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Structural strength prediction for porous titanium based on micro-stress concentration by micro-CT image-based multiscale simulation

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ABSTRACT

For the design of porous titanium component, differently from its use as functional materials, structural strength prediction algorithm is proposed based on the micro-stress concentration analyzed by the multiscale simulation. The modeling of real microstructure is carried out by the image-based technique with X-ray micro-CT. The multiscale computational method consists of asymptotic homogenization and finite element mesh superposition (FEMS) techniques. A criterion is proposed to predict the nonlinearity initiation point in the load and displacement curve by means of micro-stress distribution expressed by histogram. Only the constituent's yield strength is referred regardless of the microscopic morphology. The originality of this paper lies in the validation of the homogenization process, the modeling guideline of micro-mesh superposition onto macro-mesh in FEMS, and the strength prediction algorithm. L-shaped components with different pore diameter were discussed in both experiment and simulation.

1. Introduction

Porous metals including porous titanium are becoming a matter of concern not only for various types of functional materials but also for structural materials [1]. When we design mechanical components or dental implants [2], fracture due to stress concentration must be taken into consideration. From the viewpoint of the fabrication process and microscopic defects, one of the authors has proposed a novel precise technique named powder space holder metal injection molding (PSH-MIM) method [3,4], which can produce porous titanium and porous stainless steel with high porosity ratio. So far, liquid infiltration property has been measured for usage as functional material [5]. On the other hand, structural strength prediction algorithm to design porous titanium component is proposed in this paper.

We can find some studies on the compression test and bending test of porous metals including the case with graded porosity [6,7]. In those studies, only the maximum load is discussed. However, the load and displacement curve shows nonlinear behavior before the maximum load [6,8]. The nonlinearity may be due to microscopic plastic deformation and microscopic damage. For the component design, the nonlinearity initiation point seems to be better and more useful than the maximum load. In addition, the relation between load and displacement is almost linear before that nonlinearity initiation point in the macroscopic sense. Therefore, in this paper, we aim at developing an algorithm to predict the nonlinearity initiation point by numerical simulation.

The important issue is that not only the porosity ratio but also the pore diameter and shape should be taken into account. The classical rule of mixture fails to express the microscopic morphological effects and to bridge the gap between micro-stress and macro-stress. Hence, multiscale simulation by the mathematical homogenization theory based on the asymptotic expansion method [9,10] and X-ray micro-CT (computed tomography) image-based modeling technique [11] is utilized in the proposed algorithm. One of the authors has so far proposed a microstructure-based fracture prediction algorithm for porous alumina ceramics [12]. However, in the four-point bending test of this brittle material, we could not observe the nonlinear behavior before the fracture. Moreover, that algorithm [12] is not validated in the component design with severe stress concentration. Therefore, this study aims at predicting the nonlinearity initiation point for porous titanium L-shaped component. Additionally, the validation of the homogenization has been done for low-porosity materials with 3–30% [13], but, in this paper, the validation of the homogenization as well as macroscopic modeling is shown for higher porosity porous titanium.

Concerning the multiscale fracture analysis, we can find some literature that discusses microscopic cracks in the framework of

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the homogenization method [14], but the assumption of the periodic arrangement of cracks is far from reality. In the case of porous titanium, we propose to evaluate the micro-stress distribution by histogram display and compare with the yield strength, rather than focusing on point stress. Similar idea is applied in fracture prediction of human bone [15]. In order to capture the microstructure architecture, X-ray micro-CT is used. It is useful for various porous media even for PZT ceramics including lead [16] and trabecular bone [17].

Furthermore, the micro-stress calculation near the stress concentration zone should be remarked. The above-mentioned homogenization theory fails because the periodicity of the micro-stress field is assumed in this theory. To solve this critical problem, one of the authors has developed finite element mesh superposition (FEMS) method [18] and three-scale method that utilizes both homogenization and FEMS [19]. The original idea of FEMS comes from the s-version FEM [20], which is recently applied to crack problems [21]. Directly from other papers [20,21], the heterogeneity is taken into account based on the micro-CT images [22]. In this paper, guideline for FEMS modeling is newly proposed to accomplish the structural strength prediction algorithm.

