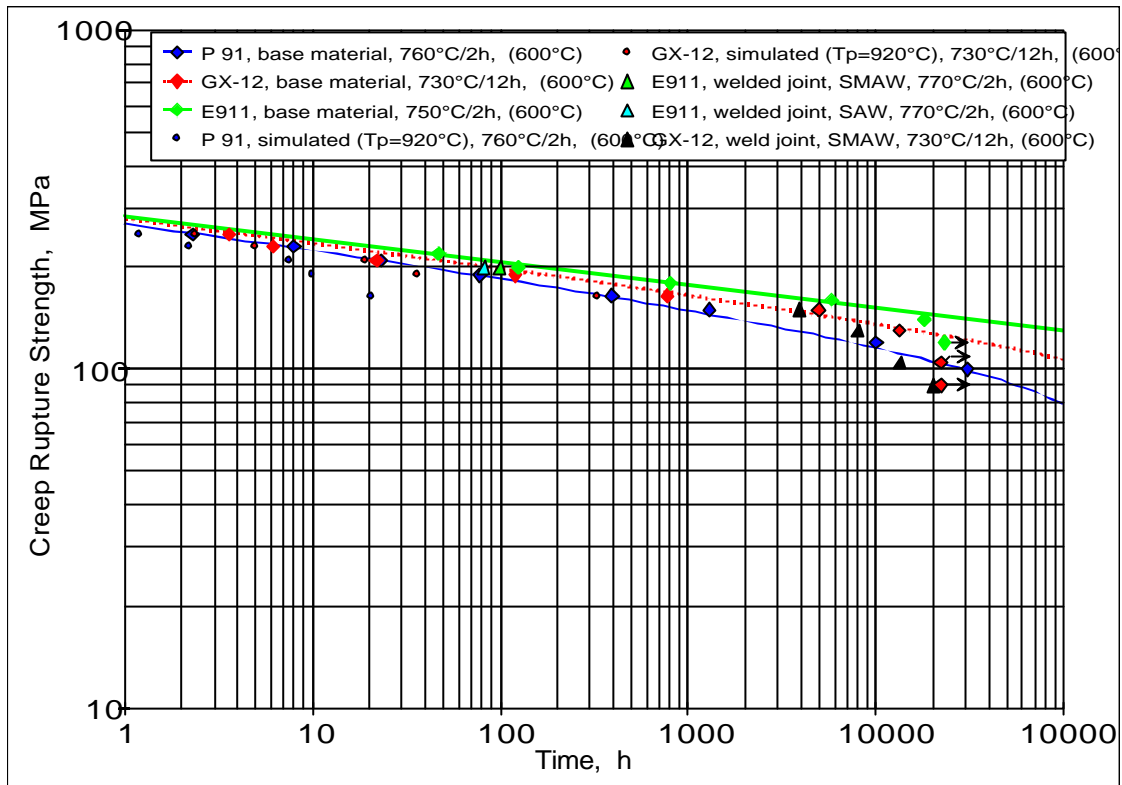

Figure 20: Results of creep rupture tests of P91, E911, and G-X12CrMoWVNbN 10 1 1 base material, welded joint and soft zone HAZ simulated materials [3].

Comparing the behaviour of HAZ simulated material P91 to HAZ simulated materials E911 and G-X12CrMoWVNbN 10 1 1 it can be seen that the softening effect in the tungsten modified casting material on the creep behaviour, at high stress levels, is lower than that of material P91. Creep tests performed on original welded and stress relieved samples of the cast steel show similar behaviour. At high stress levels the creep resistance of HAZ simulated samples lay below that of the base material. As a result of the restraining effect in the HAZ region, the creep rupture strength of welded joints are at the same level as that of the base material. At lower stress levels, HAZ simulated materials and welded joints show the same creep resistance.

5.2.5 Creep rupture tests on crossweld samples

The current status of the creep tests at 600°C with a testing time of 30.000 hours is shown in figure 20. The cast steel G-X12CrMoWVNbN 10 1 1 and pipe version E911 appears to have a creep strength which is at least as high as that of modified 9%CrMo steel P91. Crossweld samples of the repair weld (code E) of the pilot valve body was tested. At high stress levels the fracture is located in the base material. As the applied stress decreases and the rupture time increases, the fracture location shifts from the base material into the fine grained region in the HAZ. Results of microstructural investigation and hardness tests of broken creep rupture samples are shown in figure 21.

