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Introduction

Most of the information on ferritic/martensitic steels for nuclear applications comes from studies on commercial Cr-Mo steels, primarily 9–12% Cr, 1–2% Mo, 0.1–0.2% C with small amounts of V, Nb, W, Ni, etc. (Compositions throughout the book will be in wt% unless otherwise stated.) These were the ferritic steels considered first for fast breeder fission reactors in the early 1970s and then in the late 1970s for fusion applications. The steels became of interest because of their swelling resistance compared to austenitic stainless steels, which were the primary candidates for both applications up to that time [1,2].

In recent years, most of the developmental studies on the ferritic/martensitic steels for nuclear applications have been for fusion, and much of the discussion in this book will be on that application. Since the mid-1980s, the fusion materials programs in Japan, the European Union, and the USA have been developing ferritic/martensitic steels that would lessen the environmental impact of the irradiated and activated steel after the service lifetime of a fusion reactor. As discussed throughout this book, these new "reduced-activation" ferritic/martensitic steels display the same general behavior as the conventional steels, but there are quantitative differences. Often, some of the properties of the reduced-activation steels are better than those of the conventional steels.

The amount of data available for reduced-activation steels either in the unirradiated or irradiated condition is not as extensive as for the conventional steels, since many of the conventional steels are used for elevated-temperature applications to 550 to 600°C in the power-generation and petrochemical industries. As a result, the metallurgical characteristics and mechanical and physical properties of the conventional steels are reasonably well understood, and comprehensive mechanical properties compilations are available.

Fusion applications require information on some mechanical properties that differ from those normally measured (e.g., thermal fatigue). However, from the wealth of data available, indications are that a range of ferritic/martensitic steels have properties that make them viable candidates for fusion applications to 550 to 600°C. The maximum operating temperature will be determined by the creep properties and, under some circumstances, by the compatibility with the operating media (i.e., water, liquid lithium, liquid Pb-Li eutectic, etc.) of the fusion power plant. The major difference in the fission and fusion environments and the environments of most other applications is the neutron flux of the nuclear applications. Fast fission and fusion applications differ in this respect—a much higher-energy neutron flux is produced by fusion neutrons.

Chapter 2 provides some information on fission and fusion systems for which the high-chromium ferritic/martensitic steels are to be used. In fast reactors, ferritic/martensitic steels are considered primarily in the fuel subassembly as fuel pin cladding and wrapper material. The use of these steels as structural materials for a fusion reactor first wall and blanket structure provides a much bigger challenge, and considerable work on determining a range of properties has been carried out for this application. Much of the work on irradiated steels for both fast fission and fusion applications has been on steels irradiated in fast reactors. Because in recent years the development of fast fission reactors has been de-emphasized while work on the fusion application continued, much of the emphasis of the discussion in this book is on the fusion application. However, most of the information obtained in the fusion program applies for fast fission applications, because most neutron irradiations were carried out in fission reactors, and mostly in fast reactors.

This book will show that fission and fusion reactors present a difficult challenge for the materials community, but it will also demonstrate that considerable progress has been made. The following two sections of this chapter will provide a brief introduction to some of the ways ferritic/martensitic steels will help meet the challenge.

ADVANTAGES AND LIMITATIONS OF MARTENSITIC STEELS FOR FUSION

Austenitic stainless steels were the first structural materials considered for both fast fission and fusion applications. To reach higher operating temperatures (≥700°C) in a fusion plant, superalloys and refractory metal (Nb, Mo, V, and Ti) alloys were considered. Ferritic/martensitic steels were not considered originally for fission because of elevated-temperature strength and coolant compatibility considerations. They were not considered originally for fusion because of the fear of possible complications caused by the interaction of a ferromagnetic material within the high magnetic fields in a fusion plant. The steels were considered only after preliminary calculations [3–5] indicated that possible problems caused by a ferromagnetic material can be handled in the reactor design.

Two types of problems are of concern with the use of a ferromagnetic material in the high magnetic field of a fusion reactor: (1) the effect of the field perturbation caused by the ferromagnetic material on the plasma, and (2) the magnetostatic forces on the ferromagnetic structure due to the magnetic field. Early calculations [3–5] indicated that the field pertubations were small and confined to the end region and on the same order of magnitude as the field ripples produced by the central cell magnets. Based on the calculations of the magnetostatic forces on a ferritic steel pipe in the magnetic field of the machine, the stresses were found to be small but not negligible, and it was concluded that they must be incorporated in the stress analysis of the design [3–5]. Similar results have been obtained by later calculations [6–10]. It must be emphasized that the favorable conclusions on the ferromagnetic interactions were reached from simplified calculations (e.g., the calculation of stresses on a coolant pipe, etc.). No comprehensive analysis of ferromagnetic effects for the blanket structure and primary coolant circuit has been attempted, although such studies are presently in progress in Japan [9]. Experimental work is also in progress in Japan, where a ferritic steel liner is being installed in a small tokamak vessel [10].

As a result of work during the last 20 years or so, most of the refractory metals have been eliminated for use as the structural material of the first wall and blanket structures because of inadequate physical or mechanical properties or because they did not meet the reduced-activation criteria to be discussed below. Austenitic stainless steels are considered unsuitable for a fusion power plant because of high swelling rates and high thermal stresses caused by the low thermal conductivity and high thermal expansion coefficient. Austenitic stainless steels are still considered as the structural material for experimental fusion machines, such as the International Thermonuclear Test Reactor (ITER). At present, there are only three materials considered viable candidates for structural components for a fusion power plant: vanadium alloys, SiC/SiC composites, and ferritic/martensitic steels.

Martensitic steels containing 9–12% Cr with about 1% Mo, 0.1–0.2% C and combinations of small amounts of V, W, Nb, etc., have the strength, including elevated-temperature strength, and thermal properties (conductivity and expansion coefficient) that result in excellent resistance to thermal stresses [1]. Creep strength of these types of steels is adequate to 550 to 600°C, and they have been used at these temperatures in the power-generation and chemical and petrochemical industries.

Because of the widespread use in industrial applications, the technology for production and fabrication of all types of product forms exists [11]. All conventional melting practices as well as various special melting techniques, including electron-beam, electroslag, and vacuum melting, have been used to produce the steels. The steels are hot and cold workable by all methods. Forgings up to 70 tons have been produced, and the steels can be rolled to thin sheet and strip. Standard heat treatment facilities are adequate for the normalizing and tempering or quenching and tempering conditions that the steels require before use.

Any structural material used for fabrication of a fusion power plant would have to receive the appropriate code approval for the country in which the plant was constructed (i.e., ASME Boiler and Pressure Vessel Code, etc.). Conventional ferritic/martensitic steels of the type being considered for fusion have been approved for design by code bodies in the USA, Europe, and Japan. In the USA, modified 9Cr-1Mo (nominally Fe-9Cr-1Mo-0.25V-0.06Nb-0.1C) and 2¼Cr-1Mo (nominally Fe-2.25Cr-1Mo-0.1C) steels are included in the ASME Boiler and Pressure Vessel Code Section VIII for petrochemical and chemical pressure vessels and in Section III for nuclear pressure vessels, including high-temperature liquid metal fast fission reactor systems, as described in ASME Code Case N-47.

Welding will be required in the fabrication of a fusion power plant, and ferritic/martensitic steels are readily weldable. However, stringent procedures are required to obtain quality welds with maximum properties. For the 9–12% Cr steels, a preheat of 150 to 450°C [12–14] is generally required. In some cases, interpass temperature control can be used to prevent transformation to untempered martensite. Finally, a post-weld heat treatment (PWHT) is required as soon as possible after welding to temper the martensite in the high-chromium (5 to 12%) steels. (Low-chromium steels, e.g., 2¼Cr-1Mo, are weldable with fewer restrictions.) Welding will be discussed in detail in Chapter 7.

A fusion power plant will require field erection, which means that for a 9–12% Cr structural steel the preheat and PWHT will be performed in the field. The technology of field fabrication is well developed [15]. Pressure vessels for nuclear and petrochemical applications have been built in compliance with the ASME Code. Examples of large structures that have been fabricated in the field include: (1) nuclear containment vessels 46 m in diameter, over 73 m high, weighing over 6350 tons with the entire structure given a PWHT in the field; (2) 91-m-high heavy water columns up to 8.5-m diameter (1900 metric tons) with the entire structure given a field PWHT; and (3) coal-conversion vessels 59-m high with unit weights of 760 metric tons and wall thicknesses up to 89 mm [15]. Therefore, the technology for field fabrication of a steel fusion structure will not have to be developed.

Of the three materials presently considered for fusion applications, ferritic steels have the advantage for the construction of the massive structure of a fusion power plant based on past experience. For both vanadium and SiC/SiC composites, the techniques for constructing such a structure (joining, etc.) must still be developed. In addition, these materials have numerous problems that must be solved before the feasibility of their use can be proved. Besides the problem of a ferromagnetic material in high magnetic fields discussed above, the most serious problem faced by ferritic/martensitic steels is the effect of neutron irradiation on the fracture behavior, which will be discussed in detail in later chapters.

