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Homogenized elastic–viscoplastic behavior of plate-fin structures with two pore pressures

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ABSTRACT

We investigate the homogenized elastic–viscoplastic behavior of plate-fin structures subjected to two pore pressures, p_1 and p_2. The plate-fin structures considered are assumed to be periodic and composed of metallic materials. Hill's macrohomogeneity equation is used to show three special cases in which one of p_1, p_2 or p_m (the mean of p_1 and p_2) entirely affects the homogenized viscoplastic behavior in the steady state. To verify the three special cases, we perform FEH (finite element homogenization) analysis of an ultrafine plate-fin structure subjected to p_1 and p_2, for which two base metals with different strain-rate sensitivities are considered. It is demonstrated that the three special cases typically occur under uniaxial tension and compression in the stacking direction, depending on the strain-rate sensitivity of the base metals. It is further shown that a macromaterial model reproduces well the homogenized stress–strain relations attained in the FEH analysis if p_1, p_2 or p_m is entered for Terzaghi's effective stress in the viscoplastic equation in the macromaterial model.

1. Introduction

Plate-fin heat exchanges are likely candidates for compact and highly efficient heat exchangers in modern high-temperature gas-cooled reactors [1–3]. For this purpose, ultrafine plate-fin cores have been fabricated by brazing plates and fins, which have considerably small thicknesses of 0.5 and 0.2 mm, respectively [1,3]. The fabricated cores thus have anisotropic open-cellular structures consisting of alternately stacked plates and fins, as analyzed in detail in recent studies [4–7]. This cellular structure is designed to be subjected to high pore pressures in addition to thermal stresses [1,3]. Perforated thick plates in fast reactor heat exchangers are also subjected to high pore pressures and thermal stresses [8]. The plate-fin cores and perforated plates mentioned above can be regarded as macrobodies that have anisotropic open-porous microstructures in which pore pressures act independently of thermal stresses.

Full-scale finite element meshing of the plate-fin cores and perforated thick plates invariably results in high computational costs because of the large number of plate-fin layers and circular cylindrical holes. For example, more than 1000 layers of plates and fins need to be stacked in compact heat exchanger cores [1]. If a macromaterial model is available, the high computational costs can be drastically reduced.

Ohno et al. [9] described micro–macro relations relevant to periodic unit cells of anisotropic open-porous bodies subjected to a pore pressure, and showed the following constitutive features using Hill's macrohomogeneity equation [10]: Terzaghi's effective stress [11] is work-conjugate to the viscoplastic macrostrain rate, and the constitutive relation of this work-conjugate pair has the same stress exponent as Norton's power law assumed for the base metals of open-porous bodies. Ohno et al. [9] then developed a macromaterial model in which the viscoplastic macrostrain rate was represented as an anisotropic power function of Terzaghi's effective stress. The resulting macromaterial model was applied to an ultrafine plate-fin structure with uniform pore pressure, and the corresponding finite element homogenization (FEH) analysis was performed for comparison. It was thus demonstrated that the developed macromaterial model simulates the FEH analysis results well despite there being no fitting parameter for the effect of pore pressure.

The ultrafine plate-fin cores mentioned have primary and secondary flow channels that alternate in the stacking direction, as schematically illustrated in Fig. 1; for recuperative heat exchangers, primary and secondary flow channels are designed to be subjected to considerably different pore pressures [3]. This raises the question of which pore pressures is effective for the homogenized elastic–inelastic behavior of the ultrafine plate-fin cores, though only a uniform pore pressure was assumed in the above

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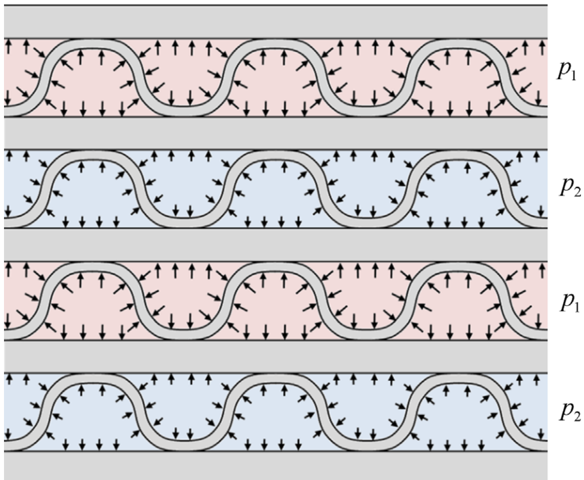

Fig. 1. Plate-fin structure with primary and secondary flow channels subjected to pore pressures p_1 and p_2.

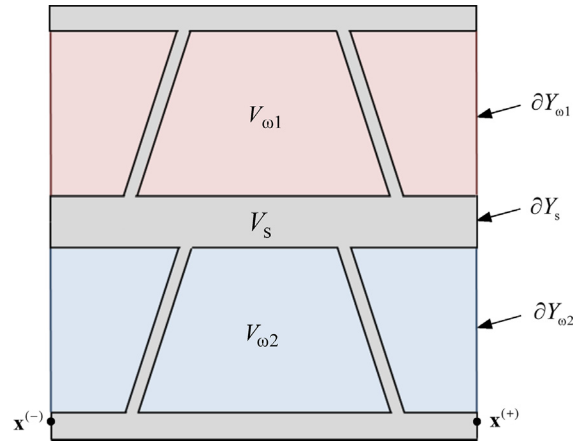

Fig. 2. Plate-fin, periodic unit cell Y consisting of a base solid region V_s and two open-pore regions $V_{\omega 1}$ and $V_{\omega 2}$ indicated in red and blue colors, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

mentioned study by Ohno et al. [9]. Incidentally, two pore pressures were considered to examine their effect on void growth and coalescence in polycrystalline metals containing large and small voids, which were observed as intergranular and intragranuler voids [12–14].

