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STRAIN-RATE DEPENDENT COMPRESSIVE PROPERTIES OF INVERTED HONEYCOMB LATTICE AND BULK CYLINDRICAL SAMPLES 3D PRINTED BY MSLA METHOD

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Abstract: *Masked Stereolithography (MSLA) is an additive manufacturing process based on the photocuring of an entire printed layer of resin at once with the use of a UV light source, in this case a monochrome LCD display. The prints can be used not only for visualization of structures and parts, but also for development of elements of real constructions. The main objective of the study is to describe the mechanical properties under different types of loading, in particular to analyze the strain-rate sensitivity of compression response in bulk and inverted honeycomb lattice samples with three different strut widths. The specimens were experimentally investigated under quasi-static and high strain rate loading. Split Hopkinson Pressure Bar (SHPB) apparatus was used for the high strain rate experiments. The experiments were observed with a high-speed camera to allow analysis of the deformation processes. Digital Image Correlation (DIC) software was used to evaluate the displacement and stress fields. The results revealed a strong effect of strain rate, especially between quasi-static and high strain rate loads. An auxetic behavior was observed for the inverted honeycomb structure, which depends on the thickness of the struts.*

Keywords: Lattice structure, Photocurable resin, Quasi-static behavior, Dynamic behavior, Digital image correlation.

1. Introduction

In recent years, the use of various types of additive manufacturing (AM) has been frequently encountered, not only in industry, allowing rapid and relatively inexpensive production not only of prototypes but also of final products (Ge 2020). Stereolithography (SLA), in which a liquid polymer is used as the starting material and cured layer by layer using light, is one of the methods of 3D printing that enables a high level of detail in the printed part. When the LCD is the source of the curing light, it is called mask stereolithography (MSLA). Because MSLA technology exposes each entire layer at once instead of ablating it with a laser, much faster print times can be achieved with MSLA. To move from prototype parts to real functional parts, it is necessary to know how the 3D material behaves under different loading conditions and strain rates. Therefore, the knowledge of material behavior is very valuable. The aim of this research is to determine the main behavior of the printed material under quasi-static and dynamic loading.

2. Materials and methods

2.1. Specimens

In this study, the lattice structures generated by a volumetric periodical assembly of inverted honeycomb cells (INVH-3D) with three different widths of struts are investigated. In addition, cylindrical bulk specimens were tested as representative of the whole material. All specimens were printed from photopolymer resin (BR3D-UV-Firm, PhotoCentric3D, UK) using an MSLA printer (Sonic Mighty 4K, Phrozen, Taiwan). The printed samples of the structures are shown in Figure 1. The main mechanical properties of the resin specified by the manufacturer are: Hardness 65 Shore D, tensile strength 26 MPa,

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elongation at break 14.9%. The print layer thickness was set at 0.05 mm with an XY resolution of 52 μm. Post-processing consisted of UV irradiation for 30 minutes and heat treatment in an oven at 70°C for 120 minutes. The overall dimensions of the samples were 15x15x16.4 mm (W x D x H) according to the dimensions and performance of the SHPB setup. The unit cell dimensions were chosen to have at least 5 unit cells in both directions of the specimen cross-section. This number was chosen according to the general requirements for the RVE. For each specimen geometry, three specimens were used for the quasi-static experiments and two specimens for each strain rate were used for the high strain SHPB tests.

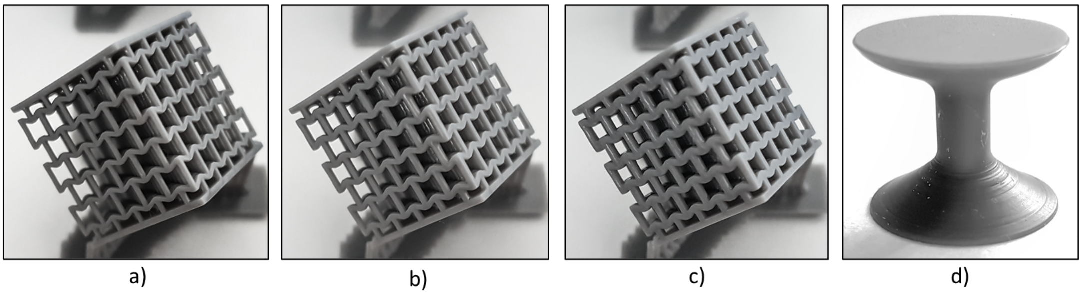

Fig. 1: Preview of INVH-3D specimens with struth width of a)~0,4mm, b)~0,5mm, c)~0,6mm, and bulk specimen d).

