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Sodium effects on mechanical performance and consideration in high temperature structural design for advanced reactors

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A B S T R A C T

Sodium environmental effects are key limiting factors in the high temperature structural design of advanced sodium-cooled reactors. A guideline is needed to incorporate environmental effects in the ASME design rules to improve the performance reliability over long operating times. This paper summarizes the influence of sodium exposure on mechanical performance of selected austenitic stainless and ferritic/martensitic steels. Focus is on Type 316SS and mod.9Cr–1Mo. The sodium effects were evaluated by comparing the mechanical properties data in air and sodium. Carburization and decarburization were found to be the key factors that determine the tensile and creep properties of the steels. A beneficial effect of sodium exposure on fatigue life was observed under fully reversed cyclic loading in both austenitic stainless steels and ferritic/martensitic steels. However, when hold time was applied during cyclic loading, the fatigue life was significantly reduced. Based on the mechanical performance of the steels in sodium, consideration of sodium effects in high temperature structural design of advanced fast reactors is discussed.

1. Introduction

Advanced materials are critical element in the development of next generation fast reactor technologies. Enhanced materials performance not only improves safety margins for component performance and provides design flexibility, but also is essential for the economics of advanced sodium reactors. Structural materials of these reactors will be exposed to harsh operating environments including high temperature, sodium exposure, and neutron irradiation for period up to 60 years. Degradation due to high temperature and irradiation damage are common issues to all types of reactor materials, while environmental degradation in liquid sodium is unique to sodium-cooled reactors.

Code qualification and licensing of advanced materials are major needs for developing and implementing advanced fast reactor technologies. As advanced recycling reactors (ARRs) will operate at higher temperatures (up to 550 °C under normal conditions) than the current light water reactors (LWRs, operating at ≈320 °C), the design of elevated-temperature components must comply with ASME Boiler and Pressure Vessel (B&PV) Code Section III Subsection NH, and also must consider time-dependent effects of the exposure environment on creep, creep–fatigue, and creep ratcheting. A detailed analysis/evaluation is essential to establish the performance envelopes for long-term reliable service. The development of a mechanistic understanding of critical material issues and development of predictive models are also necessary to optimize/minimize testing efforts and to facilitate sound structural design and analysis. So far, only five structural materials pertinent to sodium reactors have been qualified in the ASME Code for elevated-temperature use for nuclear components, i.e. Types 304 and 316 stainless steels, 2.25Cr–1Mo steel, modified 9Cr–1Mo steel, and alloy 800H.

This paper addresses the critical degradation issues in liquid sodium for the two classes of alloys that are of most interest for the ARR structural applications: austenitic stainless steels and ferritic/martensitic steels, with a focus on Type 316SS and mod.9Cr–1Mo. Code qualification and licensing issues of ARR structural materials are discussed first. The influence of sodium exposure on mechanical properties including tensile properties, creep, fatigue, and creep–fatigue is then summarized, based primarily on experimental experience obtained in past reactor programs. Considerations of sodium environmental effects in the high temperature structural design of advanced fast reactors are proposed.

2. Code qualification and licensing issues for structural alloys pertinent to ARRs

Nuclear structural components for elevated-temperature service are required to comply with the ASME Code Section III Subsection NH. Subsection NH evolved from prior Code Case N-47, originally intended for use in the design of the Clinch River Breeder

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Reactor Project (CRBRP) [1]. Significant advances in elevated-temperature structural design technology have been made since CRBRP and incorporated into Subsection NH. As the ARR design is substantially similar to that of CRBRP, a comprehensive understanding of issues either addressed or to be addressed in Subsection NH will leverage development resources for the ARR. It is important to note that Subsection NH has not been endorsed by the US Nuclear Regulatory Commission (NRC) and this puts an added burden on licensing for ARR. Thirteen major issues with regard to material performance and high temperature design technology relevant to the ARR have been identified, based on past experience and the proposed ARR design, and these are summarized below:

