Effects of weld preheat temperature and heat input on type IV failure

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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. A great deal of research effort has been directed at understanding the underlying mechanisms for this type of failure, but most have approached the problem from a metallurgical standpoint, and comparatively little effort has been directed at understanding the effects of welding variables. Here the effects of parameters such as the preheat temperature and heat input on the tendency for type IV failure in 9–12%Cr steels have been quantitatively estimated. These calculations have subsequently been verified experimentally to form the first systematic study of welding parameters on type IV cracking. The joint geometry and preheat temperature have been found to ameliorate type IV failures, while the effect of heat input is less significant.

Keywords: Creep, Heat affected zone, Steel, Type IV, Welding parameters, Welding procedures

Introduction

It clearly is useful to enhance the efficiency of fossil fired power plants, and significant gains can be realised through increases in steam temperature and pressure. This requires better steels capable of sustaining the harsher conditions and there is considerable work in progress to design alloys for service temperatures and steam pressures of 630°C and 35 MPa respectively.[1,2] Whereas the overall properties of such alloys are clearly important, welding introduces localised changes in the structure which become the life limiting factor. In particular, type IV cracking is a phenomenon in which there is an enhanced rate of creep void formation in the fine grained and intercritically annealed heat affected zone (HAZ).[3]

A number of researchers have studied the metallurgy of type IV failures in ferritic power plant steels.[4–11] The authors have approached the problem from a different perspective, by interpreting the results of published cross-weld creep tests using neural networks in a Bayesian framework.[12] This analysis identified quantitatively and for the first time the effects of many welding parameters, including the heat input and preheat temperature, on the tendency for type IV failure. As a result of this analysis, a programme of creep testing was initiated that systematically interrogated the influence of these parameters on type IV cracking tendency. The results of the experiments support the findings of the neural network analysis, so that the authors are now able to report the effects of preheat temperature and heat input on type IV failures in 9–12%Cr steels.

After a brief description of the predictions from the authors' published neural network model, this paper describes the experimental programme initiated to assess the predictions, and concludes with a discussion of the implications of the work on weld design and integrity.

Analysis of published data

Details of the Bayesian neural network method have been described elsewhere,[13,14] but it is important to note that the technique is associated with two measures of uncertainty. When conducting experiments, the noise results in a different output for the same set of inputs when the experiment is repeated. This is because there are variables which are not controlled, so their influence is not included in the analysis. The second kind deals with the uncertainty of modelling; there might exist many mathematical functions which adequately represent the same set of empirical data but which behave differently in extrapolation. This latter uncertainty is useful in assessing the significance of calculations carried out in input domains where knowledge is sparse.

The data used to create the original model were obtained from Refs. 4 to 9. It is the rupture stress that is modelled as a function of the test temperature, creep life and welding parameters. The justification for using the rupture stress as the output is mathematical,[15] i.e. because it always has a finite value, whereas the creep life tends to infinity as the stress is reduced. The database on which the model was created is summarised in Table 1, consisting of data from 53 experiments in which type IV failure occurred in 9–12%Cr steels and 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.

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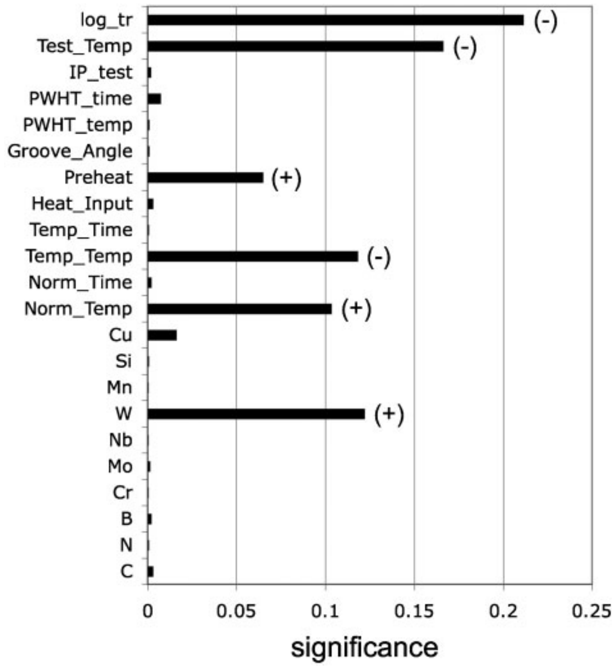
Table 1 Range in composition, heat treatment, welding parameters and test conditions covered by 53 sets of published data on type IV failures in Refs. 4–9

