3rd International Conference on Integrity of High Temperature Welds, 24-26 April 2007, pp.399-408, IOM Communications Ltd., London, ISBN 1-86125-166-1.

Welding Procedures and Type IV Cracking Tendency – an Experimental Study

J A Francis*, W Mazur† and H K D H Bhadeshia#

* University of Manchester, United Kingdom
School of Materials, Grosvenor Street, Manchester M1 7HS
john.francis@manchester.ac.uk

† CSIRO Manufacturing and Materials Technology, Australia

University of Cambridge, United Kingdom
Department of Materials Science and Metallurgy,
Pembroke Street, Cambridge, CB2 3QZ
hkdb@cam.ac.uk

Keywords: creep, heat affected zone, steel, type IV, welding parameters.

Abstract

Type IV cracking refers to the premature failure of a welded joint due to an enhanced rate of creep void formation in the fine-grained or intercritically annealed heat-affected zone. Although a great deal of research effort has been directed at understanding the underlying mechanisms for this type of failure, most researchers have approached the problem from a metallurgical point of view. Comparatively little effort has been directed at understanding the effects of welding variables. In an earlier study, the authors used neural networks in a Bayesian framework to make the first predictions for the effects of different welding variables on the tendency for type IV failure in 9-12 Cr steels. In the current work, the results of an experimental study on the effects of weld heat input, preheat temperature and groove angle are reported for P91 steel, and are discussed in the context of earlier predictions.

1. Introduction

The need to reduce CO_2 emissions from fossil-fired power plants has led to a search for materials that are capable of withstanding increasingly harsh operating conditions. The National Institute for Materials Science in Japan, for example, has a long term goal of developing alloys that would be suitable for components such as headers and the main steam pipe in ultra supercritical plants, with service temperatures and steam pressures of 650 ^{o}C and 35 MPa respectively [1]. At present, 9-12 Cr ferritic steels appear to offer the most promise in this respect [2]. While a great deal of progress has been made in the development of suitable materials, the life-limiting factor is often the performance of welded joints [1,2]. The premature failure of welds in such steels is often attributable to Type IV cracking; a phenomenon in which there is an enhanced rate of creep void formation in the fine-grained and intercritically-annealed heat-affected zone (HAZ).

A number of researchers have studied type IV failures in ferritic power plant steels [3-8]. However, most studies appear to have been carried out from a metallurgical standpoint. In order to approach the problem from a different perspective, the authors recently carried out an analysis of the results of cross-weld creep tests that have been reported in the literature using neural networks in a Bayesian framework [9]. This analysis suggested that the weld preheat temperature has a significant effect on creep life, while the weld heat input was perceived to have an insignificant effect. It appears that, until now, the effects of heat input and preheat temperature on cross-weld creep life have not been studied systematically. In this article, preliminary results are reported from an experimental study that is in progress. We will commence by summarising the predictions arising from the neural network analysis. The experimental method for a programme of cross-weld creep testing is then described. Finally, the preliminary results of the creep testing are presented and discussed in the context of the neural network predictions.

2. Analysis of Published Data

The neural network method has been described elsewhere [10,11]. However, an overview is given here to provide the background for the current work.

A neural network analysis is a form of non-linear regression in which a mathematical relationship is established between parameters that are designated as independent (or input) variables and one or several dependent (or output) variables. The relationship is generated by presenting a network with a database comprising a set of input conditions for which the value of the output(s) is known. The network then "learns" a relationship between the input conditions and corresponding values for the output in a procedure that is referred to as training the network. Owing to their flexibility, neural networks are suited to situations in which the number of variables (which could include details of the composition of the steel, the heat treatment, welding parameters and post-weld heat treatment) is large and where there are no physical models for the parameter(s) of interest (such as, for example, cross-weld creep strength).