- Materials property allowable data/curves for 60 year design life.
- Validated weldment design methodology.
- Reliable creep–fatigue design rules.
- Hold-time creep–fatigue data.
- Mechanistically based creep–fatigue life predictive tools.
- Understanding/validation of notch weakening effects.
- Adequate methodology for analyzing Type IV cracking in 9Cr–1Mo weldment.
- Inelastic design procedures for piping.
- Validated thermal striping materials and design methodology.
- Quantification of irradiation effects on materials properties.
- Quantification of thermal aging effects on materials properties.
- Quantification of sodium effects on materials properties.
- Material degradation limits in the presence of sodium–water reaction.

3. Effects of sodium exposure on mechanical properties

Issues associated with liquid sodium exposure are unique to ARR structural materials. Effects of sodium environments on mechanical performance must be addressed to ensure the structural integrity of the reactor components. Mechanisms that contribute to sodium corrosion damage in structural alloys include dissolution, mass transfer, and interstitial impurity effects. Mass loss and wall thinning, selective leaching of alloying elements and formation of surface ferrite layers, carburization/decarburization and nitridation/denitridation can occur in liquid sodium, depending on the sodium and alloy chemistry, service temperature, and time of exposure. These corrosion processes can lead to microstructural changes and degradation in mechanical properties of the structural components. The effects of sodium exposure on tensile properties, creep, fatigue, and creep–fatigue behavior are discussed in the following sections.

3.1. Tensile properties

The effect of a sodium environment on tensile properties is largely dependent on the degree of carburization/decarburization that occur in austenitic stainless steels and ferritic/martensitic (F/M) steels during long-term exposure to sodium, which can significantly affect microstructural stability and mechanical properties of the steels. In a mono-metallic sodium system, austenitic stainless steels tend to decarburize in the reactor core region and carburize in the IHX region [2]; low-Cr ferritic steels, such as 2.25Cr–1Mo, are susceptible to decarburization in sodium due to its inherently high C activity [3–5]; high-Cr materials such as 9Cr and 316 steels have a relatively lower C activity and are more resistant to carbon loss in a sodium environment [6–8]. In bimetallic sodium loops constructed of austenitic and ferritic steels, the ferritic steel located in the low temperature region tends to decarburize and the austenitic stainless steel located in the high temperature region tends to carburize [9–11].

