Modeling of microstructure evolution during creep in metastable materials at extremely low temperatures

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Metals and alloys used at extremely low temperatures are expected to exhibit ductile behaviour and significant plastic and creep deformation prior to rupture. While creep has been extensively studied at high temperatures, it has often been overlooked at cryogenic temperatures. Yet, studies show that creep persists even near absolute zero (e.g., 4.2 K), producing measurable strain and largely conventional behaviour [1]. Although strain rates are rather low, they exceed predictions based on simple activation energy extrapolation by several orders of magnitude. Moreover, unlike the diverse plastic flow modes observed at low temperatures (intermittent plastic flow), creep deformation remains continuous. An important question is whether creep in metastable materials, like the austenitic stainless steels, is accompanied by microstructural evolution due to fcc-bcc phase transformation. Another important feature is that creep occurs across the entire temperature range, from absolute zero to room temperature, i.e., from a weakly to a highly excited lattice. Experimental results show significant creep deformation throughout this range. Tests conducted between the boiling points of liquid helium (4.2 K) and liquid nitrogen (77 K) confirm the presence of both primary and secondary creep. Primary creep begins immediately upon loading, and both its duration and obtained strain are stress-dependent, increasing with applied stress. Once the primary stage ends, the creep rate decreases markedly, and steady-state secondary creep is established. To confirm this, preliminary experiments were conducted at room temperature (293 K). Flat, paddle-shaped specimens made of AISI 304 austenitic stainless steel – susceptible to strain-induced phase transformation and widely used at extremely low temperatures – were examined for creep. For the first time, in situ measurements of the ferromagnetic phase content (martensite) were performed. Fifty-hour creep tests were carried out at various prestress levels, both below and above the yield point. Magnetometric results confirm that when the prestress exceeds the material's yield point, a significant increase in the secondary phase content occurs during the test, resulting from creep strain-induced martensitic transformation. Although tests at cryogenic temperatures are planned for the next stage, low-temperature experiments conducted worldwide (primarily in Japan) confirm the occurrence of creep in austenitic stainless steels near absolute zero [2], [3]. The most widely observed type of creep at extremely low temperatures is the so-called logarithmic creep. However, the activation energy at these temperatures is usually much lower than that at intermediate or elevated temperatures [3]. To describe both primary and secondary creep, a more complex approach is required. One possible approach is the strain-hardening model developed in the present paper. In particular, it is assumed that, similarly to plastic flow phenomena, creep processes at low temperatures are accompanied by the phase transformation, which must be taken into account in the constitutive model. For this reason, a new kinetics of creep strain–induced phase transformation is proposed.

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