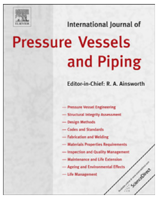
International Journal of Pressure Vessels and Piping xxx (2016) 1–9

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

journal homepage: www.elsevier.com/locate/ijpvp



Low temperature creep and irradiation creep in nuclear reactor applications: A critical review

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ARTICLE INFO

Article history:
Available online xxx

Keywords:
Low temperature creep
Irradiation creep
Environmentally-assisted cracking
Strain rate
Damage mechanics
Stress corrosion

ABSTRACT

The mechanisms and characteristics of low temperature creep and irradiation creep of structural alloys in light water reactor service are briefly reviewed. The significance of creep is made clear in relation to the environmentally-assisted cracking (EAC). It is shown that while total creep itself may not be significant the attendant slow strain rates are likely contributors critical to the manifestation of EAC. This interrelation of the creep and EAC is further assessed with validation of a continuum damage mechanics approach to quantify the EAC kinetics. Limitations of the formulation and other approaches are discussed, with a note that the influence of irradiation creep on EAC appears not to have been taken into account at present. These aspects are discussed identifying possible useful refinements in assessing the role of creep in EAC.

1. Background and objective

Creep of a metallic component, as a time-dependent deformation under a set of fixed stress and temperature, has been investigated for at least over a century; its physics and phenomenology have been amply summarized by many [e.g., 1–4]. In service, the creep related deformation typically occurs under variable stress and/or temperature which act to enhance the creep. This deformation and associated strain rates are generally not taken into account in the design of metallic components operating below about 650 K (or about 0.39 on homologous scale), as the creep effects are considered to be insignificant at these temperatures. However, the structural metals and alloys do creep below this temperature down to normal room temperature, which is referred below also as the low temperature creep.

Also, environmental effects on material degradation are typically not included in the design process, in part, due to the designer's lack over operational control or of applicable data. For example, in the case of light water reactor (LWR) systems the possible (accelerating) effects of aqueous corrosion or irradiation on environmentally assisted cracking (EAC) due to cyclic or steady loads are not explicitly addressed in the component design. This poses a question and a need to assess the design adequacy for these effects, especially over long-term operation. The objective of this paper is to examine the potential role of creep at low temperature and/or under irradiation in the material degradation of LWR components due to EAC. The paper also describes a possible approach to quantify the EAC damage based on strain rate considerations, and illustrates its implementation and validation.

From years of investigations by many, it has been well recognized that stress corrosion cracking (SCC), and EAC in general, is a result of the conjoint action of three factors broadly classified as the environment (temperature and chemical characteristics), the material (microstructure), and the stress (deformation mechanics). At the same time, universal acceptance or knowledge of a definitive or detail mechanistic understanding of how this conjoint action results in the damage evolution or (sub-critical) cracking is generally lacking, making it difficult to judge the appropriate balance or relative significance of these three factors for general application. As such, some knowledge of these varied but essential disciplines is a required basis for engineering management and quantitative assessment of this form of damage. An interdisciplinary approach, even if simplified, that has a plausible semi-empirical basis is to be preferred; totally physics based approach has proved to be illusive or too complex for engineering application, while purely empirical or statistical approach becomes quite limited in scope, especially for extending data from laboratory (accelerated) conditions to service conditions, or for meaningful ranking of susceptibility from one set of component/conditions to another.

With the above background, the mechanisms and

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http://dx.doi.org/10.1016/j.ijpvp.2016.02.002

characteristics of low temperature creep and irradiation creep under normal LWR service conditions are briefly reviewed, followed by a summary assessment for the significance of creep in relation to plausible mechanistic aspects and phenomenological observations of EAC. It is shown that while the total creep deformation itself may not be significant, *per se*, the attendant slow strain rates are likely contributors critical to the manifestation and slow kinetics of the EAC degradation. This role of creep and its interaction with EAC damage are further examined within the framework of a continuum damage mechanics approach used to quantify the kinetics of degradation. Results of implementing the approach, its validation, limitations, and further useful developments are discussed.

2. Creep under low temperature and irradiation

While the low temperature creep of structural metals is fairly well known in the scientific/research communities, its effect is typically excluded from design considerations (below about 650 K in the case of steels and nickel-based alloys used in LWR applications). This exclusion may likely have contributed to the belief, at least in the engineering community in general, that the structural metals hardly, if at all, creep in the low temperature regime. As such, a brief review of pertinent creep observations is considered useful as a backdrop for the inclusion of creep below in the assessment of EAC; this review is meant to be illustrative rather than being exhaustive. A more recent review of data and related mechanisms of creep [5] also provide a confirmation of the low temperature creep of several structural metals.