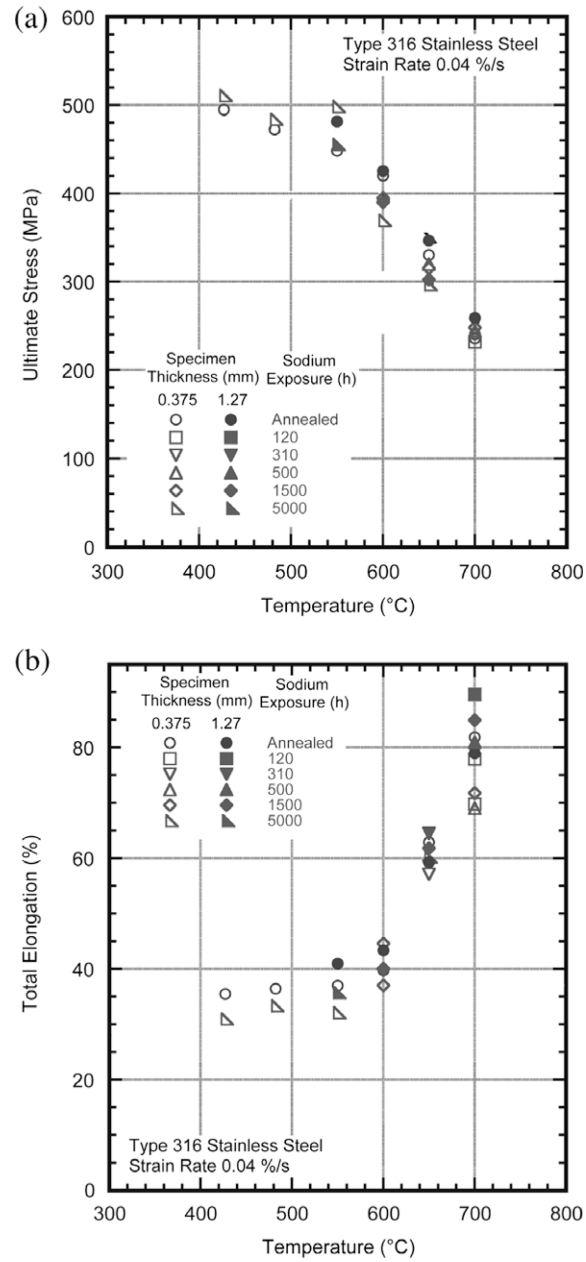

Fig. 1. Effect of sodium exposure on (a) ultimate tensile strength and (b) total elongation of Type 316SS.

Fig. 1 shows the combined effect of sodium exposure and thermal aging on ultimate tensile strength and total elongation of Type 316SS over the temperature range 400–800 °C [12–18]. Tensile data were obtained from specimens pre-exposed to sodium to specific C-penetration depths (≈0.1–0.3 mm) with increases in the average bulk carbon concentration up to 0.2 wt%. Carburization (resulting from sodium exposure) resulted in a slight increase in strength and a decrease in ductility. Overall, the influence of sodium exposure on tensile properties of austenitic stainless steels is insignificant.

Decarburization of 2.25Cr–1Mo steel in a sodium environment exposed at temperatures up to 550 °C progressively reduces the tensile and yield strengths of the steel [19,20]. However, the rate of decarburization is strongly influenced by the initial microstructure of the steel, stability and composition of the carbides in the steel, and the carbide dissociation kinetics [3]. Data on the tensile properties of high-Cr steels in sodium are sparse. Limited data indicate that tensile properties of Fe–9Cr–Mo steels are not affected by sodium exposure at temperatures below 550 °C [13,21–23]. Additional long-term data are needed for confirmation.

3.2. Creep properties

Sodium appears to have a more significant effect on creep properties of 304SS than of 316SS. Degradation of creep properties of Type 304SS in sodium has been reported in several studies, e.g. in references [24–27]. In a carburizing sodium environment, i.e. when C activity in sodium is greater than that in steel, reduction in rupture life occurs due to reduced ductility in the tertiary creep regime. Tertiary creep embrittlement is more severe at higher test temperatures. Minimum creep rate and time-to-onset of tertiary creep are not affected by a carburizing sodium environment. In a decarburizing Na environment, enhanced creep rate and earlier onset of tertiary creep were observed in addition to the shortened rupture time. Cracking along the affected grain boundaries lead to reduction in load-bearing cross section that, in turn, shortens the rupture time for a given applied stress.

Sodium exposure has nearly no effect on creep rupture properties of Type 316SS, as shown in Fig. 2 (WARD = Westinghouse Advanced Reactor Division) [28–30]. Creep rupture properties of Type 316SS showed little change after 10,000 h exposure to sodium at 593 °C. This is probably due to the presence of fine molybdenum carbides in 316 steel. The creep rupture strength of the specimens tested at ANL was lower than the ASME Code minimum due to a low-N content of the steel. The sodium effect was observed in sensitized 316L(N), exhibiting two stages of secondary creep during long-term creep tests (>6000 h) [31]. When combined with neutron irradiation, sodium environment can cause significant reduction in rupture strength of Type 316SS [32].

For the 2.25Cr–1Mo steel, a loss of creep rupture strength in sodium was observed, and decarburization was shown to degrade the property beyond that attributable to thermal aging only [19]. A reduction of 10% of the creep rupture strength was estimated for a service life of 100,000 h in sodium at 510 °C. Little information is available on the creep rupture properties of ferritic/martensitic steels exposed to high temperature sodium. No creep rupture data are available for mod.9Cr–1Mo steels in flowing sodium. Fig. 3 (with data from reference [33]) compared with the ASME design curves of mod.9Cr–1Mo [28]) shows little difference in creep strength between as received and sodium-exposed (with simultaneous thermal aging) specimens of mod.9Cr–1Mo. No effect of pre-sodium exposure (associated carbon gain/loss) was observed after 5000 h exposure to sodium at 500–550 °C.