2.2. High strain rate testing

For high strain rate experiments Split Hopkinson Pressure Bar (SHPB) setup was used. In these experiments, the specimen was located between the incident and transmission bar. The specimens were deformed by the propagating wave coming from the impact zone of the striker and incident bar. Nitrogen gas was used to accelerate the striker. Length of the acceleration barrel was 2100 mm. The materials of all bars (striker, incident- and transmission bar) used for the experiments are 1.2379 steel and their diameter is 20 mm. Length of these bars are 350 mm, 1500 mm, and 1500 mm respectively. In order to obtain the strain values of the incident- and transmission bars, strain gauges were glued on the bars. Furthermore, strain gauges were connected to the data acquisition system (SIRIUSi HS 8x, DEWESoft) with a half-bridge configuration. 6V input voltage was provided by the data acquisition system and ratio of output voltage with respect to input voltage could be attained at every sampling time (10^{-6} s). High speed camera (Fastcam SA-Z, Photron, Japan) with region of interest set to 384x160 pixels and frame-rate of 210 kfps was set to record the deformation process of the specimens.

2.3. Digital Image Correlation

The camera recordings from both the quasi-static and high strain rate experiments were subjected to a DIC analysis to evaluate the strain and stress fields. DIC is an image processing method that uses tracking and image registration techniques to measure changes in a sequence of images. In this case the modified algorithm of augmented-Lagrangian DIC (Yang 2019) providing global kinematic compatibility is used. Vertical displacements were evaluated and compared to determine potential auxetic behavior of all structures at Q-S and high strain rate loading. The shear stress fields were also evaluated to investigate deformation behavior structure failure differences between Q-S and high strain rate loading.

3. Results

The mechanical response of the investigated structures to quasi-static uniaxial compressive loading was expressed by the average engineering stress-strain diagram. It can be seen that the stress increases significantly with the higher width of the strut. To reveal a possible strain-rate sensitivity of the deformation response, high strain compression tests using the SHPB apparatus were conducted at three different strain-rates. The average stress-strain diagrams obtained from the high strain rate experiments compared to the quasi-static results for the particular structures are shown in Figure 2.

