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Effect of particle size on three dimensional printed mesh structures

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A B S T R A C T

Three dimensional printing is a unique technique that can print complex 3D structures that cannot be produced by other means, especially for rapid prototyping purpose. In this study, 3D mesh structures are created by three dimensional printing with four different TiNiHf powder sizes. Mesh structure green strength and surface smoothness are characterized in order to produce high quality 3D structures. Binder spreading time and spreading rate in the TiNiHf powders are measured in order to understand binder penetration difference in the mesh structures. The study shows that smaller TiNiHf particle size produces higher mesh structure green strength and surface smoothness, consistent with the observation that binder spreading is slower for smaller TiNiHf particles.

1. Introduction

Three dimensional printing (3DP) is a unique technique that can print complex 3D structures that cannot be produced by other means, especially for rapid prototyping purpose [1–4]. During 3DP, a 3D structure model, formatted into a [.stl] file (standard triangle language), is converted by a slicing routine into a compilation of two-dimensional slices representing the 3D part. The slice file is further formulated into instructions that control the movement of the 3D printing components. The powder is spread by a counter-rotating roller onto a build platform inside a build box. By means of ink-jet printing technology, a printhead, containing an array of binder fluid jets, rasters across the layer of the powder and deposits binder droplets in those locations defined by the current 2D slice of the 3D structure model. Subsequently, the build platform advances downward by one layer thickness and a new layer of powder is spread, which is then printed by the printhead. This procedure is repeated layer after layer until the 3D part is completed. After the designed 3D part is printed, the particles are held together by the binder used. The printed part can be removed from the surrounding unbound powders. However, the printed structures are not strong enough to be used directly and need to be sintered to densify the matrix.

The 3DP technique has demonstrated the capability of fabricating parts of a variety of materials, including ceramics, metals, and polymers with an array of unique geometries [3,5–9]. However, substantial work is still needed to explore and improve the ability of forming intricate fine structures. This is because the quality of the printed structures is affected by many factors such as binder saturation level, printing layer thickness, and particle size. The first two factors have been studied in our prior work [10]. In order to obtain printed 3D structures with high integrity, small feature sizes, and accurate dimensions, particle size effects need to be studied.

In order to advance the understanding of particle size effect on the properties of printed 3D structures, a gradient 3D mesh structure has been designed. The green strength and surface smoothness of the printed mesh structures are compared for four different size TiNiHf powders. Since the interaction between the particles and binder play an important role in the 3D mesh structure creation, binder spreading time and rate for different size TiNiHf particles are studied with a high speed digital optical microscope. Mesh structure integrity and surface smoothness are closely related to the particle size and binder spreading.

2. Experimental procedure

Four TiNiHf powders with different particle sizes were specially made (Crucible Research, Pittsburgh, PA) in order to evaluate particle size effect on 3D mesh structure properties. The choice of TiNiHf powder was based on our on-going research needs and the availability of the powder types [11]. The approach and knowledge gained should be applicable to many other powder systems. The particle size ranges were: less than 20 μm (−635 mesh), 20–45 μm (+635 to −325 mesh), 45–75 μm (+325 to −200 mesh), and 75–150 μm (+200 to −100 mesh). The particle size distributions of the four TiNiHf powders from laser light scattering analysis (Horiba, LA-950, Irvine, CA) are shown in Fig. 1.

A gradient 3D mesh structure was designed as shown in Fig. 2. There were three layers in the mesh structure and each layer had three circular wires with diameters of 5, 10, and 15 mm, respectively. Each

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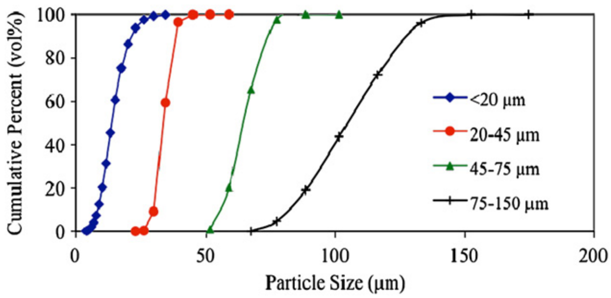

Fig. 1. Particle size distributions of four different TiNiHf powders used in the study.

layer had different numbers of radial wires: top layer, 16 wires; middle layer, 8 wires; and bottom layer, 4 wires. Wires on each layer had square cross-section shape with 400 μm edge length. Vertical wires between the adjacent layers had round cross-section shape with 400 μm diameter. This round shape was used in order to achieve good junction nodes in the mesh structure.

A 3D printer (RX-1, ProMetal, Irwin, PA) was employed to print the designed 3D mesh structure. An acrylic-based proprietary binder was used during the printing process. Based on the previous study with less than 20 μm TiNiHf powders [10], binder saturation level of 170% was used for each powder (the 3D printer allowed the binder saturation level to vary from 40–200%). Printing layer thickness was set to be twice of the largest particle size for a given powder. For the four powders used in this study (less than 20 μm, 20–45 μm, 45–75 μm, and 75–150 μm), the printing layer thicknesses were 40, 90, 150, and 300 μm, respectively. Each printed layer was cured by a built-in heat lamp at 90% power for 60 s before the next layer was printed. After the 3D mesh structure was printed, it was further cured at 170 °C for an hour in an oven to strengthen the green structure. The loose powder surrounding the printed mesh structure was removed with an air blower.