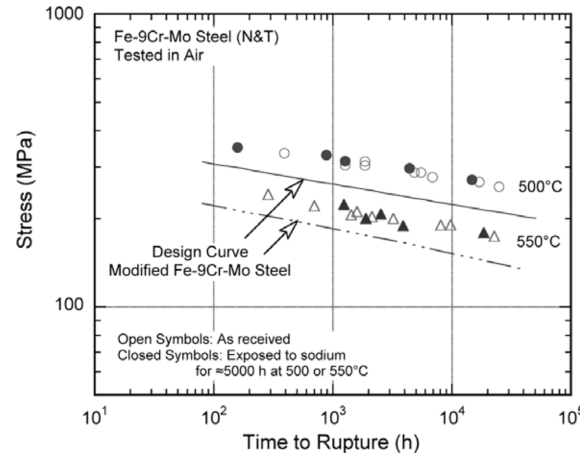

Fig. 3. Effect of sodium environment on creep rupture properties of mod.9Cr–1Mo.

3.3. Fatigue and creep–fatigue performance

The effect of sodium exposure on fatigue properties has been evaluated by fatigue testing in flowing sodium and testing specimens pre-exposed to sodium environments. A beneficial effect of sodium on fatigue life was observed in austenitic stainless steels when tested under continuous fatigue loading. The fatigue life of Type 316SS in sodium is significantly longer than in air, as shown in Fig. 4 [34–38]. For the sodium exposure conditions used in these studies, the specimens developed a carbon concentration profile that varied from ≈0.4 wt% at the surface to the initial concentration in the steels at a depth of 0.01–0.02 cm. The results indicate that moderate carburization of the steel in sodium has negligible effect on the fatigue life and that the fatigue lives of the sodium-exposed material are comparable to those of the annealed or thermally aged material. Surface oxidation, when tested in air, may facilitate early crack initiation, leading to the shortened fatigue life. The absence of surface oxidation in sodium increases the fatigue life considerably, when tested in fully reversed fatigue loading.

The creep–fatigue behavior of austenitic stainless steels in sodium has been investigated using a slow-fast sawtooth waveform or a triangular waveform with tensile-hold period [39]. The results show significant reduction in fatigue life. A tensile-hold period leads to creep damage and reduces fatigue life, whereas compressive- or symmetric-hold periods have little or no effect. The creep damage during a tensile-hold time depends on the material grain size. The 50 μm grain size rod material is resistant to bulk cavita-

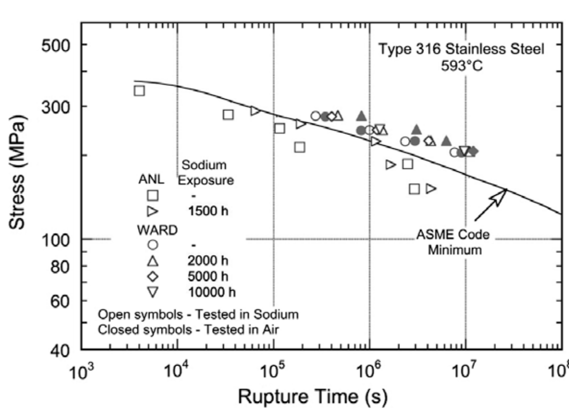

Fig. 2. Effect of sodium environment on stress-rupture behavior of Type 316SS.