In summary, our multiscale simulation using the homogenization, FEMS and micro-CT image-based modeling can evaluate the micro-stress concentration in a component, and the nonlinearity initiation point is predicted by the micro-stress histogram. Section 2 describes the target porous titanium component, and the proposed algorithm is shown in Section 3. The application is shown in Section 4, where the criterion is determined by the porous titanium with 90 μm pore diameter and the proposed algorithm is validated by the porous titanium with 180 μm pore diameter.

2. Materials

2.1. Fabrication

The powder space holder metal injection molding (PSH-MIM) uses polymethlmethacrylate (PMMA) spherical particles to keep spaces into titanium powders after debinding in order to fabricate porous metals with high porosity ratio by sintering. Please see the author's previous papers [3,4] for more details.

In this study, two types of porous titanium are used. The averaged pore diameter and the porosity ratio of them are 90 μm and 63% for type A and 180 μm and 70% for type B, respectively. Fig. 1 shows the microstructures taken by X-ray micro-CT with 3.8 μm resolution. The pore is almost sphere because PMMA particles with narrow size distribution diameter are used as space holder.

The L-shaped components were fabricated for both material types, whose dimensions are shown in Fig. 2.

2.2. Component fracture test

One end of the L-shaped component is fixed and the load is applied as shown in Fig. 2. The load and displacement curves are shown in Fig. 3. Just after the maximum load point, as shown in Fig. 4, crack was observed at the corner point of the L-shaped component. Once visible crack initiated, the load drops to almost 10–20% of the maximum load. Hence, the maximum load is not appropriate for the component design value, and we can hardly find the logic to determine the safety factor. On the contrary, the nonlinear initiation point as seen in Fig. 3 may be useful for component design. Before the nonlinear initiation point, the load and displacement relationship is almost linear, and therefore we apply the linear multiscale computational methods to predict this point.

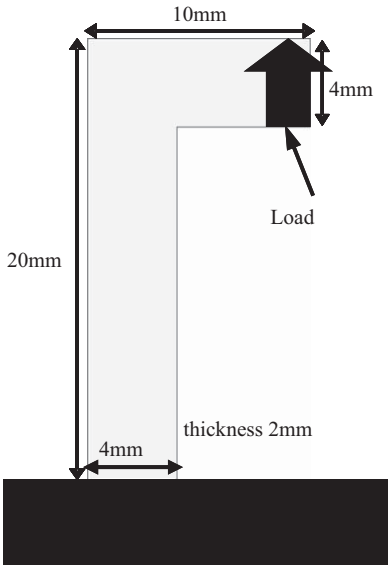

Fig. 2. L-shaped component.

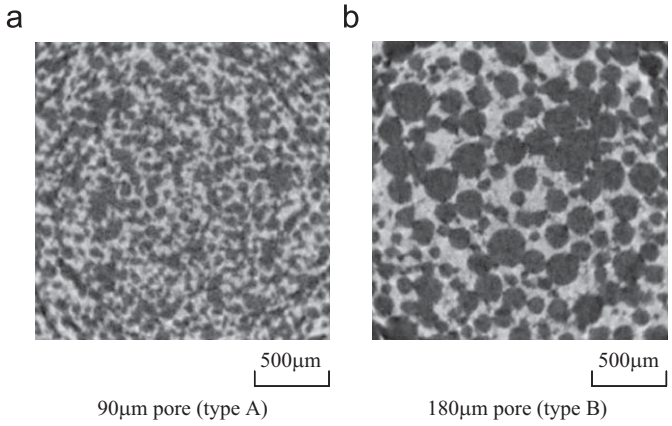

Fig. 1. Microstructures by X-ray micro-CT.

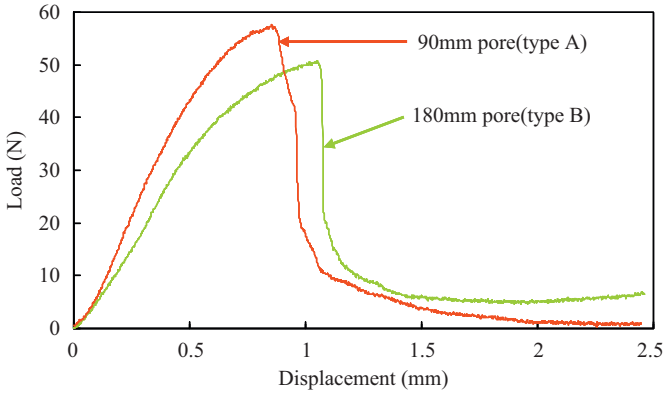

Fig. 3. Load and displacement curve.