An example of the structure of a neural network is shown in Figure 1. There is an input layer, containing the values of the input variables, x_j. There is a hidden layer of nodes, and then an output layer which in this case contains only one node. The process of generating a prediction (or output) involves a forward propagation from the input layer. The values of the input variables, x_j, are multiplied by the network weights, $w_{ij}^{(1)}$, where i denotes the relevant node in the hidden layer, j denotes the input variable and the "$^{(1)}$" indicates that the weights are associated with the first layer of nodes. Thus, each node in the hidden layer receives a value referred to as the activation for that node, which is the sum of each input variable multiplied the respective weight for that node plus a value referred to as the bias, $\theta_i^{(1)}$. (Since there is a value of the bias associated with each node the bias is often represented as a network weight and multiplied by a "1" in the input layer, as is shown in Figure 1.) The activation for each node in the hidden layer becomes the argument of a transfer function, which is often chosen to be a smooth function such as a sigmoid or hyperbolic tangent. The output from the transfer function at each node in the hidden layer then becomes an input to the next layer (which in the case shown is the output layer). The only difference between the output node in Figure 1 and the nodes in the hidden layer is the incorporation of a linear transfer function rather than a hyperbolic tangent. The resulting value for y is the network output.

A neural network is a transparent mathematical function that is completely characterised by the number of input variables, the number of hidden layers and the number of nodes in each layer, the transfer functions and the values of the network weights. Prior to training, everything about the network is known except for the values of the weights. Thus, the process of training a network involves finding a set of weights that relate the input conditions to the corresponding values for the output. In a Bayesian analysis, part of the database is usually withheld during the training stage so that the predictions of the trained network can be compared with known values of the output for unseen input conditions. The performance of the network in making predictions on unseen data can then indicate whether the trained network has captured a meaningful relationship or whether it is likely to make unreliable predictions. Furthermore, the training process in a Bayesian analysis generates probability distributions for the network weights rather than discrete values. Consequently, the predictions generated by the network also have associated confidence intervals. Thus, a Bayesian framework enables the user to assess when the network is confident about the predictions that are made.

A Bayesian neural network analysis was carried out by the authors on cross-weld creep data published in the literature [9]. Three-layer feed forward networks, such as the one shown in Figure 1, were used in the analysis. The network structure had only one output, and the rupture stress was chosen as the parameter to be modelled, with the test temperature and creep life being treated as input conditions. The justification here is mathematical [12]; the rupture stress always has a finite value, whereas the creep life tends to infinity as the stress becomes low. The database is summarised in Table 1. There were 53 sets of data on type IV failures in 9-12 Cr steels for which details of the composition of the steel, the heat treatment, welding parameters, post-weld heat treatment and creep test conditions had all been reported. Neural networks are not able to deal with situations in which there is an absence of data, so the selection of input variables had an impact on the number of complete sets of data that were available. The variables in Table 1 were thought to constitute a pragmatic list.

A valuable feature of a neural network analysis is the ability to assess the extent to which each input variable is correlated with changes in the output. The significance of each input variable in explaining changes in the cross-weld creep strength, as perceived by a Bayesian network, is shown in Figure 2 [9]. The perceived significance is analogous to a partial correlation coefficient, but does not necessarily indicate the magnitude of the effect. It can be seen, however, that the creep life and test temperature have been identified as having the strongest correlations with the rupture stress. The well-known effects of normalising temperature [12], tempering temperature and tungsten content [2] were also correctly identified. Interestingly, the preheat temperature during welding was also perceived to have a significant effect on rupture stress, while the weld heat input was perceived to have an insignificant effect. Given that the network had recognised well-known effects it was possible, for the first time, to infer the effects of preheat temperature and weld heat input with some confidence. In a Bayesian framework, the significance does not indicate the sign of the effect, but this can be established by making predictions with the trained network. The sign of the effect is indicated in Figure 2 for each variable that was perceived to have a high significance. Increases in preheat temperature were predicted to translate to an increase in the rupture stress for a given creep life and test temperature.

3. Cross-Weld Creep Tests

A programme of cross-weld creep testing was initiated to investigate the effects of welding parameters. A section of P91 pipe with an outer diameter of 356 mm and a wall thickness of 53 mm was used as the base material in all experiments. This material was cut so that in all cases a welded joint was formed between two 180 mm long sections of pipe. The pipe was supplied in the normalised and tempered condition. The chemical composition was measured by optical emission spectroscopy and is summarised in Table 2.