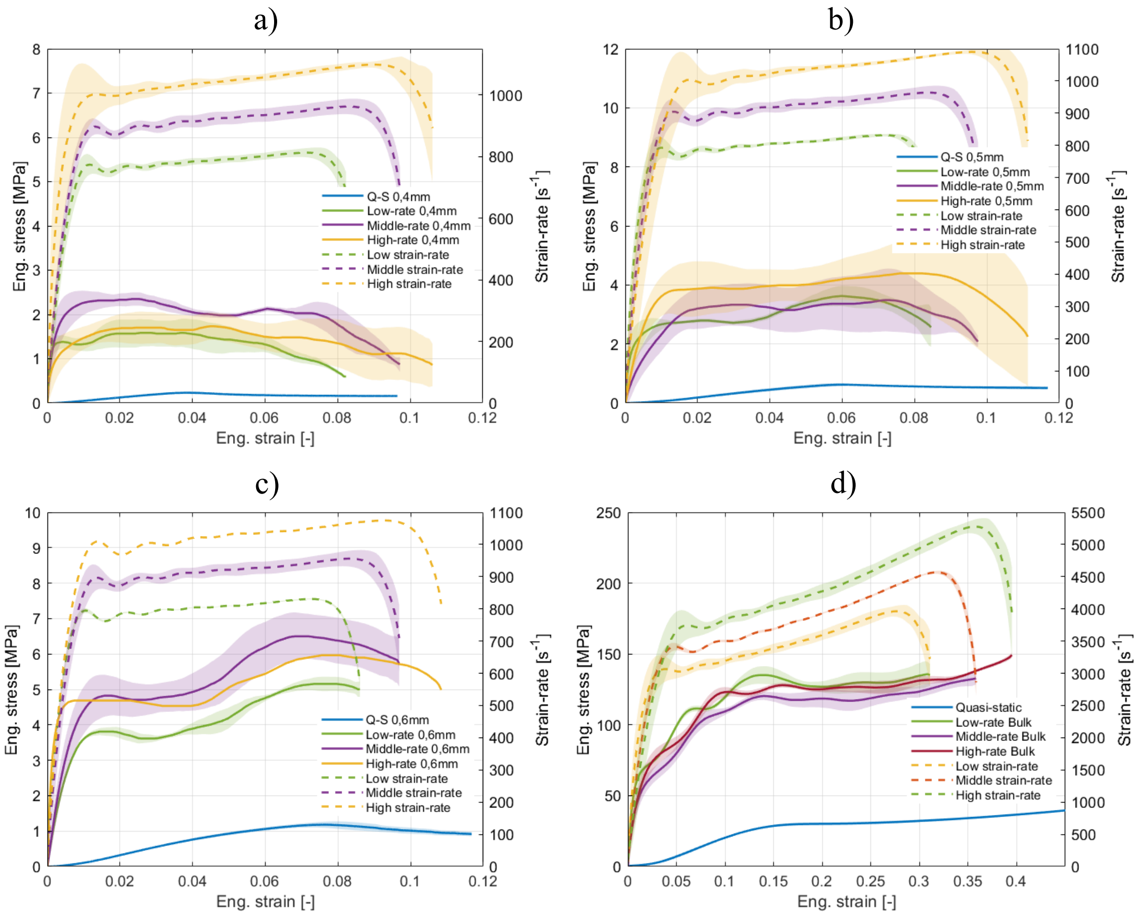

Fig. 2: Average stress-strain diagrams for various widths of structure INVH-3D a)~0,4mm, b)~0,5mm, c)~0,6mm, and d)Bulk specimens.

Auxetic behavior of lattice structures was confirmed/denied based on analysis of displacements in the direction perpendicular to loading. Showing auxetic behavior under dynamic loading of a thickest structure with a strut width of 0.4 mm Figure 3.a) and with increasing width of strut transition to non-auxetic behavior of structure with strut width of 0.6 mm Figure 3.c). No auxetic behavior was observed during quasi-static loading of tested structures see Figure 4. as an example, representing the behavior of all tested specimens.

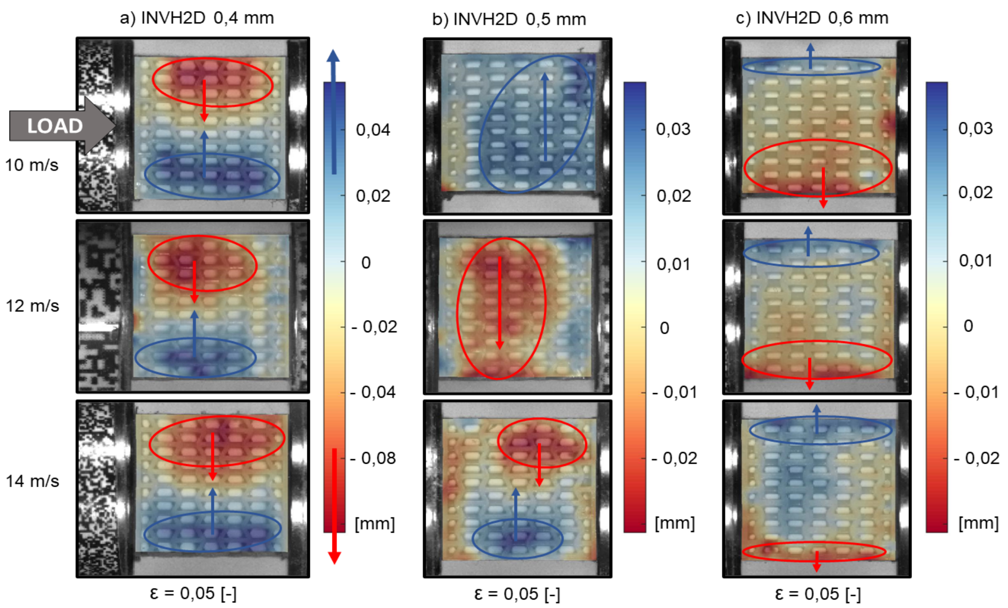

Fig. 3: Displacements in vertical direction showing structures behavior a)auxetic, b)semi-auxetic, c) non-auxetic.

