Note

Estimation of Type IV Cracking Tendency in Power Plant Steels

J. A. FRANCIS, W. MAZUR and H. K. D. H. BHADESHIA[1)]

CSIRO Manufacturing and Infrastructure Technology, 32 Audley Street, Woodville North, SA 5012, Australia.
E-mail: john.francis@csiro.au
1) Department of Materials Science and Metallurgy, University of Cambridge, Pembroke Street, Cambridge CB2 3QZ, UK.
E-mail: hkdb@cus.cam.ac.uk

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1. Introduction

The cracking of welded joints is usually classified according to the position of the crack; Type I and Type II modes occur within the weld metal, the former confined to the weld metal whereas the latter may grow out of the weld into the plate; Type III cracking occurs in the coarse grained region of the heat-affected zone. Type IV cracking is a feature of welded joints in creep-resistant steels. It is associated with an enhanced rate of creep void formation in the fine grained and intercritically annealed heat-affected zones of the weld, leading to premature failure when compared with creep tests on the unwelded steel. These zones contain coarse carbide particles, leading to a reduction in creep strength; the particles also help nucleate voids. In a cross-weld test, the weakened Type IV region is sandwiched between the stronger base plate and coarse-grained heat affected zone. The resulting accumulation of creep damage in the Type IV region causes the premature failure.

Type IV cracking is prominent in the stronger 9–12 wt% chromium steels. Since the problem arises from the heterogeneous microstructure of the weld heat-affected zone, it can be eliminated by a reaustenitisation and tempering heat treatment.[1)] Unfortunately, this rarely is a practical option. Instead, components have to be designed allowing for a reduction $\Delta\sigma$ in the creep strength (or equivalent reduction in creep life) due to Type IV cracking.[2)]

The magnitude of $\Delta\sigma$ is known to depend on the chemical composition, heat treatment and the state of stress. It therefore has to be estimated experimentally for each application. This clearly is a limiting factor in the design process, whether it involves alloy development or welding. The purpose of the work presented here was to develop a method which allows for the estimation of Type IV limited creep rupture life, as a function of the steel composition and heat treatment.

2. Estimation Method

There have been many constitutive equations formulated to represent creep deformation, many of which are based on a detailed understanding of creep mechanisms.[3)] The equations are not, however, capable of making predictions based on the large number of variables that control the properties of modern steels. It is in this context that neural network models have been developed for ferritic steels.[4–9)] It is now possible to calculate the creep rupture life of these alloys as a function of the large number of variables listed in **Table 1**, which also shows the huge range of compositions and processing parameters which are represented in a single model. The corresponding range of creep rupture times is illustrated in **Fig. 1**. Given the Bayesian framework[10,11)] implemented in these neural networks, it is even possible to safely conduct calculations for novel sets of inputs because the predictions are associated with reliable measures of uncertainty.

The neural network model for creep[7)] is based on a huge knowledge base, consisting of more than 5 420 sets of creep rupture data on unwelded steels; this model is henceforth referred to as the *plate model*; the rupture stress calculated using this model is written σ_{PM}. Type IV cracking is, on the other hand, a feature of welded samples. Nevertheless, it is

Table 1. The standard set of input parameters in a neural network model of creep rupture strength. The chemical compositions are all in wt%. The cooling rate can be set discreetly to air cooling, furnace cooling or quenching.

Test temperature / K	353– 1023	Test time / h	≤193,000
Normalising temperature / K	1123–1473	C wt%	0.004–0.48
Duration / h	0.17–33	Si	0.01–0.86
Cooling rate		Mn	0.01–0.92
Tempering temperature / K	798–1323	P	0.001–0.0029
Duration / h	0.5–83.5	S	0.0005–0.02
Cooling rate		Cr	0.59–14.72
Annealing temperature / K	300–1023	Mo	0.0–2.99
Duration / h	0.5–90	W	0.0–3.93
Cooling rate		Ni	0.0–2.0
V wt %	0.0–3.0	Cu	0.0–1.56
N	0.001–0.1651	Nb	0.01–0.312
B	0–0.064	Al	0–0.057
Ta	0–1.6	Co	0–3.09
Re	0–1.69	O	0.003–0.035

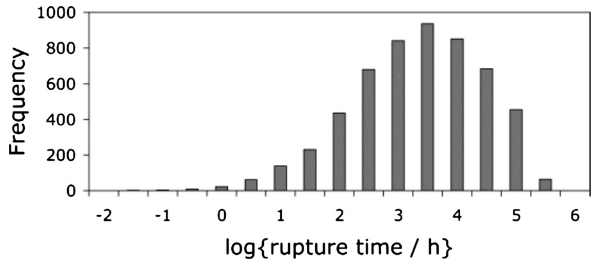

Fig. 1. The distribution of creep rupture times in the dataset used to create the published model for the estimation of the creep strength of ferritic steel plates.

well known that a cross-weld sample does not always fracture in the Type IV region. At high stresses, fracture occurs in the base plate away from the heat affected zone; it should then be possible to estimate the cross-weld rupture strength using the plate model.

On the other hand, if the plate model is applied to a cross-weld sample which fractures in the Type IV region then it is expected to overestimate the fracture strength by a factor $\Delta\sigma$.

