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On quantification of helium embrittlement in ferritic/martensitic steels

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Abstract

Helium accumulation due to transmutation has long been considered a potential cause for embrittlement in ferritic/martensitic steels. Three Charpy impact databases involving nickel- and boron-doped alloys are quantified with respect to helium accumulation, and it is shown that all predict a very large effect of helium production on embrittlement. If these predictions are valid, then use of ferritic/martensitic steels for fusion first wall applications is highly unlikely. It is therefore necessary to reorient efforts regarding development of these steels for fusion applications to concentrate on the issue of helium embrittlement.

1. Introduction

Helium accumulation due to transmutation has long been considered a potential cause for embrittlement in ferritic/martensitic steels. A concern in developing structural materials for fusion power systems is the consequence of transmutation-induced helium and hydrogen on material properties. For the advanced ferritic steel fusion materials option, helium (in appm) will be generated at about 10 times the dpa rate, and hydrogen approximately 10 times more rapidly than helium. Experiments to define the effect of helium remain controversial, but severe effects of helium accumulation on fracture toughness have been claimed [1,2]. It is therefore very important to evaluate these transmutation effects and attempt to quantify the magnitude of the behavior in order to establish whether steels can be successfully adapted for fusion applications.

2. Databases

Three studies of Charpy impact response due to neutron irradiation in ferritic/martensitic steels have shown large shifts in ductile-to-brittle transition temperature (DBTT), and the authors have shown a correlation with helium production during irradiation [3–5]. Klueh and Alexander at ORNL studied nickel-doped alloys similar to HT9 (12Cr–1MoVW) and T91 (9Cr–1MoVNb) with additions of up to 2% Ni and determined the shift in DBTT. They found that shifts in DBTT could be as large as 340°C in 12Cr steels containing 2% Ni following irradiation in HFIR (Oak Ridge, TN), and when these results were compared with results available on similar steels irradiated in EBR-II (Idaho Falls, ID) and HFIR, an explanation could be found based on helium-affected fracture. The authors did not do so but the response could be quantified as a function of helium generation [6] as shown in Fig. 1 for specimens irradiated at about 400°C. The correlation indicates bi-linear behavior with a large increase in DBTT for low levels of helium generation to 2 appm He followed by linear behavior for higher levels of helium.

Materna-Morris and coworkers at FZK Karlsruhe, studied irradiation embrittlement in a series of low-activation martensitic steels (7–12CrWVTa) following irradiation in the HFR (Petten, Netherlands) at 250°C and found shifts in DBTT as large as 145°C. They were able to correlate this behavior with B content in the alloys and predicted that the behavior was controlled by transmutation production of helium. They supported their predictions with electron microscopy showing helium bubbles. Their quantification of the behavior is

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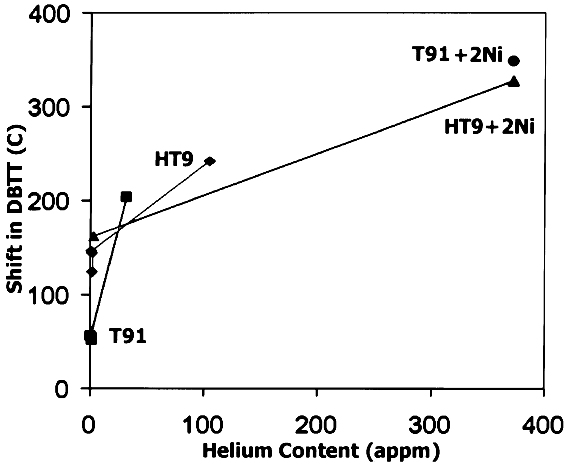

Fig. 1. Shift in DBTT as a function of helium content following irradiation of Ni-doped 9Cr and 12Cr steels in HFIR and EBR-II at 390–400°C.

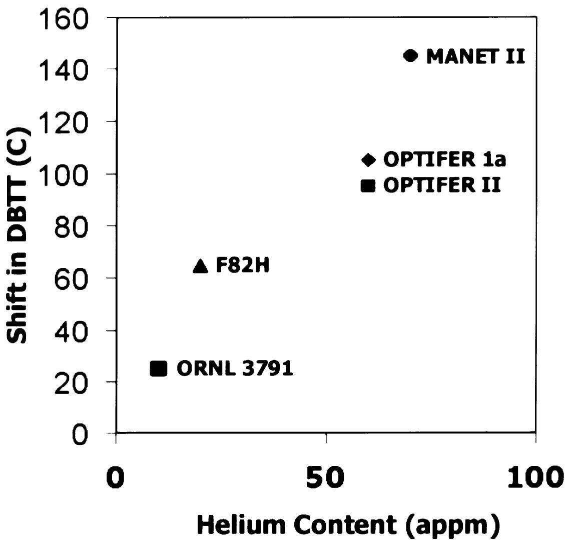

Fig. 2. Shift in DBTT as a function of helium content following irradiation of ^{10}B-doped low-activation martensitic steels in HFR at 250°C.

reproduced in Fig. 2 showing shift in DBTT as a function of He content as calculated based on complete burn-up of ^{10}B. Fig. 2 shows somewhat different behavior from Fig. 1, with approximately linear response with increasing He content.