Variable	Min.	Max.
C, wt-%	0·09	0·13
N, wt-%	0·041	0·078
B, wt-%	0	0·003
Cr, wt-%	8·45	12·0
Mo, wt-%	0·34	0·96
Nb, wt-%	0·05	0·13
W, wt-%	0	2·21
Mn, wt-%	0·40	0·81
Si, wt-%	0·02	0·35
Cu, wt-%	0	3
Normalising temperature, °C	1050	1080
Normalising time, h	0·5	2
Tempering temperature, °C	760	820
Tempering time, h	1	6
Heat input, kJ mm^{-1}	0·8	3·8
Preheat temperature, °C	100	250
PWHT temperature, °C	740	760
PWHT time, h	0·25	8
Internal pressure test (0/1)	0	1
Test temperature, °C	600	700
Test duration, h	113	11 220
Rupture stress, MPa	40	150

The significance perceived by the neural network, of each input variable in explaining changes in the cross-weld creep strength, is shown in Fig. 1. This quantity is analogous to a partial correlation coefficient, and it should be noted that it does not indicate the sensitivity of the output to the input. The logarithm of the rupture life (logt_r) and test temperature have reasonably been identified as having the strongest correlations with the rupture stress. The well known effects of normalising temperature,[15] tempering temperature and tungsten content[2] have also been correctly identified. Interestingly, the preheat temperature during welding has also been perceived to have a significant effect on rupture stress, but not so the weld heat input. The sign of the effect is indicated in Fig. 1 for each variable that has been perceived to have a high significance. In summary, increases in preheat temperature are predicted to translate into an increase in the rupture stress for a given creep life and test temperature.



1 Significance of each input variable in explaining variation in type IV rupture stress in cross-weld creep tests on 9–12%Cr steels, as perceived by Bayesian network trained on data in Refs. 4–9: perceived significance is analogous to partial correlation coefficient, but does not necessarily indicate magnitude of effect; sign of effect for input variables that were perceived to have significant correlation with rupture stress is indicated in figure; alloying additions are in wt-% and refer to base metal

Cross-weld creep tests

All previous individual studies on type IV cracking have kept the welding conditions constant but the authors were able to perceive, using the neural network, the effects of these conditions by combining data from different sources. This is the first time that a programme of cross-weld creep testing was initiated to investigate systematically the effects of welding parameters.

Welding procedures

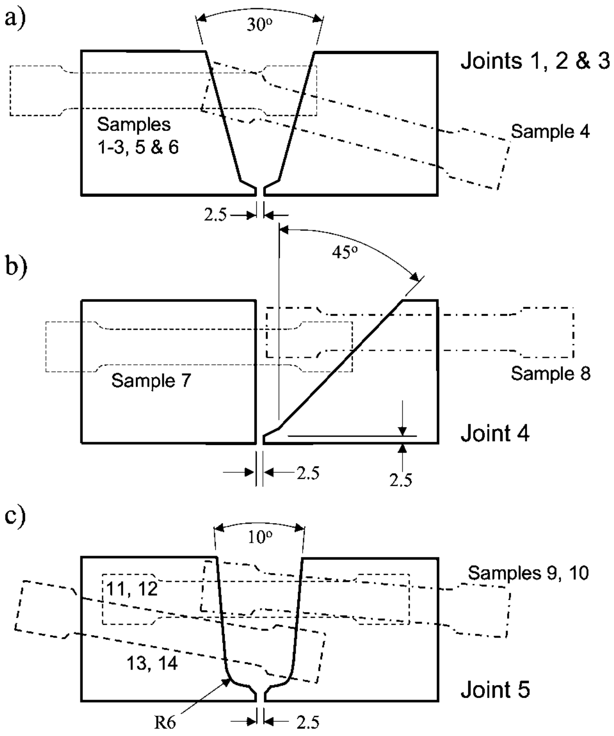
A section of P91 pipe supplied in the normalised and tempered condition, with an outer diameter of 356 mm and a wall thickness of 53 mm, was used as the base material in all of the welded joints in this study. This material was cut so that in all cases a weld was formed between two 180 mm long sections of pipe. The chemical composition of this pipe section was measured by optical emission spectroscopy and is summarised in Table 2.