3.1 Welding

One-sided welding was carried out in a semi-mechanised manner. The pipe was rotated during welding and the torch was maintained in the downhand position for all weld passes. Preheating was carried out with resistance heating blankets. The pipe manufacturer recommended a preheat temperature of 250 ^{o}C, and an interpass temperature always within the range between 200 and 300 ^{o}C. After welding, it was recommended that the joint be allowed to cool to a temperature below 100 ^{o}C to complete the transformation to martensite. A post-weld heat treatment procedure was also necessary, and all welds were heat treated at 760 ^{o}C for 2 hours.

At the time that welding experiments were initiated, the compilation of published cross-weld creep data and the associated neural network analyses had not been completed. Thus, it was decided to follow the manufacturer's recommendations regarding preheat and interpass temperature. As such, early experiments investigated the effects of heat input and joint preparation, noting that an effect of the joint preparation angle has recently been reported [5].

The joint preparations used in the experiments are illustrated in Figure 3. A single-Vee preparation with an included angle of 30 degrees was used in the majority of experiments (Fig. 3(a)). A weld with a single bevel at 45 degrees was also prepared to enable the effect of the preparation angle to be studied (Fig. 3(b)). After the completion of the neural network analyses an additional joint was fabricated to test an improved welding procedure. This joint utilised a preheat temperature of 350 ^{o}C and had a joint preparation with an included angle of 10 degrees, as shown in Figure 3(c).

In the early experiments the root runs and one additional "hot pass" were made by manual-metal-arc welding (MMAW). The filling passes were completed using flux-cored arc welding (FCAW) in all cases. For the additional joint with a higher preheat temperature, gas-tungsten arc welding (GTAW) was used for the root pass and hot pass, while FCAW was used for filling passes. In all cases the welding consumables were chosen to match the composition of the base material.

3.2 Extraction of Specimens

Creep specimens with a diameter of 11.3 mm and a gauge length of 62 mm were extracted from each of the welded joints. In the majority of experiments, the specimens were extracted in such a way that there was only one HAZ in each sample (Figs. 3(a) and 3(b)). For the weld with a high preheat temperature and an included angle of 10 degrees, this was not possible owing to geometry, so there were two HAZ's in the samples extracted from this weld (Fig. 3(c)). In all cases, the axis of the creep specimen was parallel to the axis of the pipe and transverse to the direction of welding, and the distance between the nearest shoulder of the specimen and the HAZ was approximately 15 mm. Furthermore, all coupons were extracted from locations in the weld that corresponded to filling passes, which were made by FCAW in all cases, rather than the root region.

3.3 Test Conditions

The test stresses were chosen so that the most probable location for rupture was in the type IV region. The authors have shown previously that type IV failures predominate in 9-12 Cr steels when the stress level is below 100 MPa [13]. At higher stress levels failures in the parent material become increasingly likely. Two stress levels were selected in this work; 93 and 81 MPa. The test temperature was 620 ^{o}C and the tests were carried out in air in all cases. P91 steels are intended for service at 600 ^{o}C. It is desirable to utilise a test temperature that is close to the intended service temperature for the material, so that the thermodynamic stability of the test coupons does not differ significantly from intended service conditions. In all cases creep testing was carried out in accordance with ASTM E 139 – 83.

A summary of all experiments is given in Table 3. It can be seen that three different weld heat inputs were utilised; namely 0.8, 1.6 and 2.4 kJ/mm. These heat inputs were thought to span a representative range of welding conditions.

4. Results and Discussion

The results of creep testing are plotted in Figure 4. Metallographic analyses confirmed that all of the ruptured samples had failed in the type IV region. The solid points in the figure correspond to samples that were extracted from welds that differ only in heat input. It can be seen that these points appear to be grouped at both stress levels. It is possible that there is a slight increase in creep life with increasing heat input, since the longest creep lives correspond to the highest heat input. However, the experiments cover a significant range (0.8 to 2.4 kJ/mm) and it can be concluded that any effect of heat input is small. This result is consistent with the predictions that were made by the Bayesian neural network analysis.