Shiba and coworkers at JAERI have been irradiating low-activation martensitic steels doped with ^{10}B in the JMTR (Oarai, Japan) at 300°C and 400°C. The base composition was F82H (7Cr–2WVTa) and ^{10}B levels were 0.006 or 0.03 at.%. The database is limited and the

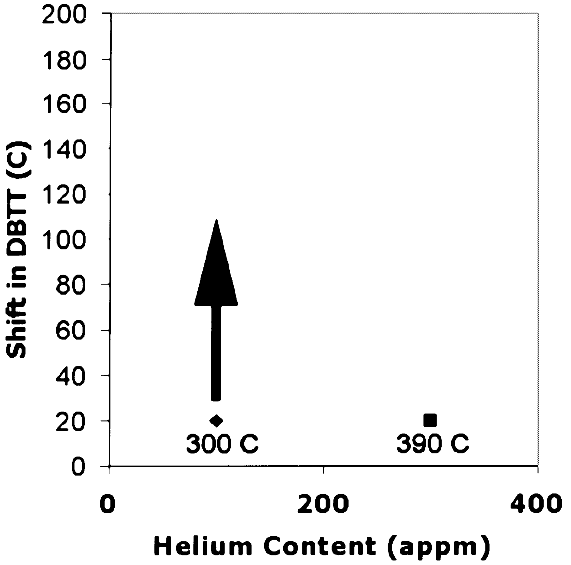

Fig. 3. Shift in DBTT as a function of helium content following irradiation of ^{10}B-doped low-activation steel F82H in JMTR.

doses in JMTR are low, but an effect of helium can be demonstrated. Irradiation of the standard alloy produces a shift of 50°C following irradiation at 230–320°C, whereas the ^{10}B-doped alloy is found to remain fully brittle 20°C above the DBTT in the unirradiated condition. Therefore, the shift in DBTT for the ^{10}B-doped alloy must be greater than 20°C. At 400°C, the shift due to ^{10}B additions is approximately 20°C. Shift in DBTT response as a function of calculated helium production is shown in Fig. 3 with an arrow provided for the 230–320°C irradiation (and labeled 300°C) to indicate that the shift in DBTT was larger than 20°C. Without a better definition of shift in DBTT for the lower irradiation temperature testing, this figure can only demonstrate a stronger effect at the lower irradiation temperature. Therefore, this work appears to support the German conclusions for irradiation at about 250°C but quantification is difficult without more data.

It can be noted that other studies have drawn opposite conclusions based on precipitation, hydrogen generation, and charged-particle irradiations [7–9], but these studies will not be described in detail here. Suffice it to say that there is insufficient information to conclude absolutely that the above descriptions correctly describe helium embrittlement in ferritic/martensitic steels in a fusion environment.

3. Implications for a fusion machine

Transmutations expected in a fusion environment will create approximately 10 appm He and 100 appm H per dpa. Machine designs often specify 10 MW yr/m^2 first wall lifetimes corresponding to doses in the order of 100 dpa. Therefore, He generation in a fusion first wall will create lifetime levels in the order of 1000 appm He, an order of magnitude higher than those studied in the above examples.

If the above estimations of embrittlement due to He transmutations are valid, it is apparent that design engineers will have a major task incorporating a ferritic steel first wall with properties that change dramatically, and become embrittled at only modest dose. Also, if the design issues are too challenging for ferritic/martensitic alloys, it is unlikely that we will find that our other candidate alloy systems will avoid this problem. Therefore, it can be concluded that if the above description of helium embrittlement is valid, it is unlikely that it will be possible to construct a commercial fusion power plant based on present concepts.

4. Discussion

Unfortunately, it is difficult to verify or refute the above claims of helium embrittlement. Experiments to study transmutation effects really require the correct neutron spectrum, but similar neutron or charged-particle spectra can be used and elaborate experimental setups based on charged-particle irradiations, adding transmutable components such as Ni and ^{10}B, or by using isotopic tailoring [7,8] can be useful.

Furthermore, reactor designers are expected to be unwilling to develop designs based on Charpy impact data; fracture toughness measurements will likely be needed. Miniaturization of Charpy impact testing is considerably further developed than is miniaturization of fracture toughness testing (although fractographic information may some day lend itself to a simplified procedure for fracture toughness estimation). Therefore, experiments to provide the necessary confirmation of embrittlement behavior due to helium production for design applications are needed. A 14-MeV neutron source may be required, but simpler experiments can be envisioned to confirm or refute the results shown here. Certainly, if the above behavior applies, it is unlikely that any materials are available for construction of a fusion machine intended for commercial energy production.

5. Conclusions

Three databases are available that predict large effects of embrittlement due to production of helium from transmutation in ferritic/martensitic steels. Although these predictions are controversial, it is apparent that validation of the behavior in a fracture toughness database is not now possible within the constraints of available funding and irradiation facilities. Furthermore, if sufficient resources that are found to demonstrate these pessimistic predictions are valid, it is unlikely that any of the candidate materials now being considered for fusion structural materials will allow construction of a viable commercial machine and production of energy by fusion as we now envision it will be impossible.

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