The welding experiments were planned in parallel with the compilation of the neural network database;[12] the authors decided in the first instance to follow the manufacturer's recommendations[16,17] relating to preheat temperature. As such, four welded joints were manufactured to investigate the effects of heat input and joint preparation on type IV failures, noting that an effect of the joint preparation angle has been reported.[6] At a later stage, the results of the neural network analysis inspired the manufacture of a fifth joint, in order to confirm the influence of preheat temperature on type IV limited creep life.

The welding parameters used to fabricate each of the five joints are summarised in Table 3. A single Vee preparation with an included angle of 30° was used for the welds numbered 1–3, as is illustrated in Fig. 2*a*. Weld no. 4 (Fig. 2*b*) incorporated a single bevel at 45° to assist in interrogating the effect of the joint preparation angle. Joint no. 5 was fabricated to test an improved welding procedure, utilising a higher preheat

Table 2 Composition of base material used in current work as determined by optical emission spectroscopy, wt-%

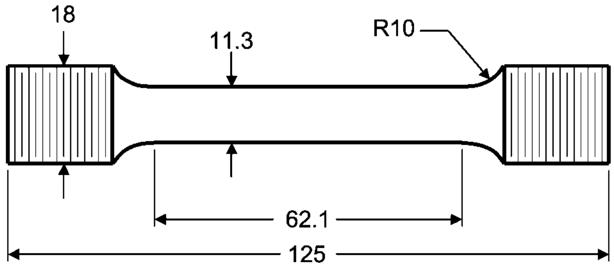
C	Si	Mn	P	S	Al	Cr	Ni	Mo	V	Nb	N
0·09	0·28	0·40	0·01	0·01	<0·005	8·5	0·15	0·89	0·21	0·06	N/A



2 Schematic representation of joint preparations for each weld in current work, and locations of extracted creep specimens: with exception of samples 11 and 12 (Table 3), all specimens had only one HAZ within gauge length; samples 11 and 12 had two HAZs within gauge length; in all cases, the HAZs were ~15 mm from nearest shoulder of specimen; note that different orientations between HAZ and loading axis of creep specimen could be achieved by rotating axis of extracted specimen with respect to axis of pipe

temperature (350°C) and incorporating a joint preparation with an included angle of 10° (Fig. 2*c*). It is important to note the way in which the joint preparation angle has been defined in Fig. 2*a* and *c*, i.e. as the included angle within the Vee preparation, rather than the bevel angle that has been applied to either side of the joint.

In all cases, one sided welding was carried out in a semimechanised manner, with the pipe being rotated during welding, while the torch was maintained in the downhand position for all weld passes. Preheating was carried out with resistance heating blankets and interpass temperatures were generally maintained within 20°C of the specified preheat temperature. After welding, it was recommended that the entire joint be allowed to cool to a temperature below 100°C to complete the transformation to martensite. A post-weld heat treatment procedure was necessary, and all welds were heat treated at 760°C for 2 h.



3 Configuration of creep test specimens in current work: all dimensions are given in mm

For joints 1–4, 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 joint 5, 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 weld filler metal was chosen to match the composition of the base material.

Extraction of specimens

Fourteen creep specimens were extracted from the five welded joints. In all cases, the specimens had a gauge diameter of 11·3 mm and a gauge length of 62 mm (Fig. 3). Care was taken to ensure that all specimens were extracted exclusively from the region of the weld corresponding to the filling passes, which were deposited using FCAW in all of the joints. Table 3 lists the specimens that were extracted from each joint, and Fig. 2 provides a schematic representation of the location from which each specimen was extracted. Most specimens had only one HAZ within the gauge length, although for two specimens, there were two HAZs within the gauge length (specimens 11 and 12 in

Table 3 Summary of cross-weld creep testing conditions in current work

Joint no. (Fig. 3)	Welding process (root/fill)	Heat input, kJ mm^{-1}	Preheat temperature, °C	Creep specimen ID	Joint angle included, °	Test temperature, °C	Test stress, MPa
1	MMAW/FCAW	0·8	250	1	30	620	93
				2	30	620	81
2	MMAW/FCAW	1·6	250	3	30	620	93
				4	0*	620	93
3	MMAW/FCAW	2·4	250	5	30	620	93
				6	30	620	81
4	MMAW/FCAW	1·6	250	7	0	620	93
				8	90	620	93
5	GTAW/FCAW	1·6	350	9	0*	620	93
				10	0*	620	81
				11	10	620	93
				12	10	620	81
				13	30*	620	93
				14	30*	620	81

*An equivalent single Vee included angle that was achieved by rotating the axis of the creep specimen relative to the axis of the pipe (Fig. 2).

