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Constitutive parameter identification of 3D printing material based on the virtual fields method

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ABSTRACT

In recent years, 3D printing technology has grown rapidly, and also has shown the great potential to be utilized in different fields. The identification of the constitutive parameters of materials fabricated by 3D printing is very important for product designing and technique selection. In this paper, a constitutive parameter identification method for 3D printing materials combining the integrated deformation carriers with the virtual fields method (VFM) is presented. The experimental process consists of three steps: fabricating the specimen with integrated deformation carriers by 3D printing; measuring the deformation fields by a full-field optical method; identifying the constitutive parameters by VFM. In the first step, the design method of the integrated deformation carriers is described in detail. Serving as a practice of the above process, a bending specimen with integrated deformation carriers was manufactured by the stereolithography technique, and the orthotropic constitutive parameters of this specimen at different temperatures were identified. The successful experimental results verify the feasibility of the proposed method, and show its advantages on aspects of high efficiency and easy processing as well.

1. Introduction

In the field of manufacture, there are three generic methodologies which include: subtractive methodology, formative methodology and additive methodology, for the production of prototypes or manufactured parts [1]. The first two methodologies are widely used, but show some drawbacks, e.g. difficulty in fabricating a part with a composite shape in the subtractive methodology; high cost when the output is small due to the expensive mold used in the formative methodology. The additive methodology is a relatively new approach to the manufacture of prototypes and end-use parts, and it used to be referred to as rapid prototyping (RP) [2,3], which is generally being called 3D printing now.

The 3D printing includes a group of techniques that enable it to quickly fabricate a scale model of a physical product or an end-use part according to the three-dimensional computer aided design (CAD) data, and there is no high requirement of complex implement and skilled model maker. In a 3D printing process, CAD data are reformatted into a special file in which the model is sliced to be many layers; then this file is transferred into a selected 3D printing system; afterwards this system will reproduce the model layer-by-layer; and finally a physical model of the original CAD data can be exported. Up to now, different methods have been developed to achieve these CAD data, such as magnetic resonance imaging (MRI), computed tomography (CT) scanning as well as point cloud data generated by engineering scanning or digitizing systems [3].

Since its emergence in 1980s, 3D printing has been witnessed rapid development: various forming techniques have been proposed [3,4], more and more materials and structures can be manufactured [5,6], and the application

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fields are growing fast [7,8]. Recently, increasingly 3D printing parts have been used as end-use parts, and hence it is vital for the designers to characterize the mechanical properties of the materials produced by 3D printing system in order to optimize the material specification in their design process. However, as limited relevant literatures are available [2] and there are growing requirement to understand the mechanical behavior of 3D printing materials, the relative research is in urgent need.

In this paper, our work focuses on the study of the constitutive parameter identification of 3D printing materials, and a constitutive parameters identification method combining the integrated deformation carriers with the VFM [9] is presented. The operation of this method includes three main steps: firstly, fabricate a specimen with integrated deformation carriers by 3D printing, and the integrated deformation carriers can be the lattices or speckles according to the selected optical method; then add the load on the specimen step-by-step and obtain the full-field displacement by an optical method, such as digital image correlation (DIC) [10–14], geometric phase analysis (GPA) [15–17], grid method [18] or moiré method [19]; finally, the VFM is employed to identify the desired constitutive parameters by using the data of the full-field displacement. The integrated deformation carriers could be fabricated on an interested area of specimen as needed, and then is used in the deformation measurement, so no more extra sensor is required (e.g. strain gauge or extensometer). The VFM [9,20,21] is a high efficient method which can identify many constitutive parameters in one test simultaneously, and thus it is time-saving and low cost; besides, the VFM is effective for both isotropic and anisotropic materials. In order to demonstrate the superiority of the presented method, the orthotropic constitutive parameters at different temperatures of a stereolithography [22] specimen with integrated lattices were identified. Besides, the influence on the identified parameters caused by missing data near the edge of calculated area of DIC method was analyzed by the finite element analysis (FEA).

2. The design of 3D printing specimen with integrated deformation carriers

In general, deformation carriers are essential components for optical methods, for example, speckles for DIC, lattices or grid for GPA and grid method, grating (large-area lattices or grid) for moiré method. The deformation carriers are individually prepared after specimen is manufactured, and some conditions should be satisfied for obtaining the matched deformation carriers. For example: the material of deformation carriers should be compatible with the material of specimen (no reaction, easy bonding, small reinforced effect, low thermal mismatch). But it may be very difficult to meet these requirements. In order to tackle the difficulty, the deformation carrier and specimen can be generated with an integrated designing and fabrication. Benefiting from the flexibility of the 3D printing, the specimen and deformation carriers can be manufactured simultaneously; besides, the type, position, size and area of these carriers can be adjusted as needed.

In the measurement, the deformation carriers should match the selected optical method, specimen size and the deformation range. In addition, the machining accuracy of 3D printing process should not be neglected since it may limit the critical size of the deformation carriers. From our experience, two issues should be considered in the designing of integrated deformation carriers: firstly, the type of deformation carriers should be determined according to the selected optical method; second, the parameters of the deformation carriers (e.g. critical size and spatial area) should be optimized based on the sensitivity of the selected optical method.

There are several suggestions that should be noted:

1. The original surface of the general 3D printing specimen may be rough, and it could serve as natural speckles, but some local region may lose the correlation in the DIC calculation. Therefore, the speckles are better to be directly fabricated on the measured surface. Besides, in some cases the lattices structure could serve as the speckles [23] which will be demonstrated in Section 4.
2. The critical size of the deformation carriers should be larger than the machining accuracy, otherwise the fabricated deformation carriers may be merged and cannot be recognized.
3. The height or depth of the deformation carriers should be less than 1/10 of the thickness of the specimen. It has been proved that when the carriers depth does not exceed 1/10 of the specimen thickness, the influence of the carriers on the mechanical properties of the specimen is very small [24].

3. The principle of VFM

VFM, proposed by Grédiac [9], is a constitutive parameters identification method based on the principle of virtual work and full-field heterogeneous deformation data. Compared with other available identification methods based on full-field deformation data, such as finite element model updating method [25], constitutive equation gap method [26], equilibrium gap method [27] and reciprocity gap method [28], VFM is non-iterative, noise tolerable and easy processing [29]. In addition, VFM has low requirement for the boundary condition of load since the virtual field can be changed flexibly to eliminate the disturbance of some unknown loads. In this paper, the main principle of VFM is introduced briefly, and the detailed description can be found in Refs. [20,30].

Suppose a solid with any shape is subjected to a prescribed loading and displacement, as shown in Fig. 1. Our target is to identify the constitutive parameters of this material from the deformation fields and the corresponding load that is measured by using load sensor. If ignoring the body forces, only the load condition over S_f and displacement condition over S_u need to be processed. Generally, the load over S_f could be expressed as $\boldsymbol{F}$ (P, $\boldsymbol{n}$), and the displacement could be prescribed $\mathbf{u} = \bar{\mathbf{u}}$ over S_u, where P and $\boldsymbol{n}$ indicate any point of S_f and the vector perpendicular to S_f at point P, respectively. Then, the principle of virtual work can be expressed as [30]: