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On the creep deformation of nickel foams under compression

Déformation par fluage de mousses de nickel sous contrainte de compression

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ABSTRACT

A finite-element computational strategy is developed to study the viscoplastic deformation mechanisms at work in a nickel foam sample under compression creep. The constitutive law for pure nickel accounts for both diffusional and dislocation creep mechanisms. The finite-element results show the competition between both mechanisms due to the strong heterogeneity of the stress distribution in the foam. The initiation of the viscoplastic buckling phenomenon leading to cell crushing in tertiary creep is illustrated. The overall model prediction is compared to the results of compression creep tests performed in vacuo at 900 °C.

RÉSUMÉ

Une stratégie de calcul par éléments finis a été développée dans le but d'étudier les mécanismes de déformation viscoplastique à l'oeuvre dans une mousse de nickel sous fluage en compression. La loi de comportement du nickel pur intègre à la fois les mécanismes de fluage diffusionnel et de fluage-dislocations. Les résultats des calculs par éléments finis font apparaître une compétition entre ces deux mécanismes du fait de la forte hétérogénéité de la distribution des contraintes dans la mousse. L'initiation du phénomène de flambage viscoplastique aboutissant à l'écrasement des cellules en fluage tertiaire est illustrée. La réponse globale obtenue à l'aide du modèle est comparée aux résultats d'essais de fluage en compression réalisés sous vide à 900 °C.

1. Introduction

The creep of foams has been the subject of numerous studies initiated by [1] and dedicated to syntactic [2] and metallic foams [3,4]. The first contributions tackle the problem of creep modelling for cellular solids based on a simple

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two-dimensional approach [5], and more recently on more sophisticated homogenization methods [6]. Idealized unit cell models are used as simple tools to understand the possible mechanisms at work in open cell foams undergoing creep [7]. The objective is to understand how the applied overall stress redistributes in the parts of the foam and to investigate whether the induced strong heterogeneity in stress is detrimental or not for the otherwise outstanding properties of metallic foams. Periodic microstructures like 2D honeycombs [8] and 3D hollow-sphere structures under creep [9,10] can be used to identify the creep mechanisms and associated failure modes. Creep failure mechanisms corresponding to the beginning of tertiary creep were identified as viscoplastic buckling of struts in open-cell foams or walls and junctions in closed cell foams in [11–13], based on idealized cell morphologies like a pentagonal dodecahedron cell geometry. More elaborate modelling relies on creep simulation of large material volume elements taking into account the random structure of the foam, for instance in the case of ice foam [14].

The objective of the present work is to discuss the creep deformation modes at work in open-cell nickel foams used for battery or filtering applications. The material processing of this kind of foams was described in [15]. The morphology of the cell distribution and its size was studied in detail in [16] by means of computed microtomography and the corresponding systematic image analysis delivering a statistical description of cell population. Due to the existence of a polymeric precursor in the processing of the nickel foam, the struts are hollow beams with typical plateau border cross-sections. As a result, the nickel grains in the 10-μm thin walls of the struts form a bamboo structure with columnar grains. The effect of grain size on the tensile behaviour of these foams at room temperature was investigated in [17].

The macroscopic creep properties of nickel foams and a first insight into deformation mechanisms in the cells were provided in [7,18,19]. The effects of strut geometry and pore fraction were evidenced in [20]. These works serve as a basis for the analysis of the creep of nickel-based superalloy foams [21], more readily suitable for high-temperature applications due to oxidation. The tensile creep behaviour of the nickel foam was studied in [18], and the present work deals with the case of compression creep.

The importance of microtomography in deciphering the deformation and damage mechanisms of foams must be underlined [22,23]. The obtained images serve as the starting point for a finite-element computational approach of the mechanics of closed-cell foams [22,24,25] and [7,18] for open-cell nickel foams. The computational strategy defined in [26] for the design of optimal foams with targeted mechanical properties is applied in the present work to analyse the compression creep mechanisms of nickel foams. In particular, it has been shown in [26] how high-performance finite-element computing can be used to design optimal cell morphology regarding the anisotropy of mechanical tensile properties. This computational strategy is further developed in the present work to explore the creep deformation mechanisms in nickel foams from a computational perspective, as done for instance in [27] for the multiaxial creep of low-density open-cell foams.

The attention is focused on the competition between diffusional and dislocation creep mechanisms that will be shown to be simultaneously activated in the foam due to the tremendous heterogeneity of the stress in the microstructure. The computational approach is validated by means of compression creep tests at high temperature under vacuum to avoid oxidation. The considered nickel foams are produced in the form of 1.5-mm thick sheets and compression creep is applied within the thickness of the foam samples. In order to optimize the creep test conditions, some monotonic compression tests were performed to determine the stress levels to be used during creep experiments and the deformation values for creep failure. These values depend on foam cell shape and size. After this threshold value is reached, the foam structure collapses and the creep rate strongly increases [28].

The prediction of creep behaviour through a computational homogenization method requires a detailed knowledge of the constitutive behaviour of pure nickel, which is the subject of Section 2, where literature results are compiled. A constitutive elastoviscoplasticity model for pure nickel is formulated, including the diffusional and dislocation creep deformation mechanisms and the corresponding material parameters are identified. The experimental part of the work is presented in Section 3. The finite-element results are reported in Section 4. They include the design of a finite-element mesh of a group of about 30 cells and the distributions of stress and viscoplastic strain during creep at a low stress and at a high stress level. They are discussed in Section 5 focusing on the comparison between predicted and experimental creep curves.

Regarding notations, symmetric second-order tensors are denoted by a tilde, like for instance the stress tensor, $\underset{\sim}{\boldsymbol{\sigma}}$. The time derivative of a second-order tensor is written $\dot{\underset{\sim}{\boldsymbol{e}}}$.

2. Creep of pure nickel

The creep behaviour of polycrystalline pure nickel is heavily dependent on temperature and stress levels. At low temperature or, equivalently, at large stresses, viscoplastic deformation is governed by the slip of dislocations. At higher temperatures, the stress level dictates the viscoplastic deformation mechanism. Relatively high stresses lead to dislocation creep mediated by bulk vacancy diffusion or by pipe-diffusion along dislocation cores. Low stresses induce diffusion creep resulting from the motion of vacancies in the bulk or along grain boundaries [29].

2.1. Compiling results from literature

Deformation mechanism maps, as available in [30], can be drawn in the space of normalised shear stress and homologous temperature, for a given grain size. The typical limits of the domain of diffusional flow, power-law creep and plasticity are