The included angle in the joint preparation appears to have a significant effect on cross-weld creep life. However, it appears that benefits are only realised for included angles close to zero (i.e. with the fusion line perpendicular to the loading direction). The majority of the creep tests were conducted on welds with an angle of 30^{o}, and it appears that there is no penalty in creep life associated with increasing the included angle from 30 to 90^{o}. Although this effect has been reported previously [5], at present the reasons are unclear. It is curious that benefits only arise once the included angle is reduced to less than 30^{o} (as this corresponds to a fusion line/HAZ orientation only 15^{o} off normal to the loading direction). It was not possible to assess any effect in the neural network analyses, owing to insufficient reporting of this parameter in the literature. It is possible that the effect is mechanical in nature, since the maximum macroscopic shear stresses in a uniaxial cross-weld specimen will occur in planes that make a 45^{o} angle with the weld centre line, whereas these shear stresses are nominally zero in planes that are parallel to the weld centreline. With increasing joint preparation angles, the type IV region may become more favourably aligned with planes of maximum shear stress, thus promoting localised damage. Regardless of the mechanism, the results suggest that narrow-gap welding configurations and U-preparations can offer significant benefits to creep performance.

The samples extracted from the weld made with a 350 ^{o}C preheat temperature and the joint preparation shown in Figure 3(c) are achieving the highest creep lives. This weld was fabricated in order to validate an improved welding procedure. Although an included angle of zero appears to be desirable, it may not always be practical, since welding torches with narrow-gap configurations will generally be required. Furthermore, in components such as headers and the main steam pipe, the quality of the root run is critically important, and it may not be feasible to deviate from a more conventional GTAW configuration. As such, an included angle of 10^o was seen to provide a sensible compromise.

While the performance of the samples with a 350 ^oC preheat temperature is superior to welds made with 250 ^oC, it is at present difficult to assess the relative contributions of preheat temperature and joint preparation angle to the improved creep life. It appears that reducing the included angle from 90 to 30^o offers no benefit, whereas significant benefits arise when it is reduced from 30^o to zero. The degree to which benefits arise with angles between 30^o and zero is unknown. Nevertheless, it is plausible that the predictions of the Bayesian neural network analysis, in perceiving increases in preheat temperature to be beneficial, are correct. The sample with a 350 ^oC preheat temperature and an included angle of 10^o appears to match the performance of the sample with a 250 ^oC preheat temperature and an included angle of zero. It should be noted that the samples with a higher preheat temperature are also the only samples to have two HAZ's in the gauge length, which will generate a downward bias in creep lives relative to the other samples. Further creep testing is currently being initiated to gain further insight.

5. Conclusions

In this work, it has been demonstrated that there is scope to improve resistance to type IV cracking in 9-12 Cr steels through the optimisation of welding procedures. Further testing is now required to confirm that the effects of welding procedures translate to service lives greater than 10,000 hours.

The weld heat input does not have a significant effect on the propensity for type IV failure. This result was predicted by a Bayesian neural network analysis and has now been confirmed by experiments.

The joint preparation angle has a significant effect on cross-weld creep life. In cross-weld creep tests, the best creep performance is achieved when the included angle is zero (so that the fusion line and HAZ are perpendicular to the loading direction). This is consistent with the findings of other researchers but it remains unclear whether the effect translates to service lives greater than 10,000 hours. The mechanism is also unclear.

Higher preheat and interpass temperatures during welding have been predicted to improve cross-weld creep life in 9-12 Cr steels. This prediction appears to be plausible but, at present, it is difficult to assess the extent of the benefits arising due to increased preheat temperatures. However, creep tests are still in progress and further tests are being initiated.

6. Acknowledgement

This work was undertaken as part of a project that is proudly supported by the *International Science Linkages* programme established under the Australian Government's innovation statement *Backing Australia's Ability*.

7. References

[1] M Tabuchi, T Watanabe, K Kubo, M Matsui, J Kinugawa and F Abe, "Creep Crack Growth Behaviour in the HAZ of Weldments of W Containing High Cr Steel", *International Journal of Pressure Vessels and Piping*, **78** (11-12), pp. 779 – 784 (2001).

