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Novel Aspects of Ferritic Steels for the Generation of Electricity

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Abstract

Two of the major developments which may or may not lead to reduced levels of pollution during the generation of electricity are described. The first is the promise of fusion power and the potential role of ferritic steels in critical locations within the reactor. The second deals with a fabrication issue which may allow ferritic steels to be exploited at higher stresses or higher temperatures than previously possible.

1. Introduction

There are aspects of iron which are hidden from ordinary view but nevertheless have consequences on their macroscopic behaviour. An important example is that the magnetic properties of austenite are such that it has a much larger thermal expansion coefficient that ferrite [1,2]. When considered for elevated temperature service, materials with large thermal expansivities become susceptible to thermal fatigue, especially in thick sections of the kind frequent in power generation. This is why austenitic steels, in spite of their superior creep strength, are rejected in favour of ferritic steels for the construction of power plant. Ferrite has a much smaller thermal expansion coefficient than austenite.

Ferrite has another major advantage over austenite. When bombarded with neutrons, its tendency to swell is much smaller. This makes it a phase of choice when considering the construction of the next fusion reactor, codenamed ITER.

The metallurgy of ferritic steels destined for the most efficient of power plants is a huge subject [e.g., 3-11]. I intend therefore to focus on two specific topics which are especially interesting, ferritic steels for the fusion reactor and a major development in the welding of ferritic steels, the mechanism of which is not yet understood.

2. Fusion

There has been a surge in the expectation that nuclear fusion will deliver energy within the life time of the present generation of human beings. The ITER project has begun and is supposed to be a precursor to commercial plant, once the materials issues are resolved. It is likely that steels capable of sustaining some 200 displacements per atom, and 2000 appm of transmutation helium over the intended life, will form the key structural elements of the reactor. The conditions described here are severe when compared with fisson reactors and have not been reproduced experimentally – indeed, experiments are not even possible over the next 10 years. When appropriate test facilities become available, the quantity of testing possible will be minimal when compared with the need.

In these circumstances, the only approach left is theoretical modelling. Whereas there is a lot of atomistic and molecular dynamics research on the irradiation damage and associated effects, there is little quantitative work on the changes in mechanical properties. This is because mechanical properties are complicated functions dependent of both engineering and atomic phenomena.

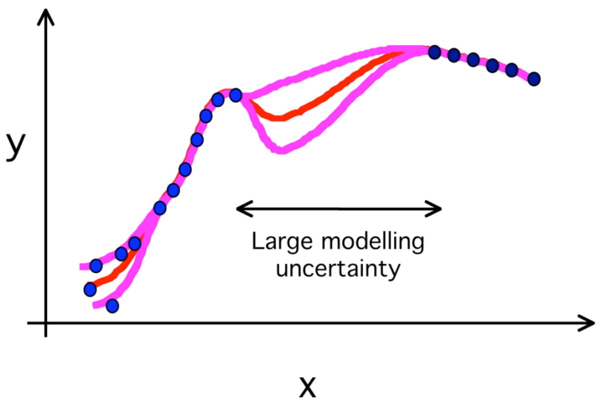

Fig. 1. Modelling uncertainty.

One approach which attempts to deal with mechanical properties at a realistic level of complexity involves neural networks. The details of the method have been described elsewhere [12], but the method is essentially multidimensional, nonlinear regression analysis. However, when implemented in a Bayesian framework [13,14], it becomes the method of choice for cases involving large numbers of interacting variables. This is because it not only yields an estimate of the level of noise in the output, but also the *modelling uncertainty* (Fig. 1). This latter quantity varies with the position in the input space where calculations are done, and is large whenever that space is sparsely populated, *i.e.*, during extrapolation. In this way, the dangers normally associated with the extrapolation of nonlinear regression functions are minimised. Figure 1 illustrates that all of the three mathematical functions represented by the curves adequately represent the experimental data but behave differently in the domain where data do not exist. That domain is said to exhibit a large modelling uncertainty, the magnitude of which may vary with the position in the input space where the calculations are done.

We now see how these concepts apply when attempting to extrapolate well beyond contemporary knowledge. Fig. 2 shows calculations for an alloy known in fusion research as Eurofer97 [15], which has the chemical composition Fe-0.1C-9Cr-1.1W-0.15Ta-0.2V wt%, essentially a reduced activation version of the 9Cr1Mo steel used in ordinary power generation [16]. The plot shows the yield strength as a function of the test temperature (in this case identical to the irradiation temperature) and the dose per atom (dpa).