LOW- AND REDUCED-ACTIVATION CONSIDERATIONS

The safety of a fusion power plant depends on (1) the structural integrity of the plant and the probability of its failure, (2) the radioactive decay heat generated in the absence of coolant, and (3) the paths for dispersion of radioactivity to the plant surroundings during an accident. The ideal structural material for accident conditions, as well as normal operations, would be a “low-activation” material, that is, one that would not activate (would not become radioactive), would activate to a benign level, or, alternatively, one that would quickly decay (within minutes or hours) to a benign level after activation [16]. A low-activation material would negate the consequences of a loss of coolant accident or any other incident that could cause an accidental release of radioactive debris. Such a material would also allow for "hands-on" maintenance of the plant, instead of the much more complicated and expensive remote maintenance required with a radioactive plant.

At present, no "low-activation" structural materials as defined above exist. A recent study (discussed in detail in Chapter 2) [17] indicates that the activation of SiC, which has often been labeled "low activation," is considerably lower than a V-5Cr-5Ti alloy and OPTIFER, a Cr-W ferritic/martensitic steel developed for "reduced activation" in the European Union. Indeed, according to the study [17], the activity of SiC about 100 y after shutdown is higher than that of V-5Cr-5Ti and OPTIFER. Therefore, safety will need to be engineered into a fusion structure constructed from a vanadium alloy, a SiC/SiC composite, or a reduced-activation ferritic steel.

Environmental effects will be produced from the disposal of fusion reactor components when they are replaced during operation or following the decommissioning of the plant [16]. This radioactive waste will have to be disposed of in a safe manner harmless to the environment. Depending on the elements present, the decay of induced radioactivity in a conventional ferritic/martensitic steel can take thousands of years. Such highly radioactive nuclear waste is disposed of by deep geological storage. To improve this situation, programs in Europe, Japan, the Soviet Union, and the USA were started in the mid-1980s to develop "low-activation" or "reduced-activation" ferritic steels [18–26] with the objective of shallow land burial or recycle of the material after its service lifetime and after some suitable "cooling-off" (radioactivity decay) period, usually assumed to be 100 years. In the USA, a Department of Energy Panel used U.S. Nuclear Regulatory Commission 10 CFR Part 61 guidelines to suggest that wastes at least meet the criteria for shallow land burial [16]. The 10 CFR Part 61 guidelines were set up for storage and disposal of low-level nuclear wastes from fission reactors, and it is not known how they might apply to fusion wastes generated many years in the future.

It should be noted that the term "low activation" is often used interchangeably with "reduced activation" to describe the vanadium alloys, SiC/SiC composites, and ferritic/martensitic steels developed to ease radioactive disposal, even though they do not meet the criteria for low activation as described above (i.e., a material that does not activate or activates to a very low level). As presently defined, a reduced- or low-activation steel is one that will be disposed of by shallow land burial (according to the 10CFR Part 61 guidelines). As an alternative, recycling has been suggested [18]. The composition of such a steel needs to be adjusted to contain only elements that form radioactive products that decay rapidly (in tens or hundreds of years rather than thousands of years) to low levels. Calculations were made to determine which elements must be replaced in conventional Cr-Mo steels to obtain a rapid decay of induced radioactivity levels after irradiation in a fusion reactor [16]. Such calculations indicated that the common alloying elements used in steels that must be eliminated or minimized include Mo, Nb, Ni, Cu, and N [16].

As discussed in Chapter 2, reduced-activation ferritic steels were developed [18–30] by replacing molybdenum in conventional Cr-Mo steels by tungsten and/or vanadium, and by replacing niobium by tantalum. Alloy development studies have shown that reduced-activation steels can be produced that offer the promise of fast-induced radioactivity decay and whose properties compare favorably with the conventional candidate materials. Final radioactivity levels for such a "reduced-activation" or "low-activation" steel is calculated to be over two orders-of-magnitude lower than for conventional Cr-Mo steels after a "cooling-off" period. It may be possible to recycle such a steel or to dispose of it by shallow land burial, instead of the much more expensive deep geological disposal, thus providing a substantial economic benefit for fusion power. Even if deep geological burial is necessary, reduced-activation steels would be of benefit because of reduced personnel exposure during the waste-disposal process.

In the development work on the reduced-activation materials, steels have been produced without adding any of the restricted elements (i.e., Nb, Ni, Mo, N) to demonstrate that the mechanical and physical properties of the steels would be as good or better than the properties of the conventional steels [22–30]. In those instances where special effort was made to lower the restricted elements, emphasis was focused mainly on eliminating niobium because of the very low concentrations (<1 wppm) of that element that will be required to meet criteria for shallow land burial or recycling [31]. Besides the elements Mo, Nb, Ni, Cu, and N, other elements (e.g., Co, Bi, Cd, Ag, etc.) that could appear as tramp impurities must be restricted to extremely low levels if the goals of shallow land burial or recycling are to be achieved [32–34].

This chapter introduced some important considerations for the conventional high-chromium ferritic/martensitic steels in relation to the nuclear applications for which they are being considered. It also introduced the new steels being developed to better adapt this type of steel to that application. In the following chapters, these and other aspects of the steels will be examined in detail.

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