For instance, in one of the early works [6] creep was measured under direct stress in a number of metals, including copper, aluminum, steel, and monel metal, where it was noted that (a) very small but definite amount of creep occurred even at very low stresses at room temperature, and (b) the creep continued for indefinitely long period, specimens having found to continue to deform after six years. Likewise, long-term (beyond 10,000 h) creep at room temperature, even below yield stress levels, was reported on standard 18-8 stainless steel [7], and beyond 2400 h at room temperature in AISI Type 347 steel near yield stress [8]. Significant post-yield creep strains were reported in mild steel and in austenitic stainless steels even at room temperature [9,10]; also, creep within the plastic enclave at a notch was noted in an otherwise elastically deforming member and the creep behavior paralleled that of the post-yield unnotched member [10]. The occurrence of creep in Alloy 600 around 633 K was experimentally confirmed [11] also concluding that the creep plays an important role in the intergranular SCC observed in Alloy 600 in high purity water. The creep of several related nickel base alloys in the low temperature regime was summarized in Ref. [12]. Similar creep observations have been confirmed in other austenitic/ferritic steels [13] and in high strength steels [14].

In general, the low temperature, low stress creep is classified as the logarithmic or primary creep where the strain rate typically falls with time due to the material hardening related to the increased resistance to dislocation glide that may be overcome with the thermally activated cross-slip process, especially in face-centered cubic alloys, dependent on the stress level. At somewhat higher temperatures the vacancy related and diffusion based mechanisms become more significant as well. Under service conditions, operational load fluctuations and the trend towards use of load-following act as an added source of strain rate due to possible re-starting of the primary phase in which the creep rate is usually enhanced compared to that at the steady state. Furthermore, local interaction and damage due to environmental effects act to sustain or accelerate the local inelastic deformation response.

Several LWR vessel internal components, even though operating below about 650 K, are also subject to irradiation, in addition to the stress and temperature conditions, which leads to material damage over time that is cumulative in nature. The inelastic and time dependent deformation is enhanced under the simultaneous action of stress and irradiation, and it is called the irradiation creep[1] that is distinct and distinguished from the commonly known thermal creep. It is another source of time-dependent straining in reactor internals, in addition to the other sources of creep noted above. This enhanced inelastic deformation is a result of the continuing material damage caused by the bombardment of high energy (about 0.1–1 MeV and above) neutrons that produce excess vacancies, interstitials, their faulted or prismatic loops, and stacking-fault tetrahedra [16–18], which, in turn, interact and influence the glide and climb motion of dislocations. The effect of irradiation damage on material creep, often attributed to these induced defects, has been reported for many years [e.g., 19,20] as a straining mechanism separate from thermal creep, although its impact on thermally activated mechanisms can't be completely excluded especially at higher range of temperature and/or stresses. The irradiation creep has often been examined or closely associated with the void swelling phenomenon under irradiation at mid-to-high temperatures, although the two are distinct.

Under the typical conditions of LWR operation the strain rate contribution due to irradiation can be significant in comparison with the thermal creep, where the former is weakly dependent on temperature and has a much lower sensitivity to stress; several reviews cover the relevant experimental observations [e.g., 19–21]. Experimental work has also confirmed irradiation creep in the case of 300-series stainless steels [22] under LWR conditions. The underlying mechanisms still involve interaction effects of stress with dislocation motion of glide/climb and vacancies, but continuing especially below yield stress with nearly linear dependence of strain rate on stress and on the irradiation (neutron) flux. Due to the irradiation induced defects the mechanism of dislocation climb is operative even at the lower temperatures as well, leading to the climb-assisted/enhanced glide of dislocations as a possible mechanism [23]. Indeed, based on a dislocation climb model for the steady-state irradiation creep of non-fissile materials at low-temperature, the linear dependence of creep rate on applied stress and on irradiation flux, independent of temperature, was predicted [24,25] and experimentally observed [25,26]. Also, various mechanisms of irradiation creep as reviewed [27,28] emphasize the involvement of dislocation processes and their interaction with other defects under stress. These mechanisms include the so-called stress-induced preferential absorption (SIPA) of interstitials at edge dislocations, the stress-induced preferred nucleation (SIPN) of dislocation loops, climb-enabled preferred-absorption glide (PAG) [29], and the radiation and stress induced difference in emission (RSIDE) of vacancies from dislocations of different orientations with respect to the external stress [30].

It is concluded that the metallic materials are subject to measurable creep deformation even under conditions of relatively low temperatures and stresses in LWR service, with or without irradiation. Although the significance of this creep may be little with regard to the component strength or total deformational considerations, this is not necessarily the case with respect to the EAC damage, especially over long periods of operation, due to the resulting slow and sustained strain rates, as discussed below.

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[1] As a note of historic interest, one of the earliest (if not the first) findings on the effect of irradiation on creep were reported by Andrade, in 1945 [15], whose name is famously associated with the primary creep law for unirradiated metals.

Please cite this article in press as: Y.S. Garud, Low temperature creep and irradiation creep in nuclear reactor applications: A critical review, International Journal of Pressure Vessels and Piping (2016), http://dx.doi.org/10.1016/j.ijpvp.2016.02.002