The plot in Fig. 2b shows the modelling uncertainties which are small at low dpa but become comparable to the actual strength at high dpa and low temperatures. Those estimates must obviously be regarded with caution, but they identify two important outcomes. Firstly, physical theory should be developed to see whether the form of the extrapolation is justified. After all, it seems reasonable to assume that low temperatures and high doses should lead to enormous hardening since defects created by radiation damage will to a greater extent be retained in the microstructure.

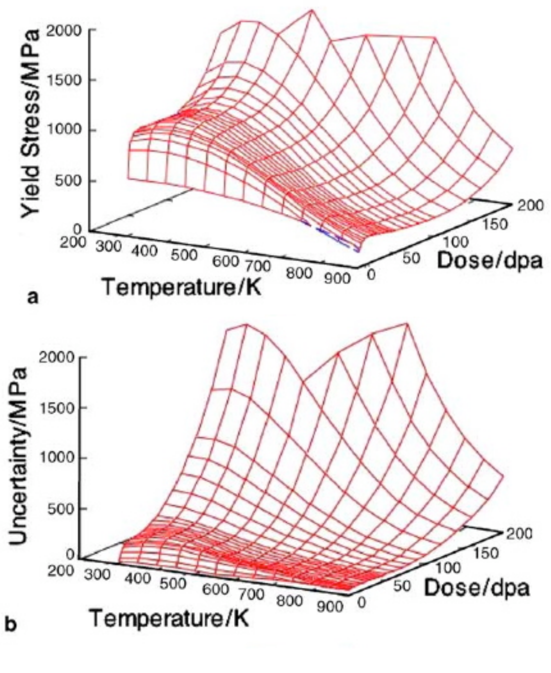

Fig. 2. The yield strength and associated uncertainties for Eurofer 97 as a function of irradiation temperature (equal here to the testing temperatures) and dose [15].

Secondly, the work identifies regions in which experiments could be most efficiently carried out when very expensive and limited irradiation-volume facilities become available over the next decade. It clearly is not worth focusing effort in the low dose, low uncertainty region of Fig. 2, but rather, the research should be most fruitful wherever the magnitude of the uncertainty is unacceptable. Predicted strengths much greater than 1000 MPa would be associated with dramatic and unacceptable reductions in toughness, and clearly should be verified experimentally or otherwise.

Fig. 3 shows some interesting predictions, also for Eurofer 97, together with some experimental data [16,17]. The predicted maximum is physically justified by the fact that at high temperatures the irradiation-induced defects can be annealed during bombardment, whereas at low temperatures the irradiation-induced cascades are not sufficiently mobile to form extended defects such a s dislocations.

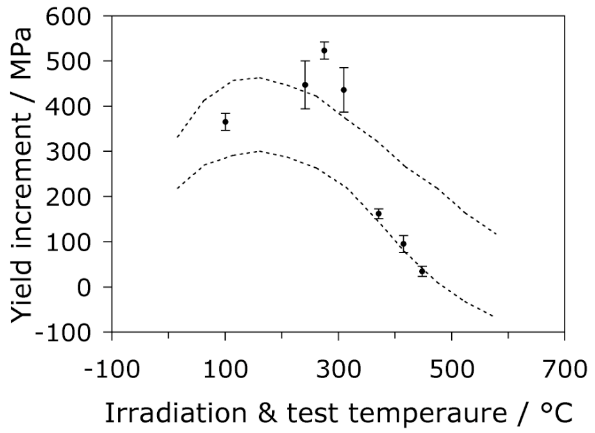

Fig. 3. The two lines represent the uncertainty of the predicted hardening range for Eurofer 97, for 3 dpa, as a function of temperature [15]. The data are due to Yamamoto *et al.* [17].

The mechanical property models described here are important in that they are the only ones capable of dealing with the real complexity of steels. They also are helpful in defining experiments, which is of extreme importance in fusion research which tends to be incredibly expensive.

