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Stability of ferritic steel to higher doses: Survey of reactor pressure vessel steel data and comparison with candidate materials for future nuclear systems

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A B S T R A C T

This paper is illustrating the potential of the well-known low alloyed clean steels, extensively used for the current light water Reactor Pressure Vessels (RPV) steels, for a likely use as a structural material also for the new generation nuclear systems. This option would provide, especially for large components, affordable, easily accessible and a technically more convenient solution in terms of manufacturing and joining techniques.

A comprehensive comparison between several sets of surveillance and research data available for a number of RPV clean steels for doses up to 1.5 dpa, and up to 12 dpa for 9%Cr steels, is carried out in order to evaluate radiation stability of the currently used RPV clean steels even at higher doses. Based on the numerous data available, positive preliminary conclusions are drawn regarding the eventual use of clean RPV steels for the massive structural components of the new reactor systems.

1. Background

Ferritic steels have been considered as candidate structural materials for fusion power plants since the late 1970s. The reason being is that the data obtained from fast reactor irradiation shows that ferritic steels are more swelling resistant than austenitic stainless steels. Moreover, their higher thermal conductivity and lower thermal expansion coefficients lead to improved resistance to thermal stresses characteristic for a fusion power plant operating in a pulsed mode.

Mainly high Cr (9–12%) steels are considered as candidates for fusion applications. High dose data after fast neutron irradiation at different irradiation temperatures were published since the 1980s [1–3]. To a lesser extent, low chromium–molybdenum steels have also become of interest as first wall and blanket structural material for fusion reactors [4].

Extensive research and development efforts have been conducted on the unmodified Cr–Mo steels, especially on 2.25Cr–1Mo. Considerable work has been also been performed on developing and characterising modified low-Cr steel with additions of V, Nb, Ti and W [5,6]. In a number of publications the tensile and impact Charpy properties of unmodified and modified low chromium steels are directly compared with high chromium (9%Cr and 12%Cr) steels [7–9].

The reasons for using more conventional low-Cr steels are several: despite the excellent behaviour of the 9%Cr steels, there are some advantages for low-Cr steel. Ferritic steel, including several Cr–Mo steels, have been found to have excellent swelling resistance [10,11] and thus, considered for fast breeder reactors. Annealed 2.25Cr–1Mo steel was selected for breeder reactor steam generators, and the present ASME code-allowable stresses for elevated-temperature nuclear applications (Code Case N-47) were determined using annealed data [4].

Significantly lower production cost for low-Cr steel is an important factor: Cr is a strategic material; pure Cr costs $32 per 100 g [12] and its conservation would have a huge economic advantage in industrial scale. Besides, 99% of the world's Cr reserves are located in Zimbabwe and the Republic of South Africa. Such a huge dependence on the Cr delivery is a pursuable incentive to

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decrease the Cr concentration of any alloy being considered for use in large tonnages. This incentive, along with the economic stimulus (cost drops with decreasing Cr concentration) are behind continues drive to replace high-Cr austenitic stainless steels with Cr–Mo alloys for elevated temperature applications [13].

Numerous publications are comparing creep data from low-Cr ferritic steels with 9Cr steels at elevated temperatures (538 °C). The available data indicate very little difference up to ~10 000 h rupture lifetimes [14,15]. Although the HT9 and modified 9Cr–1Mo steel appear slightly stronger than bainitic 2.25Cr–1Mo at 538 °C [16], there is not sufficient data available to establish one of these three steels as being distinctly superior to any of the others. A similar conclusion can be made for the modified 1Cr–1Mo [17] and the modified 2.25Cr [18] steels.

Another advantage could be the cost for post-weld heat treatment (PWHT). PWHT is absolutely indispensable for high Cr steels, whilst it might be avoided for low Cr steels: an important deliberation when complicated structures, such as fusion power reactors are involved. An economic advantage is that low-Cr steels might be used without tempering taking into account their bainitic structure [6].

Conventional low Cr steels are widely used by the industry – for structural parts (tubular sections), bolting applications up to 570 °C, or pressure vessel applications in thermal and nuclear power plants. Therefore, applications of this class of steel for future nuclear reactor vessels do not need extensive technology development. Even long term creep and thermal ageing properties are well known. Industrial experience in producing and operating low Cr–Mo steels in fossil plants up to 560 °C has been collected during the last 50 years. Where corrosion is not a serious factor, steels containing 5% and in some cases as low as 2% Cr (with 0.5% Mo) has been used in the industry for manufacturing of pressure vessels.

As regards the radiation resistance, a comprehensive set of irradiation data from industry, as well as research data up to intermediate doses during the past 30 years are available. The effect of the detrimental impurities (Cu and P) and some alloying elements (Ni) has been extensively studied and the required knowledge is available.