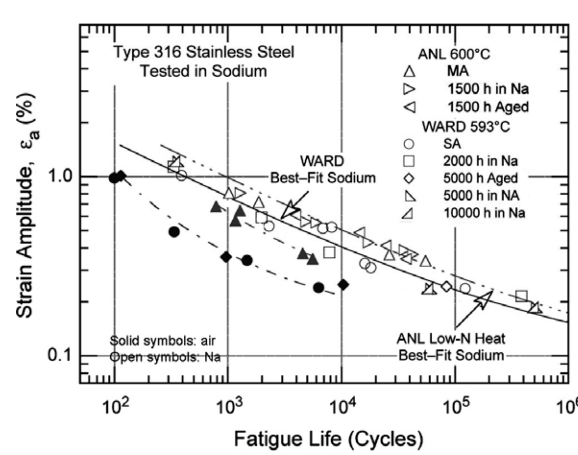

Fig. 4. Fatigue strain-life relation for Type 316SS in air and in sodium.

tion; the larger grain size plate material shows extensive grain-boundary cavities. The strain vs. life data for thermally aged Type 304 SS in sodium using a slow-fast sawtooth waveform or tensile-hold periods is shown in Fig. 5. As compared to continuous-cycle fatigue, the reduction in fatigue life is greater at lower strain amplitudes; i.e., fatigue life is a factor of ≈20 lower at strain amplitude of 0.25%, whereas life is a factor of ≈8 lower at strain amplitude of 0.5%. Although the continuous-cycle fatigue life in sodium is greater than that in air, life under creep–fatigue conditions (i.e., for the slow-fast or hold-time tests) is comparable to that in air. The slow-fast or hold-time tests in air under similar loading conditions result in a reduction in life by a factor of ≈6. These results suggest that the creep–fatigue interaction may be greater in sodium than in air, particularly at low-strain amplitudes. It is probable that the slow-fast or hold-time strain sequence facilitates crack initiation, and the apparent larger effect on life under creep–fatigue conditions is not due to creep damage but to early crack initiation. On the other hand, a substantial portion of fatigue life for continuous-cycle fatigue is spent in initiating a crack, particularly at low-strain ranges.

The fatigue life of ferritic steels, in general, is better in sodium than in air. The fatigue strain vs. life data for normalized and tempered Fe–9Cr–Mo steel in air [40–42] and in sodium [33,43] environments are shown in Fig. 6. In Fig. 6(a), the two heat treatments simulate thick section material. In air, the fatigue life of Fe–9Cr–Mo steel is comparable to that of Type 304 SS and superior to that of Fe–2¼Cr–1Mo steel. Fatigue life in sodium is a factor of 3–10 longer than in air. Also, moderate carburization after exposure to sodium has little or no effect on the fatigue life of these steels at 538 °C (Fig. 6(b)). The partial pressure of oxygen in a liquid-sodium environment is much lower than that of air and, therefore, surface oxidation effects do not influence fatigue life in sodium. In oxidizing environments such as air or steam, the oxide scale that forms on the surface of the test specimen can influence the process of crack initiation.

Only one study has been performed to investigate the creep–fatigue interaction of mod.9Cr–1Mo in sodium [33]. The available creep–fatigue data are shown in Fig. 6(b) and are compared with the fatigue data under continuous cycling in sodium. The creep–fatigue life of mod.9Cr–1Mo steel under tensile hold was significantly shorter than fatigue life under continuous cycling, both in the sodium environment and in air, and no beneficial effect of sodium exposure on fatigue life was observed, while a compressive hold in sodium was less damaging. Additional data are needed on the effect of sodium environment on the creep–fatigue behavior of Fe–9Cr–Mo steels to establish the performance limits for components fabricated from this material.