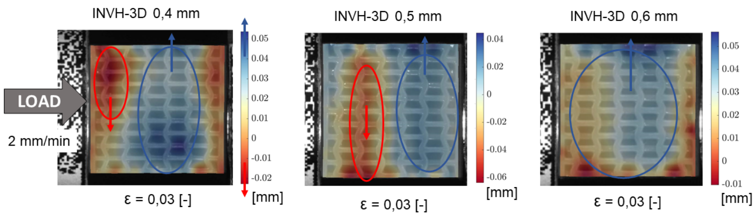

Fig. 4: Non-auxetic behavior of tested structures in Q-S loading. Displacements in vertical direction.

In quasi static loading, shear stress on all INVH-3D structures occur simultaneously all over the structure compared to the high strain rate loading where shear stress propagates through the structure until approx. 0.03 ε. and the failure of the structure is localized and occurs solely in one row of cells compared to the high strain rate loading where the deformation is more prevalent as can be seen in Figure. 5.

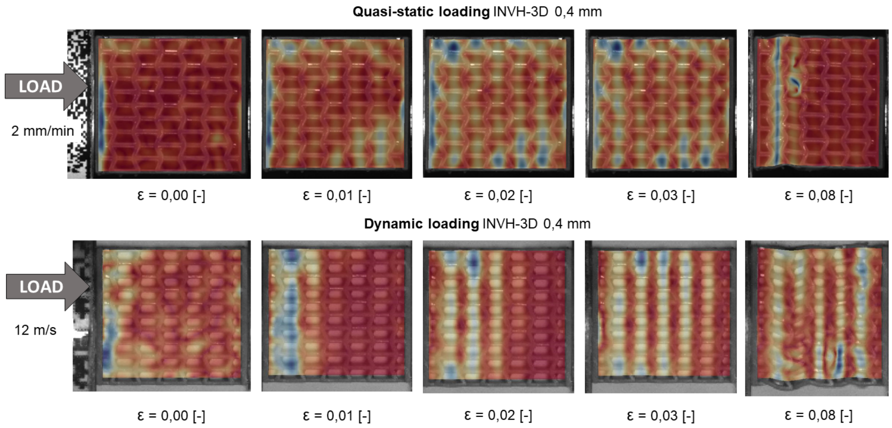

Fig. 5: Comparison of shear stress propagation in Q-S and high strain rate compression.

Based on the results obtained from the experimental investigations, it is possible to conclude:

- A major strain-rate sensitivity of all INVH-3D and Bulk specimens was indicated between Q-S and high strain rate loading. Fig. 2.
- INVH-3D exhibits strain-rate sensitivity even within small changes in strain-rate. Fig. 2.a)b)c)
- Bulk specimens exhibit no strain-rate sensitivity between different strain-rates. Fig. 2.d)
- INVH-3D with 0,4mm struts width exhibits auxetic behavior at all strain-rates. Fig. 3.
- INVH-3D with 0,5mm struts width exhibits semi-auxetic behavior at all strain-rates. Fig. 3.
- INVH-3D with 0,6mm struts width exhibits no auxetic behavior at all strain-rates. Fig. 3.
- All INVH-3D structures exhibit no auxetic behavior at Q-S loading. Fig. 4.

3. Conclusions

To summarize, compression tests of photocurable resin under quasi static and dynamic loading have been shown. In addition, the deformation behavior has been inspected using high speed camera and DIC analysis. The strengthening of the photocurable resin appeared when a higher strain rate was applied and auxetic behavior was observed on the thinnest of the tested inverted honeycomb structures.

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