Table 3 and Fig. 2*c*). In all cases, samples were extracted in such a way that the distance from the nearest shoulder of the specimen to the HAZ was ~15 mm.

In most cases, the axis of the creep specimen was parallel to the axis of the pipe and transverse to the direction of welding. However, Fig. 2 shows that some samples were oblique with respect to the axis of the pipe. These orientations were chosen in order to create specimens that effectively had a different joint preparation angle, i.e. to change the relationship between the loading direction for the sample and the orientation of the HAZ. In Table 3, those joint angles that were achieved by extracting an oblique sample are marked with an asterisk.

Experimental matrix and test conditions

A summary of the experiments is given in Table 3. Three different weld heat inputs were utilised, namely, 0·8, 1·6 and 2·4 kJ mm^{-1}, spanning a representative range of welding conditions. Coupons were also extracted from welds made with two different preheat temperatures, namely, 250 and 350°C. The latter temperature is towards the upper limit of what might be considered as an achievable preheat, but the intention here was to test the trends predicted by the neural network model, rather than to investigate practicalities. Finally, utilising the five welded joints and also extracting some oblique specimens, it was possible to interrogate joint preparation angles ranging from 0 to 90°.

With respect to the test conditions, the stresses were chosen so that the most probable location for rupture was in the type IV region. It has been shown previously that type IV failures predominate in 9–12%Cr steels when the stress level is below 100 MPa.[18] 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°C with all the tests carried out in air. P91 steels are intended for service at 600°C. It is desirable to conduct tests close to the intended service temperature for the material, so that the thermodynamic stability of the material is representative of service conditions. Creep testing was carried out in accordance with ASTM E 139-83.[19]

In these experiments, the post-weld heat treatment was not changed since the neural network analysis on previously published data[12] did not reveal a significant effect (Fig. 1). Another parameter that was not varied was the selection of filler metal, and this may influence type IV limited rupture life through an effect on the constraint that is seen in the HAZ.[3] In this work, however, the intention was not to account for every source of complexity that may arise in a power plant weld, but rather to demonstrate the effects of a few welding variables, in particular those that had been highlighted by the neural network analysis, under controlled experimental conditions. Furthermore, while scatter can be significant in creep tests, it is also known to arise as a consequence of uncontrolled variables, particularly when detailed composition variations within the specification range are neglected.[15] It should be noted that the 14 experiments reported in this work are consistent in the use of the same batch of steel, fabrication and testing. The authors expect therefore that these experiments are sufficient to demonstrate the effects that were predicted theoretically.[12]