In this study, we investigate the homogenized elastic–viscoplastic behavior of plate-fin structures with two pore pressures, p_1 and p_2. The plate-fin structures considered are assumed to be periodic and composed of metallic materials. We focus on which pore pressure is effective in determining the homogenized elastic–viscoplastic behavior. This paper is structured as follows. Section 2 describes the periodic unit cell properties assumed in the present study. In Section 3, Hill's macrohomogeneity equation [10] is used to show three special cases in which one of p_1, p_2 or p_m entirely affects the steady-state homogenized viscoplastic behavior. Here, p_m indicates the mean of p_1 and p_2. In Section 4, by performing FEH analysis of an ultrafine plate-fin structure, it is demonstrated that the three cases typically occur under uniaxial tension and compression in the stacking direction, depending on the strain-rate sensitivity of the base metals. It is shown in Section 5 that a macromaterial model reproduces the FEH analysis results well if p_1, p_2 or p_m is entered for Terzaghi's effective stress [11] for representing the viscoplastic macrostrain rate. Conclusions are given in Section 6.

In this paper, direct notations are used for vectors and tensors, and inner products between them are indicated by middle dots or colons (e.g., $\mathbf{u}\cdot\mathbf{v} = u_i v_i$, $\mathbb{D} : \boldsymbol{\varepsilon} = D_{ijkl}\varepsilon_{kl}$). In addition, the second- and fourth-rank unit tensors are denoted by $\mathbf{I}$ and $\mathbb{I}$, respectively.

2. Periodic unit cell properties

Let us consider a plate-fin, periodic unit cell Y consisting of a solid region V_s and two open-pore regions $V_{\omega 1}$ and $V_{\omega 2}$ (Fig. 2). The plates and fins are bonded to each other to be regarded as a solid region V_s. The open-pore regions $V_{\omega 1}$ and $V_{\omega 2}$ are separated to be subjected to different pore pressures. The boundary ∂Y of Y is partitioned into ∂Y_s, $\partial Y_{\omega 1}$ and $\partial Y_{\omega 2}$, as illustrated in the figure.

2.1. Microscopic material properties

We assume that the medium in $V_{\omega 1}$ and $V_{\omega 2}$ has neither rigidity nor viscosity, and that pore pressures p_1 and p_2 act in $V_{\omega 1}$ and $V_{\omega 2}$, respectively:

$$\boldsymbol{\sigma} = -p_1\mathbf{I} \text{ in } V_{\omega 1}, \tag{1}$$

$$\boldsymbol{\sigma} = -p_2\mathbf{I} \text{ in } V_{\omega 2}, \tag{2}$$

where $\boldsymbol{\sigma}$ denotes the stress in Y, and without loss of generality, we suppose

$$p_1 \geq p_2. \tag{3}$$

We assume that the solid region V_s undergoes small deformation at a high temperature, and consequently that the strain $\boldsymbol{\varepsilon}$ in V_s is additively decomposed into elastic and viscoplastic parts:

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}_e + \boldsymbol{\varepsilon}_{vp} \text{ in } V_s. \tag{4}$$

We further assume that $\boldsymbol{\varepsilon}_e$ and $\boldsymbol{\varepsilon}_{vp}$ obey Hooke's law and Norton's power law, respectively:

$$\boldsymbol{\varepsilon}_e = \frac{1+\nu}{E}\boldsymbol{\sigma} - \frac{\nu}{E}(\mathrm{tr}\,\boldsymbol{\sigma})\mathbf{I}, \tag{5}$$

$$\dot{\boldsymbol{\varepsilon}}_{vp} = \frac{3}{2}\dot{\varepsilon}_0\left(\frac{\sigma_{eq}}{\sigma_0}\right)^{n-1}\frac{\mathbf{s}}{\sigma_0}, \tag{6}$$

where E and ν are elastic constants, tr indicates the trace, the superposed dot represents differentiation with respect to time, $\dot{\varepsilon}_0$, σ_0 and n are the material parameters of viscoplasticity, $\mathbf{s}$ denotes the deviatoric part of $\boldsymbol{\sigma}$, and σ_{eq} expresses the von Mises equivalent stress defined as

$$\sigma_{eq} = \left(\frac{3}{2}\mathbf{s} : \mathbf{s}\right)^{1/2}. \tag{7}$$

2.2. Macrostrain and macrostress

Because Y is a periodic unit cell, the affine deformation part of displacement $\mathbf{u}$ in Y is considered to be due to the macrostrain $\mathbf{E}$ of Y [15,16]:

$$\mathbf{u} = \mathbf{E}\cdot\mathbf{x} + \tilde{\mathbf{u}}, \tag{8}$$

where $\mathbf{x}$ is the position of a point, and $\tilde{\mathbf{u}}$ indicates the perturbed part of $\mathbf{u}$ that satisfies the Y-periodic boundary condition:

$$\tilde{\mathbf{u}}(\mathbf{x}^{(+)}) = \tilde{\mathbf{u}}(\mathbf{x}^{(-)}). \tag{9}$$

Here, $\mathbf{x}^{(+)}$ and $\mathbf{x}^{(-)}$ are a pair of points on opposite boundary planes of Y (Fig. 2).