There have also been interesting outcomes from physical models which attempt to study limited aspects of the problem, as briefly described below. Recent work of this kind has focused on the effective treatment of the nucleation of voids in irradiated ferritic steels [18]. Irradiation leads to an excess of vacancies which in combination with transmutation-induced helium atoms, condense to form bubbles. It has been demonstrated using a quasichemical solution model and classical theory, that it is reasonable to neglect the nucleation stage of bubbles in steels serving in a fusion reactor. This surprising conclusion occurs because the steady state helium concentration expected under irradiation inside the steel is much larger than its incredibly small equilibrium concentration. The critical size of the bubble at nucleation is so small that the activation energy is negligible and calculations of swelling can begin by assuming that the process involves the growth of a fixed number density of bubbles. The increase in bubble size then depends on the rate at which helium atoms are incorporated into the bubbles.

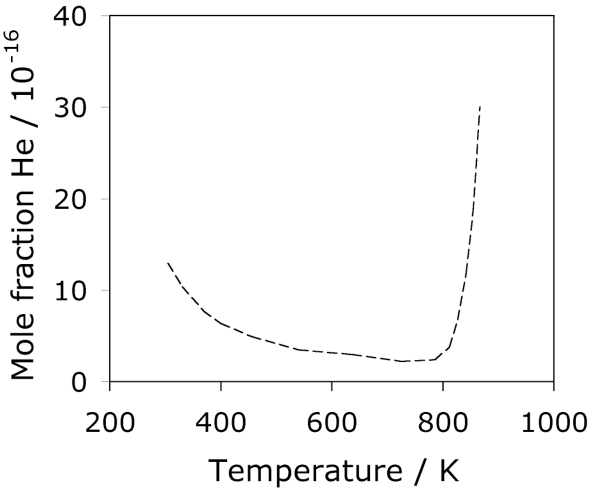

Fig. 4. Dissolved helium in iron under fusion conditions. The minimum occurs because at low temperatures resolution of He dominates whereas at high temperature vacancy-detrapping dominates. The concentrations although very small, are far greater than expected at equilibrium, thus providing a very large driving force for nucleation. [18].

4. Type IV Cracking

There have been concerted world-wide efforts to develop steels suitable for use in efficient fossil-fired power plants. Ferritic alloys containing between 9 and 12 wt % chromium are seen as the most promising materials in this respect, especially for thick-walled components such as headers and the main steam pipe in boilers. However, the performance of the improved steels has often not been realised in service, because premature failures occur in the heat-affected zone of welded joints in a phenomenon referred to as *type IV cracking* [19].

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 (Fig. 5).

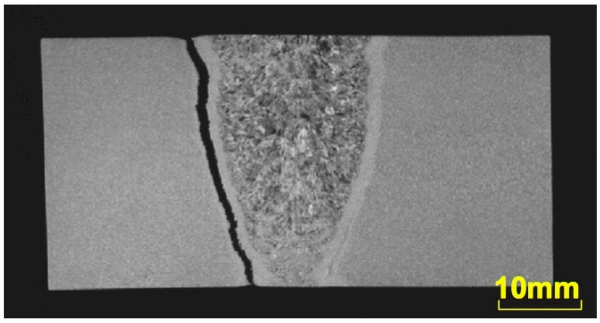

Fig. 5. An illustration of Type IV cracking in a welded joint exposed to creep deformation at elevated temperatures. Photograph courtesy of F. Masuyama.

Type IV failures occur because of gradients of microstructure in the heat affected zones of welds. The variety of regions has been categorised as follows [20]:

(a) *Coarse-grained region*, close to the fusion surface, reaching temperatures well about Ac_3. Carbides dissolve, thus removing obstacles to grain coarsening. In the 9-12Cr steels, this austenite transforms into martensite on cooling.
(b) *Fine-grained regions*, away from the fusion surface but where the peak temperature still leads to a fully austenitic grain structure, albeit limited in scale by undissolved carbides. Transforms into martensite on cooling (9-12Cr).
(c) *Intercritical region,* with peak temperature between the Ac_3 and Ac_3 temperatures. Partial transformation to austenite with remaining portion tempered.
(d) *Over-tempered region.*

From the point of view of modern steels, the microstructure weakest in creep appears to be the fine-grained region of the weld [19]. It has the coarsest (undissolved) carbides and the lowest creep rupture life at low stresses of the kind encountered in service. There is a certain degree of grain boundary sliding in this zone which leads to a relaxation of constraint, making failure easier [21].

