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Critical review of data and correlations describing key clad thermo-mechanical processes under SFR transient conditions: Alternative modelling

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A R T I C L E I N F O

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The even more demanding safety goals pursued for GEN-IV designs are driving the development of tools capable of modelling systems behaviour under accident conditions. In this regard, the response of fuel pins under off-normal events is an important safety concern, being the understanding and modelling of cladding performance a relevant issue.

A critical review of published data and correlations regarding cladding mechanical behaviour under transient conditions has been conducted. The study has been focused on the yield strength and the strain limit of 20% CW 316 stainless steel. It has been found that the database is scarce to derive sound models, especially for irradiated materials. Nevertheless, based on the missing information and the available data, a set of empirical correlations have been proposed. They have been shown to capture the experimental trends observed and to be conservative, being simpler than previous models. Despite these achievements, further validation should be conducted as soon as reliable data are available.

1. Introduction

One of the six selected options of GEN-IV designs is the sodium (Na)-cooled fast reactor (SFR) (OECD-NEA, 2014). Former fast reactor programmes established the basic technology for the SFR, much of which has been confirmed by the Phénix end-of-life tests, the lifetime extension of BN-600, the restart tests of Monju and the start-up of a Chinese experimental fast reactor. This robust basis has inspired the short-term plans for new prototype construction in several countries in the world (i.e., China, India, Russia, etc.) and, particularly, the ASTRID prototype, led by CEA in France in the coming decade (IAEA, 2013).

The highly demanding safety goals pursued for GEN-IV designs lead to include severe accidents in the design basis of the systems and, as a consequence, tools capable of simulating SFR response to severe accidents are needed. This necessity of having flexible tools capable of simulating accident events in SFR and the leading role of LWR codes modelling severe accidents (e.g., ASTEC, MELCOR), has suggested the use of these platforms as the basis for SFR code development (Girault et al., 2013; Humphries et al., 2014).

In a prompt insertion of reactivity, the potential positive reactivity feedback resulting from the Na void effect has turned this type of transient overpower into one of the major target scenarios in SFR technology. In fact, a loss of primary cooling can be accompanied by a sudden reactivity excursion during the transient due to local vaporization of Na. The response of fuel pins under these off-normal events is an important safety concern (Bailly et al., 1999; Girault et al., 2013). Particularly, the pin thermo-mechanical performance (i.e., cladding strain caused by the stress due to PCMI and/or gas internal pressure at high temperatures attained) may lead to cladding failure, giving rise to unacceptable situations from a safety point of view (i.e., fission gas release out of the pin, fuel-coolant interaction).

Mechanical models capable of predicting transient-to-failure cladding behaviour under SFR conditions should account for mechanical properties like the yield strength (i.e. elasto-plastic limit) and a failure criterion expressed in terms of mechanical variables like a strain limit (i.e., failure strain). Austenitic stainless steels like 20% CW 316 SS is the most commonly material modelled, based on data obtained from both unirradiated and irradiated cladding including mechanical tests like tensile or thermally ramped burst tests (Fish and Holmes, 1973; Johnson and Hunter, 1978; Wire et al., 1979; Dimelfi and Kramer, 1980; Fanning, 2012; Gupta et al., 2013;

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Karthik et al., 2013). Although a wide range of conditions is sought to be covered concerning test conditions (temperature, stress, strain-rate) and irradiation environment (neutron fluence, irradiation temperature), it is not possible to specify the material response for all conditions of interest because of the cost of testing irradiated material. This drawback is typically overcome through deriving sound correlations that would be reliable outside the database validity range.

The aim of the present paper is to review published data (from separate effect tests) used to derive the existing correlations to simulate the SFR cladding mechanical performance under transient conditions. Particularly, the work has been focused on the yield strength and the strain limit related to 20% CW 316 SS (most published cladding material). Data valid for the anticipated conditions have been compiled and analysed. Based on such analysis, formulations have been proposed to account for primary effects regarding the temperature and the strain rate, as well as the prior base irradiation; the derived equations (called CIEMAT's models) have been also compared to previous ones and their advantages highlighted.

2. Data review

2.1. Yield strength

The data found in the open literature for the yield strength of the target material come from uniaxial tensile tests (Wire et al., 1979; Fish and Holmes, 1973), from which the typical stress-strain curves can be obtained. It has been sought data representative of SFR transient conditions; in the case of the temperature, given the anticipated working conditions of Na in SFRs (i.e., maximum coolant temperatures higher than 770 K (Waltar et al., 2012)), data of interest have been those over roughly 800 K; for the strain rate, conditions from slow to fast transients have been looked for (10^{-5}-10 s^{-1}, approximately).