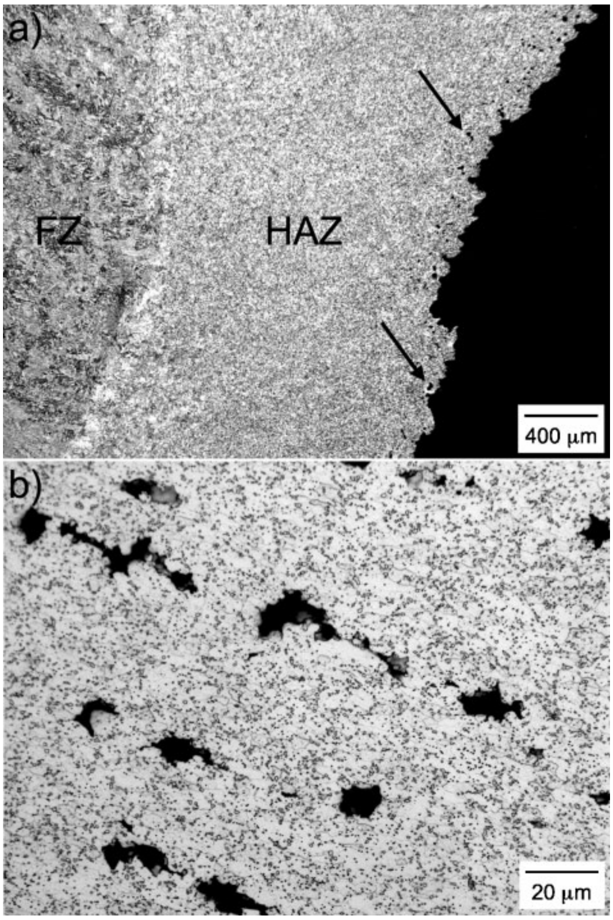
Results

The results of the creep rupture tests are summarised in Table 4. Metallographic analysis confirmed that all samples had failed in the type IV region. Figure 4 shows how void formation was localised to the fine grained HAZ, beside the fracture surface, a phenomenon characteristic of type IV failure. In constructing Table 4, it was assumed that if the axis of the creep specimen had been rotated with respect to that of the pipe, then the joint preparation angle had effectively been altered by a corresponding amount. That is to say, the effect of joint preparation angle manifested itself through a relationship between the direction of loading and the orientation of the HAZ, as opposed to there being a direct effect of the joint preparation angle itself. Thus, all of the joint preparation angles marked with an asterisk in Table 3 were deemed to be representative of a creep sample extracted from a weld with the quoted joint preparation angle, but with the axis of the specimen parallel to that of the pipe.

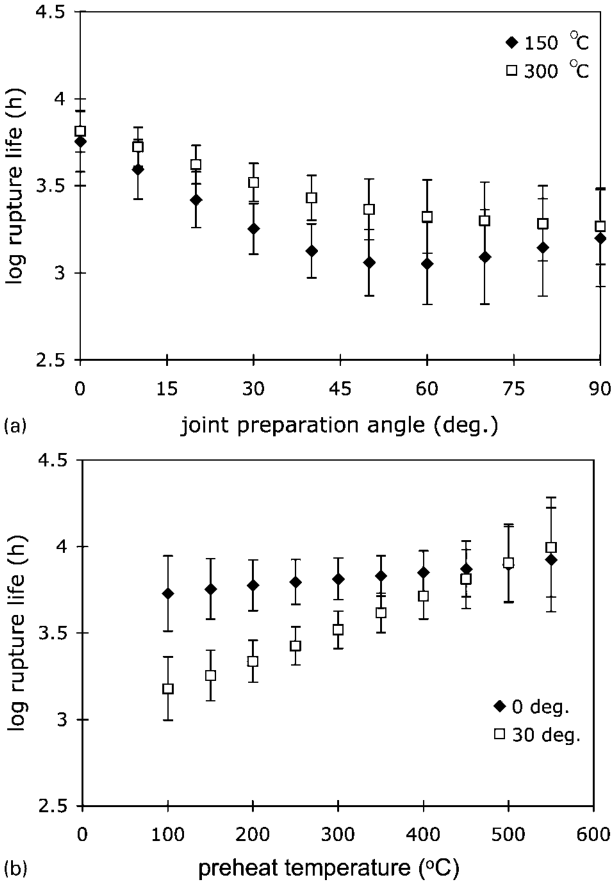
Table 4 reveals that the joint preparation has a significant effect on cross-weld creep life (compare, for example, the rupture lives for either sample 4 or sample 7 with that of sample 3). However, the benefits are only realised for included angles close to zero, i.e. with the fusion line near to perpendicular to the loading direction (rupture lives for samples 3 and 8 are comparable, whereas those for samples 3 and 4 are not). Thus, it appears that there is no further penalty in creep life associated with increasing included angle from 30 to 90°.

Table 4 Summary of results of cross-weld creep testing in current work: all tests were carried out at 620°C in air

Sample ID	Heat input, kJ mm^{-1}	Preheat, °C	Joint angle, °	Test stress, MPa	Life, h
1	0·8	250	30	93	1000
2	0·8	250	30	81	2154
3	1·6	250	30	93	1020
4	1·6	250	0	93	3426
5	2·4	250	30	93	1265
6	2·4	250	30	81	2839
7	1·6	250	0	93	3027
8	1·6	250	90	93	1204
9	1·6	350	0	93	2830
10	1·6	350	0	81	6789
11	1·6	350	10	93	2841
12	1·6	350	10	81	5614
13	1·6	350	30	93	2053
14	1·6	350	30	81	3868



4 Optical micrographs obtained from ruptured specimens showing *a* localised formation of creep voids in fine grained HAZ beside fracture surface in sample 5 and *b* creep voids beside fracture surface in sample 8 at higher magnification: in *a*, FZ denotes fusion zone; loading direction was from left to right in both images