[2] C D Lundin, P Liu and Y Cui, "A Literature Review on Characteristics of High Temperature Ferritic Cr-Mo Steels and Weldments", WRC Bulletin 454 - August 2000, *Welding Research Council, Inc.*, New York.

[3] F Abe and M Tabuchi, "Microstructure and Creep Strength of Welds in Advanced Ferritic Power Plant Steels", *Science and Technology of Welding and Joining*, **9** (1), pp. 22-30 (2004).

[4] K Shinozaki, D Li, H Kuroki, H Harada, K Ohishi and T Sato, "Observation of Type IV Cracking in Welded Joints of High Chromium Ferritic Heat Resistant Steels", *Science and Technology of Welding and Joining*, **8** (4), pp. 289-295 (2003).

[5] S K Albert, M Tabuchi, H Hongo, T Watanabe, K Kubo and M Matsui, "Effect of Welding Process and Groove Angle on Type IV Cracking Behaviour of Weld Joints of a Ferritic Steel", *Science and Technology of Welding and Joining*, **10** (2), pp. 149-157 (2005).

[6] T Kojima, K Hayashi and Y Kajita, "HAZ Softening and Creep-Rupture Strength of High Cr Ferritic Steel Weldments", *ISIJ International*, **35** (10), pp. 1284-1290 (1995).

[7] K Shinozaki, D Li, H Kuroki, H Harada and K Ohishi, "Analysis of Degradation of Creep Strength in Heat-Affected Zone of Weldment of High Cr Heat Resisting Steels Based on Void Observation", *ISIJ International*, **42** (12), pp. 1578-1584 (2002).

[8] R Wu, R Sandstrom and F Seitisleam, "Influence of Extra Coarse Grains on the Creep Properties of 9 Percent CrMoV (P91) Steel Weldment", *Journal of Engineering Materials and Technology*, **126** (1), pp. 87-94 (2004).

[9] J A Francis, W Mazur and H K D H Bhadeshia, "Welding Procedures and Type IV Phenomena", In Proceedings of the 7th International Conference on Trends in Welding Research, Pine Mountain, Georgia, 16-20 May, 2005.

[10] D J C MacKay, "A Practical Bayesian Framework for Back Propagation Networks", *Neural Computation*, **4** (3), pp. 448-472 (1992).

[11] H K D H Bhadeshia, "Neural Networks in Materials Science", *ISIJ International*, **39** (10), pp. 966-979 (1999).

[12] F Brun, T Yoshida, J D Robson, V Narayan, H K D H Bhadeshia and D J C MacKay, "Theoretical Design of Ferritic Creep Resistant Steels Using Neural Network, Kinetic, and Thermodynamic Models", *Materials Science and Technology*, **15** (5), pp. 547-544 (1999).

[13] J A Francis, W Mazur and H K D H Bhadeshia, "Estimation of Type IV Cracking Tendency in Power Plant Steels", *ISIJ International*, **44** (11), pp. 1966-1968 (2004).

Tables

Variable	*Minimum*	*Maximum*
C (wt. %)	0.09	0.13
N	0.041	0.078
B	0	0.003
Cr	8.45	12.0
Mo	0.34	0.96
Nb	0.05	0.13
W	0	2.21
Mn	0.40	0.81
Si	0.02	0.35
Cu	0	3
Normalising Temp. (^oC)	1050	1080
Normalising Time (h)	0.5	2
Tempering Temp. (^oC)	760	820
Tempering Time (h)	1	6
Heat Input (kJ/mm)	0.8	3.8
Preheat Temperature (^oC)	100	250
PWHT Temperature (^oC)	740	760
PWHT Time (h)	0.25	8
Internal Pressure Test (0/1)	0	1
Test Temperature (^oC)	600	700
Test Duration (h)	113	11220
Rupture Stress (MPa)	40	150

Table 1: Range in composition, heat treatment, welding parameters and test conditions covered by the database on type IV failures [9].