Most of the open data found come from tests on unirradiated 20% CW 316 SS (Wire et al., 1979). Fig. 1 shows the data compiled in terms of the unirradiated yield strength, σ_{y0}, as a function of the strain rate, $\dot{\varepsilon}$, at different temperatures, T. A wide range of conditions is covered, although the maximum temperature tested is well below the material melting point (around 1700 K). It can be observed that the yield strength increases with increasing strain rate (i.e., the strain rate increase enhances material strength). However, one may notice that sensitivity to strain rate is highly dependent on temperature: sensitivity increases at high temperatures, whereas at low temperatures yield strength remain practically constant (i.e., the behaviour of the material evolves from plasticity to viscoplasticity as temperature increases).

The data found regarding irradiated material come from tests on annealed 316 SS (Fish and Holmes, 1973). These experiments allowed addressing the effect of different neutron fluences and irradiation temperatures on tensile properties. It was found out an irradiation hardening (i.e., strengthening) that was attenuated with increasing irradiation temperature. The tests conditions were limited (strain rates of $3 \cdot 10^{-5}$ s^{-1} and temperatures up to 1000 K, approximately) and the neutron fluence of the specimens tested were lower than $7 \cdot 10^{26}$ n/m^2. Thus, the information available related to transient conditions is scarce. In spite of that, the data of interest have been gathered to analyse the irradiation hardening effect on the yield strength, σ_y (Fig. 2). According to these data, the irradiation strengthening growth seems to end up at high neutron fluences. Regarding the effect of the irradiation temperature, it has not been addressed due to data scarcity under the anticipated conditions.

In addition to the hardening effect of the irradiation, an increase of the yield strength along the plastic regime (i.e., flow stress, σ) happens due to the effect of the strain, ε (i.e., work hardening). Fig. 3 displays data concerning the stress-strain curve from irradiated 20% CW 316 SS submitted to mechanical testing at high temperature (Wire et al., 1979). As it can be observed, the work hardening effect is not negligible, although it is less influential than other factors analysed (e.g. temperature).

It is worth noting that the uniaxial tensile tests data can be used to model the mechanical properties of the cladding material if one assumes an isotropic behaviour. Thus, data from biaxial tests would be needed to check the data accounted for.

2.2. Strain limit

The supporting database to understand and model the strain limit should encompass the failure modes postulated (Kramer and Dimelfi, 1981; Waltar et al., 2012):

- Low temperature. Related to large stress (above the yield strength), so that the high rate of deformation results in failure at low temperature (i.e., lower than 1000 K, approximately).
- High temperature. It involves small stress (roughly below the yield strength), so that the low deformation rate results in failure at high temperatures (i.e., greater than 1000 K, approximately).

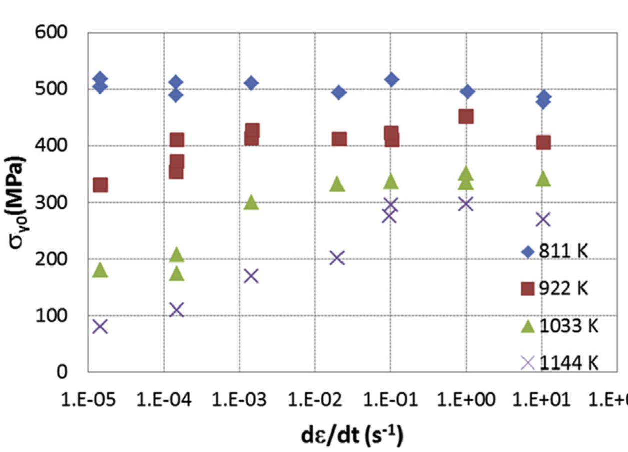

Fig. 1. 20% CW 316 SS yield strength data as a function of strain rate, expressed in logarithmic scale, for different temperatures (Wire et al., 1979).

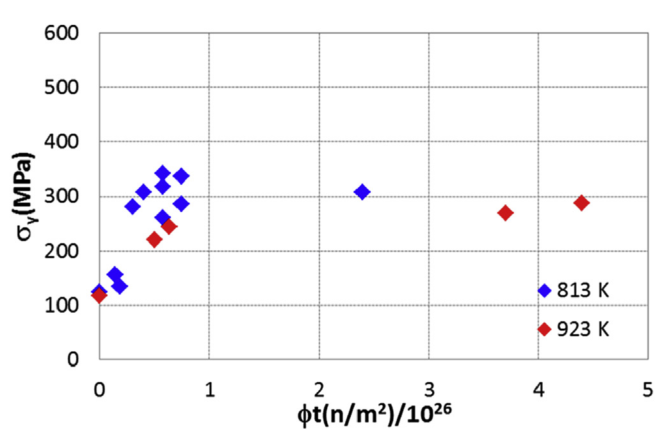

Fig. 2. Annealed 316 SS yield strength data as a function of neutron fluence, ϕt, at different temperatures with $\dot{\varepsilon} = 3 \cdot 10^{-5}$ s^{-1} (Fish and Holmes, 1973).