Therefore, anything that is done to strengthen grain boundaries, for example the addition of boron, may allow constraint to appear in a cross-weld test, thereby increasing the life for type IV fracture.

Some important results have recently been reported on the influence of boron in the 9-12Cr steels [22]. Type IV failure was completely eliminated in a 9Cr-3W-3CoVNb steel containing boron in the range 90-130 ppmw, with nitrogen kept below 0.002 wt%. Furthermore, a strange microstructure in which the austenite grains remained large at a distance of 1-2 mm from the fusion surface, where the fine-grained austenite is usually observed, was obtained. The reasons for the absence of the fine-grained zone are not clear, but is has been suggested [22] that it may have something to do with the low nitrogen content, which in turn reduces the quantity of MX precipitates, thus allowing austenite grains to coarsen.

The exciting outcome is that the creep fracture time of cross-weld specimens was found to be identical to that of the unwelded parent material. This development is of enormous industrial importance since it will allow the full exploitation of the creep-resistant steels.

To summarise, evidence suggests that type IV cracking can be completely eliminated using controlled additions of boron. The heat affected zones then do not contain a fine grained region susceptible to type IV cracking. There are details of the mechanism which are not understood [19] and warrant further fundamental research.

5. Summary

I have deliberately chosen here to focus on two specific issues rather than to describe the general field of ferritic steels for the efficient generation of electricity. Instead, I have highlighted two interesting developments which may have major repercussions. The first of these involves steels destined for the fusion reactor, where mathematical models have been used to suggest a scheme of experiments and to investigate fundamental aspects. The second deals with the possibility that the disease of Type IV cracking may now have been solved.

6. Acknowledgment

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7. References

1. R. J. Weiss and K. J. Tauer, Physical Review 102 (1956) 1490.
2. L. Kaufman, E. V. Clougherty and R. J. Weiss, Acta Metallurgica 11 (1963) 323.
3. F. Abe, Current Opinion in Solid State and Materials Science, 8 (2004) 313.
4. H. K. D. H. Bhadeshia, ISIJ International, 41 (2001) 626.
5. H. K. D. H. Bhadeshia, A. Strang and D. J. Gooch, International Materials Reviews, 43 (1998) 45.
6. F. Masuyama, Recent Developments in Creep-Resistant Steels, Liege Conference (2002).
7. K. Kimura, H. Kushima, F. Abe and K. Yagi, Materials Science and Engineering A234-236 (1997) 1079.
8. H. J. R. Blum and J. Hald, Advanced Steam Plant, Institution of Mechanical Engineers, London (1997) 3.
9. H. K. D. H. Bhadeshia, Encyclopedia of Comprehensive Structural Integrity, vol. 5, Chapter 1 (2003) 1,
10. R. W. Vanstone and D. V. Thornton, Advanced Steam Plant, Institution of Mechanical Engineers, London (1997) 87.
11. K. Ehrlich, E. E. Bloom and T. Kondo, Journal of Nuclear Materials 283-287 (2000) 79.
12. H. K. D. H. Bhadeshia, ISIJ International, 39 (1999) 966.
13. D. J. C. MacKay, Neural Computation, 4 (1992) 415.
14. D. J. C. MacKay, Neural Computation, 4 (1992) 448.
15. R. Kemp, G. A. Cottrell, H. K. D. H. Bhadeshia, G. R. Odette, T. Yamamoto and H. Kishimoto, Journal of Nuclear Materials, 348 (2006) 311.
16. R. L. Klueh, Current Opinion in Solid State and Materials Science, 8 (2004) 239.
17. T. Yamamoto et al., ORNL report DOE/ER-0313/35, Oak Ridge National Laboratories, Tennessee, USA (2003) 100-113.
18. R. Kemp, G. A. Cottrell and H. K. D. H. Bhadeshia, Energy Materials 1 (2006) 103.
19. J. Francis, W. Mazur and H. K. D. H. Bhadeshia, Materials Science and Technology, 22 (2006) 1387.
20. S. L. Mannan and K. Laha, Trans. Indian Institute of Metals, 49 (1996) 303.
21. S. T. Kimmins and D. J. Smith, Journal of Strain Analysis, 33 (1998) 195.
22. S. K. Albert, M. Kondo, M. Tabuchi, F. Yin, K. Sawada and F. Abe, Metallurgical and Materials Transactions 36A (2005) 333.