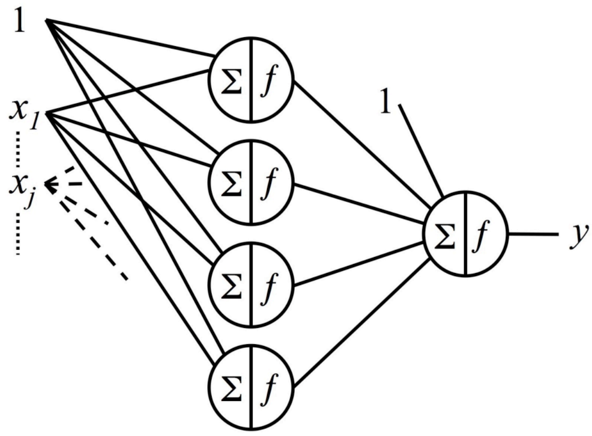
C	Si	Mn	P	S	Al	Cr	Ni	Mo	V	Nb	N
0.09	0.28	0.40	0.01	0.01	<0.005	8.5	0.15	0.89	0.21	0.06	N/A

Table 2: Composition of the base material as determined by optical emission spectroscopy (wt. %).

Sample	Welding Process (root/fill)	Heat Input (kJ/mm)	Preheat Temp. (^oC)	Joint Angle - included (deg.)	Stress (MPa)	Temp. (^oC)
1	MMAW/FCAW	0.8	250	30	93	620
2	MMAW/FCAW	1.6	250	30	93	620
3	MMAW/FCAW	2.4	250	30	93	620
4	MMAW/FCAW	1.6	250	0*	93	620
5	MMAW/FCAW	1.6	250	90*	93	620
6	MMAW/FCAW	0.8	250	30	81	620
7	MMAW/FCAW	2.4	250	30	81	620
8	GTAW/FCAW	1.6	350	10	93	620
9	GTAW/FCAW	1.6	350	10	81	620

Table 3: Summary of cross-weld creep testing conditions. The "*" denotes equivalent single-Vee included angle for samples extracted from weld shown in Figure 3(b).

Figures



$$h_i = \tanh\left(\sum_i w_{ij}^{(1)} x_j + \theta_i^{(1)}\right) \qquad (1)$$

$$y = \sum_i w_i^{(2)} h_i + \theta^{(2)} \qquad (2)$$

Fig. 1: Example of a three-layer feed forward neural network used to analyse published data [9]. The lines that link inputs and nodes represent network weights.

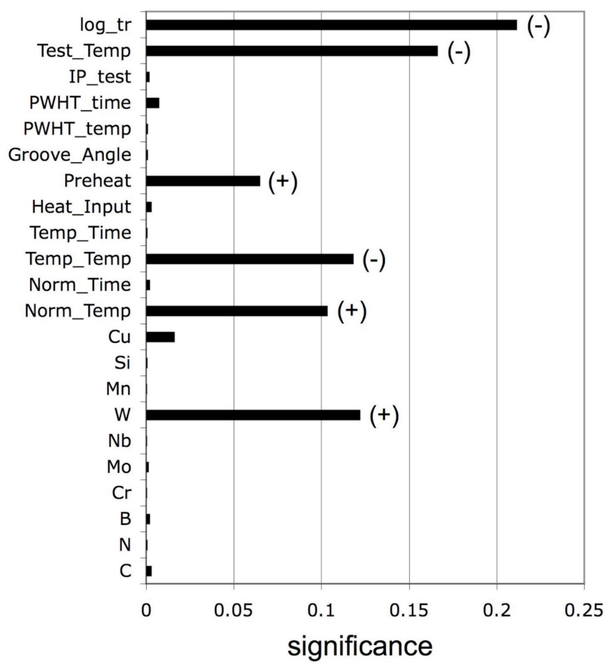


Fig. 2: Significance of each input variable in explaining the variation in type IV rupture stress in cross-weld creep tests on 9-12 Cr steels, as perceived by a Bayesian network [9]. The perceived significance is analogous to a partial correlation coefficient, but does not necessarily indicate the magnitude of the effect. The sign of the effect for input variables that were perceived to have a significant correlation with rupture stress is indicated in the figure. The alloying additions refer to the base metal.