A Texture Analyzer test console equipped with a 5 kN load cell (Stable Micro Systems, Surrey, UK) was used for green strength evaluation [12]. The console was set to record compressive load and the crosshead was lowered monotonically at a speed of 0.1 mm/min. The shape of the load vs. displacement curve was recorded and the peak load was determined from the curve as the 3D mesh structure breaking force. The green strength was taken as the breaking strength and was calculated as the ratio of the breaking force to the average cross section area in the mesh structure horizontal direction.

A syringe (1 cm^3 25G 5/8 Tuberculin, Becton Dickinson & Company, Franklin Lakes, NJ) was used to simulate the binder spray from the printhead. The binder drop size used was 0.1 mL. TiNiHf powder of a given size was put into a shallow container and then rolled even using the 3D printer. This process produced the TiNiHf powder packing that resembled what existed during the 3D printing. Because the binder spreading process was too fast to be quantified by routine timing and spreading distance measurement, a high speed digital optical microscope (KH-7700, Hirox Company, River Edge, NJ) was used to film the binder spreading process. A software (SolveigMM AVI Trimmer, Solveig Multimedia Company, Tomsk, Russia) was used to trim the video files in order to measure the binder spreading time on the scale of microseconds and binder spreading distance on the scale of micrometers. The binder spreading experiment was repeated three times for each TiNiHf powder size.

3. Results and discussion

3.1. Particle packing and green strength

In order to study particle size effect on the 3D mesh structure properties, the TiNiHf particles should be saturated with the acrylic binder to the same extent during the 3DP process. One of the critical variables is binder drop volume, which can be varied based on three parameters: printing layer thickness, binder saturation level, and powder packing rate. The 3D printer surveys these parameters and determines the corresponding binder drop volume before any printing process is started. Because of this pre-existing correlation, printing layer thickness and binder saturation level need to be pre-determined; and powder packing rate needs to be measured. As stated, the binder saturation level is 170% and the printing layer thickness is twice of the largest particle size for a given particle size distribution. These selections are based on our prior study as well as the need to spread at least one layer powder each time [10]. In this study, the printing layer thickness used is 40, 90, 150, and 300 μm, respectively for the four TiNiHf powders. The most challenging yet necessary parameter to determine is powder packing rate. This parameter determination is more involved because powder packing in the printbed is different from that of bulk loose powder packing; the roller spreading process by the 3D printer creates a different powder packing rate for each powder. In this study, powder packing rate has been measured by printing a rectangular TiNiHf powder specimen of $5\times5\times2$ mm^3 for each TiNiHf particle size. After the 3D printing, the printed sample with volume V_{print} has been completely dried and then dissolved in a graduated beaker containing distilled water. The solid volume of the loose powder, V_{powder}, is then measured in the graduated beaker. The powder packing rate ρ has been calculated using:

$$\rho = \frac{V_{powder}}{V_{print}}\times100\%. \quad (1)$$

Based on Eq. (1), the powder packing rates of the four TiNiHf powders (less than 20 μm, 20–45 μm, 45–75 μm, and 75–150 μm) are 35, 42, 54, and 62%, respectively. Clearly, the 3DP roller spreading process has a larger impact on the packing of smaller size TiNiHf powders. The powder packing rate has been substantially reduced during the 3DP process for powders smaller than 75 μm. When the

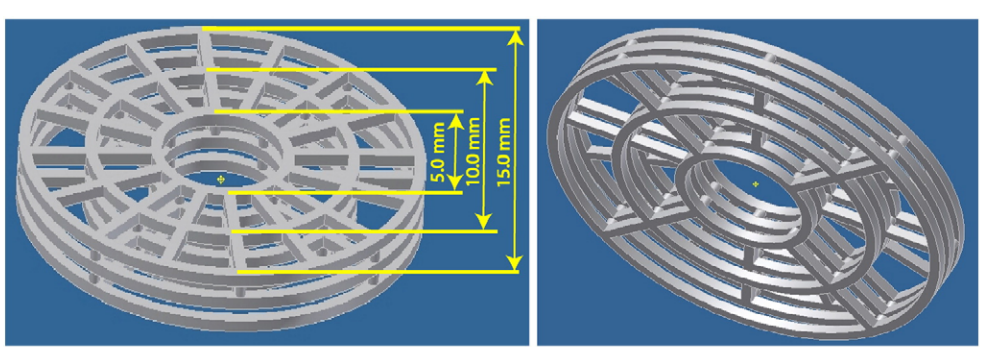

Fig. 2. 3D mesh structure design used in this study.