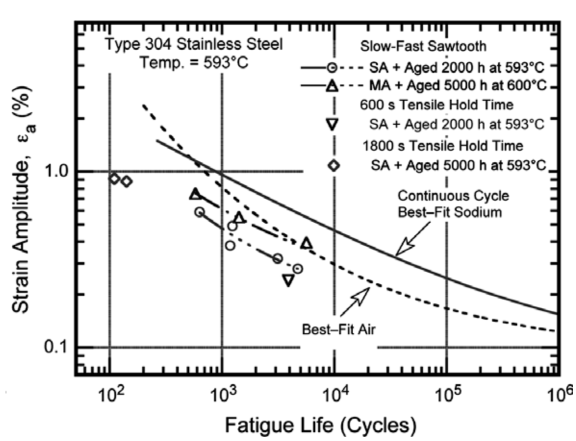

Fig. 5. Strain-life relation for Type 304SS in sodium.

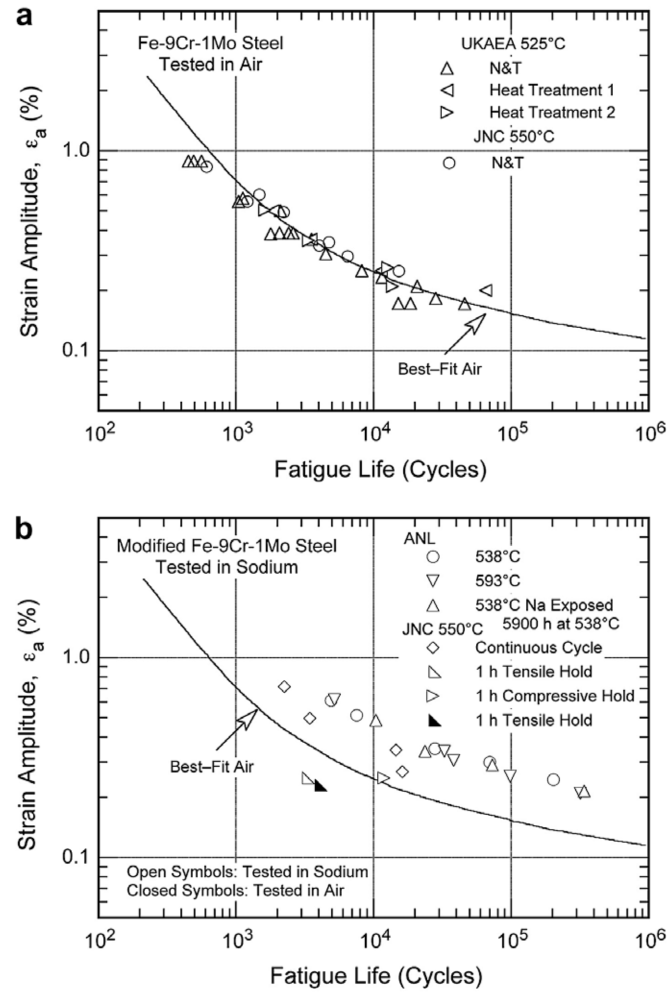

Fig. 6. Fatigue strain vs. life data for normalized and tempered Fe–9Cr–Mo steel in (a) air at 525 and 550 °C and (b) sodium at 538–593 °C, JNC data from Ref. [33].

4. Consideration of sodium effects in high temperature structural design

The sodium environment of the ARR poses unique challenges to long-term performance of materials and in high temperature design methodology to accommodate time-dependent behavior of the mechanical properties and failure modes. The ASME Code and code cases, however, do not provide specific guidelines for environmental effects and they need to be considered for NRC licensing. There is insufficient understanding of the changes in mechanical properties due to long-term sodium exposure, particularly for high-Cr ferritic/martensitic steels. Assessment of existing data and additional tests to fill the data gaps are needed to generate materials performance envelope and incorporate "knock-down" factors in design rules.

The extent of carburization/decarburization during component service is one of the key factors that determine the mechanical properties of structural alloys in a sodium environment, particularly on tensile and creep properties. A strength reduction factor has been suggested to account for strength loss due to sodium environmental effect in 2.25Cr–1Mo steel [44]. As the influence of sodium exposure on the tensile strength of 316SS and mod.9Cr–1Mo is insignificant, strength adjustment factors may not be needed for these steels. However, the effect of carburization/decarburization must be considered in the assessment of thin-walled structures. Since sodium-cooled reactor systems operate at low pressure (relative to LWRs), thin-walled sodium-containing components are common in liquid metal reactors.