However, future reactors will operate at elevated temperatures and under high neutron irradiation fluences. The higher operational temperatures might be seen actually as an advantage for relieving the irradiation induced damage: it is very well known that at temperatures of 400–500 °C significant annealing of the irradiation defects takes place. This will mitigate the effect of the higher fluences envisaged in the future reactors. Yet, the radiation stability of the low-Cr steels needs to be confirmed for very high doses.

2. Introduction

Since decades low-alloyed steels have been developed and are extensively used as RPV materials for LWR. The irradiation data from LWR during the past 30 years verify the radiation resistance of this class of steels. In particular, RPV materials with low content of impurities for the second and third generation of Nuclear Power Plants (NPP) have proven to have very high resistance to radiation damage, up to ~2 dpa. Their response to radiation is very well understood as well as the effect of deleterious impurities. Several models can be applied to predict the neutron irradiation embrittlement of RPV steels. There are three major contributors affecting the RPV damage: Cu-rich radiation induced precipitates (CRP), phosphorus segregation both intra-grain interfaces and at grain boundaries and the basic material matrix damage (MD), causing steel hardening [19,20]. Other factors, such as nickel content – acting as an amplifier, and the irradiation temperature, or the synergism between them, can also influence the irradiation damage through one or more of the three basic contributors [21]. For clean steels containing very low Cu and P content, the damage can be assumed to be dominated by the basic matrix damage due to creation of different defects during irradiation.

Typically, the values of the impurities' content for PWR reactors of the last generation are in fact very low: in the order of 0.05 wt% and 0.01 wt% for copper and phosphorus respectively. The same can be said for the recent WWER-440 and WWER-1000 RPVs, even if phosphorus levels may be slightly higher [22]. The MD is in this case mainly a result of permanent defects generated from the evolution of point defects and clusters in the bcc structure [23].

New advanced ferritic-martensitic (FM) materials have been designed for fusion applications, as for example Eurofer type steel [24]. Irradiation embrittlement data at very high doses (up to 70 dpa) for this material are already available also at 300 °C irradiation temperature [25–27].

The emphasis of the present paper is to explore the potential applicability of conventional 2.25%Cr RPV steels with very low level of impurities like Cu and P, as well as a low level of Ni as a structural bulk material in the new generation reactors for both fission and fusion. For this purpose, a comparison with high dose data mainly from Eurofer 97 steel was carried out. The analyses performed here is in fact based on direct comparison between surveillance and research embrittlement data from selected low Cr steels (1–2.25% Cr) available up to intermediate doses of 1.5 dpa and high doses (up to 10 dpa) Eurofer 97 data, as well as 9Cr2WVTa data up to 12 dpa. The comparison between all the materials is done on a common basis, using common damage index ‘dpa’, and the same reference temperature $T_{\mathrm{ref}} = 300$ °C. A straight comparison of irradiation damage rates of different clean ferritic steels is also done in order to show the similarity of the basic embrittlement kinetics of the different materials.

Additionally, high dose embrittlement research data obtained at irradiation temperature of 365 °C [9] for steels with different Cr content (from 2.25% to 12%Cr) are analysed and compared. The effect of Cr on the embrittlement kinetics is also outlined in this paper.

3. Utilised data and assumptions for their comparison

Critical sets of surveillance PWR data are used for this study. Representative clean ferritic western type PWR RPV steels [22] are selected. The upper fluence is approximately corresponding to 80–90 mdpa (milli-dpa). Additionally, surveillance data at ~270 °C taken from Russian type pressurised water reactor WWER-440 type are also considered in the study. An important remark should be made that only ‘clean’ steels with sufficiently low Cu and P content are utilised. The fluence range for WWER-440 steels [22] is higher, reaching approximately 450 mdpa, than for the western PWR steels. This data was already analysed in a previous work and published in a conference proceedings [28].

Further, new data are included in the analyses, presented hereafter. Recently published [29] WWER-440 research data from both base metal and weld metal, irradiated up to high doses reaching 1.5 dpa are also included. In order to normalise the WWER data obtained at slightly lower than 300 °C temperature, a correction factor has been introduced according to [30].

A set of surveillance RPV data up to 95 mdpa of the Dodewaard 50 MWe BWR in Dodewaard, Netherlands, decommissioned in 1997 is also used [31]. The RPV steel 1.2MD07 type A was specially developed for the Dodewaard unit. Preliminary accelerated irradiation tests on 1.2MD07 type A steel were performed at the High Flux Reactor HFR in Petten as a part of a Joint Norwegian-Dutch Steel Irradiation Project. The experiments consisted of a series of