Suppose that the magnitude of $\Delta\sigma$ could be estimated on analysing experimental data on cross-weld tests, then with this single fitting parameter, it becomes possible to predict Type IV fracture in all the steels represented by the plate model. If σ_{CW} represents the rupture stress of a cross-weld specimen, then:

$$\sigma_{CW}=\sigma_{PM} \qquad \text{fracture in plate}$$

$$\sigma_{CW}=\sigma_{PM}-\Delta\sigma \qquad \text{Type IV fracture}$$

This method assumes that the same principle for estimating σ_{CW} applies to every welded joint. We do not know whether this is justified, but any factors which have inadvertently been neglected will reflect in the standard error in estimating $\Delta\sigma$, as described below.

3. Results and Discussion

Experimental data from cross-weld tests are available in the published literature but the variables listed in Table 1 are not always reported. It was possible to find 53 sets of data where the chemical compositions and heat treatments were published in sufficient detail.[12–18] Of these, 41 represented Type IV failure and the rest fractured in the base or weld metal. The range covered by the cross-weld dataset is listed in **Table 2**. The welds were made using the gas tungsten arc or submerged arc welding processes, with heat inputs in the range 1.0–3.78 kJ mm^{-1}, preheat temperatures in the range 100–225°C, and joint preparation angles in the range 0–60°. To apply the plate model, the samples were assumed to have cooled in air from the heat-treatment temperatures, and the concentrations of Co, O, Ta and Re were assumed to be zero.

Values of σ_{PM} were calculated for each of these sets and compared against σ_{CW}, noting the position of fracture. In **Fig. 2**, it is evident that the plate model fairly accurately predicts σ_{CW} when the fracture occurs in the base plate away from the heat affected zone. As expected, the plate model on average overestimates σ_{CW} when failure is in the Type IV region. The solid points in Fig. 2 refer to fracture located in the base or weld metal; none of these points refer to the 12Cr steels since suitable data could not be found for fracture located in the plate.

Table 2. The range of concentration and heat treatment covered by the cross-weld test data.

C wt%	0.09	0.13
Si	0.02	0.34
Mn	0.41	0.81
P	0.001	0.018
S	0.001	0.006
Cr	8.6	12
Mo	0.34	0.95
W	0	2.21
Ni	0	0.35
Cu	0	3
Nb	0.05	0.15
Al	0	0.019
V	0.19	0.22
N	0.041	0.078
B	0	0.003
Normalising temperature / °C	1050	1080
Duration / h	0.5	2
Tempering temperature / °C	760	820
Duration / h	1	6
Post-Weld HT temperature / °C	740	745
Duration / h	4.5	8
Test temperature / °C	550	700
Test time / h	30	11220
Stress range	40	248

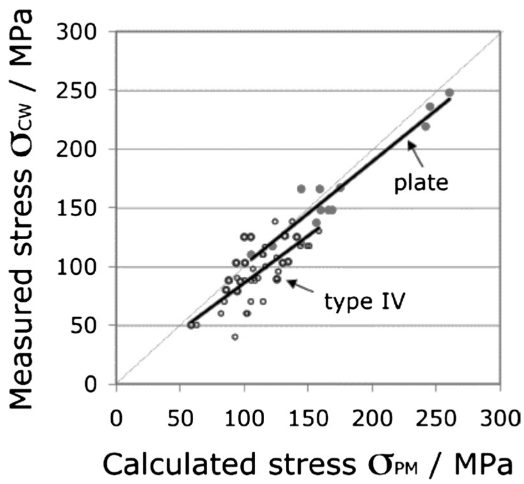

Fig. 2. Measured cross-weld rupture strength versus that calculated using the plate neural network model. The solid points correspond to failure either in the base metal or weld metal, whereas the open points correspond to tests that resulted in Type IV failure.

Figure 3 is a plot of $\Delta\sigma$, the deviation from the rupture stress calculated using the plate model. The standard error in estimating $\Delta\sigma$ is about ± 15 MPa because of the scatter in the Type IV data; this presumably arises from the assumptions implicit in the definition of σ_{CW}. The magnitude of $\Delta\sigma$ decreases as σ_{PM} decreases; this behaviour is expected given that the offset cannot exceed σ_{PM}. The offset nat-

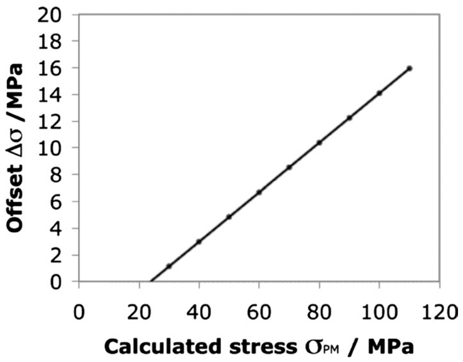

Fig. 3. Plot of estimated offset *versus* σ_{PM}.

urally does not apply when fracture occurs in the base plate; judging from published data, Type IV cracking predominates when the rupture stress is less than about 100 MPa (Fig. 2).

4. Conclusions

A methodology has been developed which permits the estimation of the weakening of a ferritic creep-resistant steel as a result of welding and the associated Type IV phenomenon. The creep rupture strength of the base plate is first calculated as a function of its full chemical composition and heat treatment. The calculated value is then offset to allow for Type IV weakening following welding. It is likely that the magnitude of the offset decreases as the applied stress is reduced. The analysis involves a variety of steels and yet, the transition from plate failure to Type IV failure seems to occur at about 100 MPa. The basis of this transition needs to be investigated quantitatively. The scatter in the cross-weld data also seems large when compared with the case where failure is in the base plate; it is possible that this is because welding parameters (process, heat input *etc.*) and weld geometry (edge preparation) are not accounted for in the present work.

Finally, it is worth noting that the software needed to do the calculations presented here is freely accessible on the world wide web; http://www.msm.cam.ac.uk/map/mapmain.html

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