5 Neural network predictions for type IV limited rupture life in cross-weld test on P91 steel at 620°C and with stress of 80 MPa showing *a* influence of joint preparation angle with two different preheat temperatures and *b* influence of preheat temperature using two different joint preparation angles: weld heat input was 1·6 kJ mm^{-1}

The authors' assumption that a rotation of the axis of a creep specimen with respect to that of the pipe is equivalent to a corresponding change in the joint preparation angle appears to be reasonable. This is evident because the rupture life that was recorded for sample 3, at ~1000 h, increased to ~3000 h when the joint preparation angle was decreased to zero, irrespective of whether the change in angle was brought about by changing the orientation of the axis of the specimen with respect to that of the pipe (sample 4) or by a change in the joint preparation angle for the weld itself (sample 7).

A comparison of the creep lives for samples 1, 3 and 5, and of samples 2 and 6, suggests that there may be a small effect of the weld heat input on type IV rupture life, with an increase in heat input leading to a small increase in life. This is consistent with neural network model estimates that the effect of weld heat input on type IV cracking tendency would be small.

The role of preheat is also correctly predicted to be much more significant. Samples 3 and 13 reveal that increasing preheat from 250 to 350°C doubles the life. A similar increase is seen when sample 14 is compared with either sample 2 or sample 6, noting that the variation in life due to changes in heat input will be small. Curiously though, the benefit of preheat temperature is not evident when the joint preparation angle is zero (cf. samples 7 and 9).

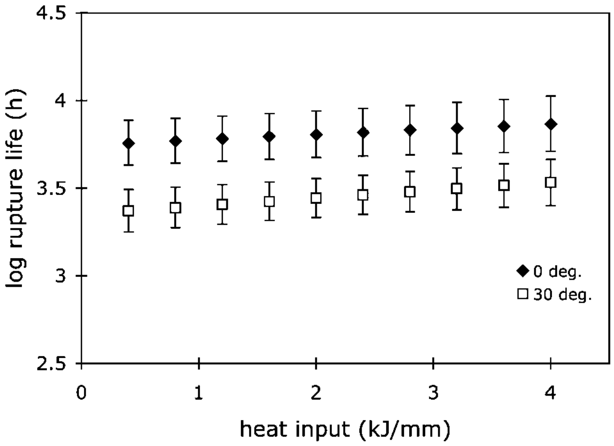
Analysis of experimental results

The new experimental data represent the first systematic study of the interaction between welding parameters and type IV cracking; they were therefore assessed using the neural network method in the hope of further insights. Furthermore, although the dataset in Table 4 is smaller than the original (Table 1), many of the experimental variables can now be eliminated, since the same parent steel and filler metal were used for all of the creep specimens, as well as the same normalising, tempering and post-weld heat treatment procedures.

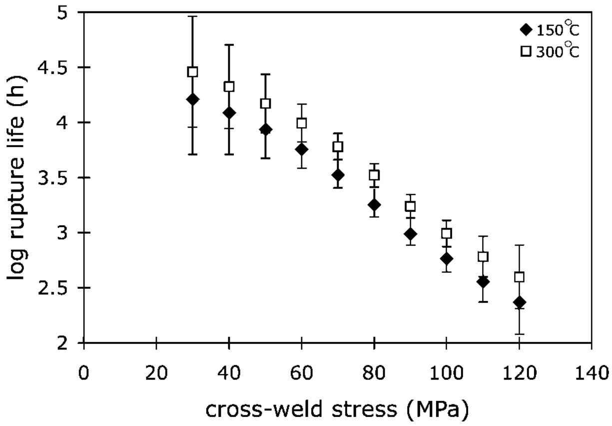
Once again three layer feed forward neural networks[12] were used in the analysis. Aside from a reduction in the size of the database, the principal difference in this analysis was that the logarithm of the rupture life ($\log t_r$) was designated as the output because only two values of stress have been studied (Table 4).