Considering the beneficial effect of sodium exposure on fatigue life of austenitic stainless steels and ferritic/martensitic steels, the fatigue data generated in air can be safely applied for the design of thick-walled components in reactor quality sodium. An understanding of this beneficial effect is needed for developing mechanistic life prediction models. The conventional universal slope model [45] that correlates tensile properties and fatigue performance cannot be applied for sodium-exposed materials, because sodium exposure has negligible effect on tensile properties whereas sodium seems to have a significant effect on fatigue under cyclic loading. The insignificant effect of sodium exposure on the tensile strength and tensile ductility in mod.9Cr–1Mo implies that surface effect and environmental effects on fatigue crack initiation and propagation may play an important role in fatigue performance in sodium environments. Life predictive models that incorporate these effects need to be developed.

Significant life reduction under creep–fatigue loading in both austenitic stainless steels and ferritic/martensitic steels is of particular concern. The ASME Code has adopted a linear or a bilinear summation rule to account for the creep–fatigue damage in structural alloys. The bilinear damage envelope was initially developed for austenitic stainless steels. When the same methodology was applied to mod.9Cr–1Mo, far more severe fatigue and creep load limits were required for mod.9Cr–1Mo [28] to establish design window. The recent assessment [46] of the ASME creep–fatigue evaluation procedure in mod.9Cr–1Mo has pointed out that several unique characteristics have not been properly considered, including cyclic softening effect (vs. cyclic hardening effect in austenitic stainless steels), environmental effect, stress relaxation during hold time, etc. Improvement in creep–fatigue design rules is an essential need in the application of high temperature design methodology.

It is worth mentioning that creep–fatigue design rules are primarily based on short-time laboratory test data generated on smooth-surface specimens and with relatively short hold times. Whether or not creep–fatigue damage will be saturated with increasing hold time is unclear. The reactor hold periods can be as long as 1500 h in liquid metal reactors. Long hold-time creep–fatigue test data are needed on smooth and flawed specimens in developing creep–fatigue models and design rules. It should be noted that loading sequence and wave form types are also important factors in determining creep–fatigue lifetime, particularly for weldments.

Given the extension of reactor life from the current design life to 60 years in the future, reliable extrapolation of short-term data to 60 years poses a significant challenge to the designers and the regulators. It is imperative to develop a mechanistic understanding of creep–fatigue damage under various loading conditions and to develop improved mechanism-based creep–fatigue life predictive models. These improved and more reliable models also need experimental validation and proper integration into the design process.

5. Summary

Time-dependent material properties and environmental effects have been identified as key factors in the high temperature structural design of sodium-cooled reactors. A large amount of information is available on sodium effects of Types 304 and 316 stainless steels and 2.25Cr–1Mo steels, while sodium data are very limited for mod.9Cr–1Mo steel. The influence of a sodium environment on tensile and creep properties in the range of chemistry pertinent to sodium reactors is insignificant in thick sections of Type 316SS and mod.9Cr–1Mo steels. However, the effect of carburization/decarburization must be considered for thin-walled structures. A beneficial effect of sodium exposure on the fatigue life was observed in both austenitic stainless steels and ferritic/martensitic steels. The beneficial effect vanished when a tensile-hold time was applied during cyclic loading. Additional data are needed to fully understand the creep–fatigue behavior of these steels. Sodium-exposure data on mod.9Cr–1Mo and their weldments are much less available than data on austenitic stainless steels, and significant testing efforts are required to establish the mechanical properties of mod.9Cr–1Mo steel in sodium environments. Effects of carburization/decarburization, long-term aging and associated microstructural stability in sodium-exposed materials and under combined environments of sodium and irradiation, and effects of long-hold time on creep–fatigue life need further investigation for eventual incorporation into the ASME Code.

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