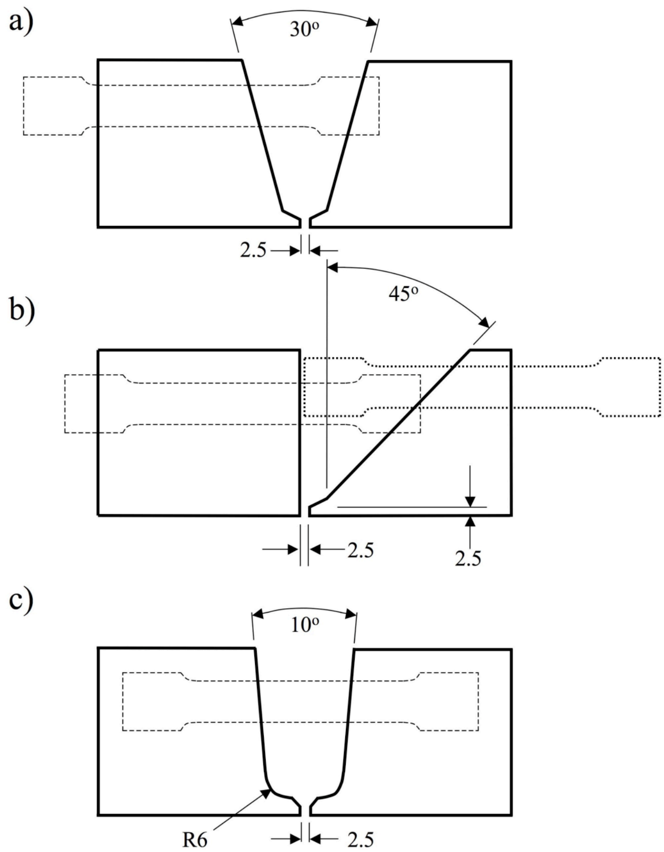


Fig. 3: Schematic representation of the joint preparations and locations of extracted creep specimens. In a) and b) there is only one HAZ within the gauge length. In c) there are two HAZ's within the gauge length. In all cases the HAZ's were approximately 15 mm from the nearest shoulder of the specimen.

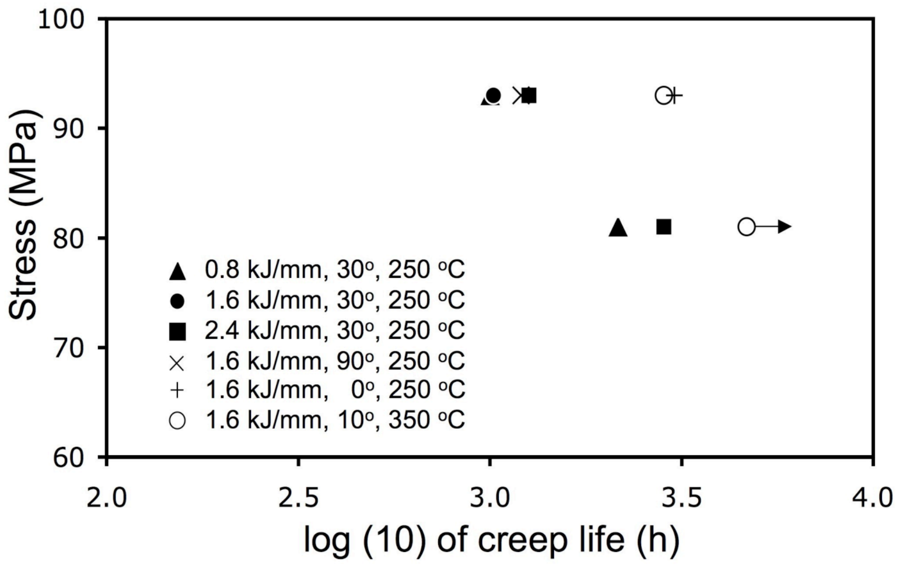


Fig. 4: Preliminary results of cross-weld creep testing at 620 °C in air. The samples are distinguished by the weld heat input, joint included angle and preheat temperature respectively. All of the ruptured specimens failed in the type IV region.