Trends

Given the smaller list of variables now under investigation, it becomes feasible to assess the sensitivity of the rupture life to each input variable by studying the trends directly when the newly trained network is used to make predictions. In Fig. 5*a*, for example, predicted rupture lives are plotted as a function of the joint preparation



6 Neural network predictions for type IV limited rupture life in cross-weld test on P91 steel at 620°C and with stress of 80 MPa: influence of weld heat input is shown for two different joint preparation angles and preheat temperature of 250°C



7 Neural network predictions for type IV limited rupture life in cross-weld test on P91 steel at 620°C: influence of stress is shown for two different preheat temperatures, joint preparation angle of 30° and heat input of 1·6 kJ mm^{-1}

angle for two different preheat temperatures and a test stress of 80 MPa. It can be seen that the best performance for a weld is likely to be achieved with a joint preparation angle of 0°, regardless of the preheat temperature. As the joint preparation angle increases, there is a corresponding decrease in $\log t_r$, but the decrease is more severe when a lower preheat temperature is used. Once the joint preparation angle becomes large (>~45°), further changes in angle do not have a significant influence on the rupture life.

In Fig. 5*b*, predicted rupture lives are plotted as a function of preheat temperature for two different joint preparation angles. Increases in preheat temperature are predicted to improve the performance of welds with joint preparation angles of both 0 and 30°. Interestingly though, when the preheat temperature is low, the joint preparation angle can be seen to have a dramatic effect on the rupture life. However, as the preheat temperature is increased, the difference between the performance of welds with the two different joint preparation angles is predicted to diminish. Indeed, although a preheat temperature of 500°C would not be practical, the network predicts that the effect of the joint preparation angle could be eliminated altogether if this preheat temperature were to be applied.

In contrast, the effects of the weld heat input on cross-weld rupture life can be seen to be much less significant (Fig. 6). This figure shows predicted rupture lives for P91 steel as a function of heat input for welds made with the same two joint preparation angles as in Fig. 5*b* (0 and 30°). In making these predictions, the preheat temperature was assumed to be 250°C in all cases and the test stress was 80 MPa. While an increase in the weld heat input seems to give rise to a small enhancement of rupture life, a greater heat input is not predicted to compensate for the differences in the joint preparation angle, although the preheat temperature can do so (Fig. 5*b*).

Predictions for the effect of stress on rupture life at 620°C are given in Fig. 7 for two different preheat temperatures, a heat input of 1·6 kJ mm^{-1} and a joint preparation angle of 30°. The stress clearly must have a strong influence on type IV limited rupture life in a cross-weld test, with higher stresses leading to dramatically reduced rupture lives. Interestingly though, the benefits associated with increasing the preheat temperature are predicted to translate to long term rupture tests. This should be treated with a degree of caution given the uncertainties associated with the predictions, which increase markedly as the stress is extrapolated.

A neural network in a Bayesian framework clearly can serve as a powerful tool for extracting sensitivities and trends from a database with many interacting variables, and in situations in which a physical model for the phenomenon under investigation (in this case, the propensity for type IV cracking) is not available. The authors' analysis has confirmed that, among the variables under investigation, the joint preparation angle has the most significant influence on the cross-weld creep tests, an effect that has been reported previously.[6] Furthermore, the weld preheat temperature has a significant influence on the tendency of 9–12%Cr steels to fail in the type IV region; increases in preheat temperature also improve weld performance, whereas weld heat input has a minor effect. Unfortunately, the mechanism(s) by which the weld preheat temperature influences type IV cracking tendency remain unclear and constitute a topic for future work.

Conclusions

The results of both neural network modelling and rupture testing experiments suggest that narrow gap welding configurations and U preparations can offer significant benefits to creep performance if the dominant loading direction is across (or transverse to) the welded joint, since these configurations are often associated with joint preparation angles of zero.

Increases in the weld preheat temperature significantly improve type IV limited rupture life. It would appear to be beneficial to specify the highest preheat temperature that can be practically applied. In situations where the principal loading direction is transverse to the weld and it is not possible to use a joint preparation angle of zero, an increase in the preheat temperature may substantially compensate for any penalty in rupture life associated with the non-zero joint preparation angle.

The experiments in this work cover a significant range in heat input (0·8–2·4 kJ mm^{-1}) and although there may be some benefit associated with using a higher heat input, it can be concluded that any effect of heat input on the tendency for type IV failure is small.

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 establish how the effects of welding procedures, as identified in this laboratory study, might translate to full size joints under more realistic service conditions where the service lives are also greater than 10 000 h.

The mechanism(s) by which the preheat temperature influences the propensity for type IV failure in 9–12%Cr steel welds remain unclear and provide a subject for future work.

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