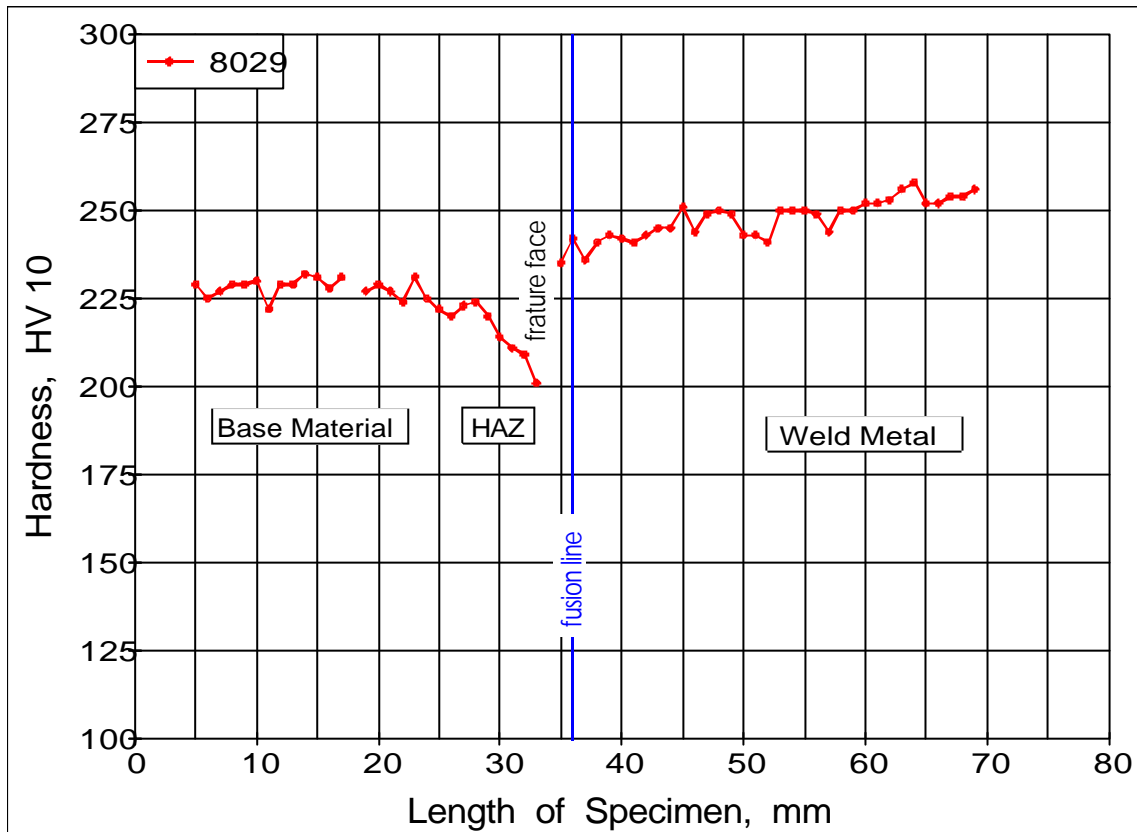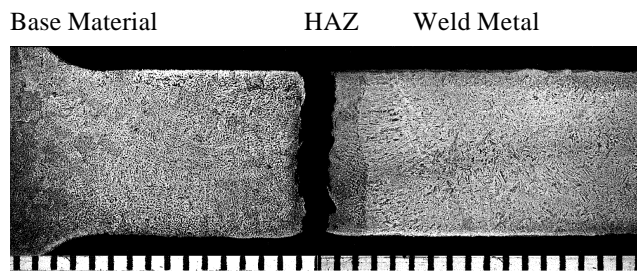Base Material   HAZ   Weld Metal

Figure 21: Fracture location and hardness profile of a crossweld sample using G-X12CrMoWVNbN 10 11 base material and Cromocord 10M filler metal (test conditions: T=600°C, σ=75MNm^{-2}, t_f=20.175 h)

5.2.6 Conclusions about the weldability of 9-12%Cr steels

Previous investigations have shown that the weldability of the heat resistant material P91 can be described as very satisfactory. Although, in the HAZ a drop in the creep resistance can be observed. Compared to the base material a loss of creep resistance measured in crossweld samples of welded P91 material of about 20-25% have to be taken into account. Basic investigations using mainly the Gleeble HAZ simulation technique revealed that this drop in the creep resistance occurred in the fine grained area of the HAZ, where the peak temperature reached a level of about 900-950°C. The aim of the work was to investigate whether newly developed tungsten containing materials, with higher creep resistance than P91 material, show similar behaviour in the welded condition. The results obtained revealed that the behaviour of the tungsten modified 10% chromium cast material G-X12CrMoWVNbN 10 1 1 shows similar

behaviour regarding the creep resistance in the HAZ to P91. Hardness tests, constant strain rate tests, and short time creep tests on HAZ simulated microstructures showed that also in tungsten modified 9-10%Cr creep resistant steels a drop of the creep strengths in the welded area have to be taken into account. The first results of HAZ simulated short time creep tests showed that this drop is less than observed in P91 pipe material. At stresses lower than 150 MNm^{-2}, the fracture location shifts from the base material into the softened fine grained HAZ. At 600°C the data points of the weldments are below those of the base material by more than 25%. In the design of welded components made from this type of materials, this effect must be taken into account.

6. HAZ simulation to generate constitutive creep equations for FEM calculations

Fundamental experimental creep tests on HAZ-simulated samples, as described above, are a necessary information for any numerical model in order to extent the findings to other boundary conditions or special cases. Although the fundamental equations to describe the physical metallurgy of welding related phenomena are known, it would be just an academic exercise without experimental support by e.g. Gleeble testing. Due to the versatile flexibility of the Gleeble device, the material behaviour can be determined in a state (like directly after solidification) where the properties differ widely in comparison e.g. with heating up tests without prior melting. Also the free combination between thermal and mechanical loading is a quite powerful possibility for any welding research activity. The exact definition and application of the testing conditions together with very accurate measurements of the material response allows to provide special model parameters and on the other hand, the verification of any numerical result obtained by finite element models. An example of FEM-modelling of the creep behaviour in the HAZ with data from HAZ-simulated creep samples is given in ref. [7,8].

7. Conclusion

Weldability tests by physical based methods, like by the Gleeble device, provide valuable information to the scientists as well as to welding engineers. Due to the rapid heating rate, the accurate setting of any thermo-mechanical loading condition and the accurate measurement of the material response under rather complex testing conditions, very detailed information can be gathered, which allows further developments of the base and weld materials as well as the welding procedure (see also [9]). The versatile applicability and the feasibility to enlarge very small HAZ regions in order to allow other material tests favours this physical simulation techniques in comparison with other weldability tests.

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