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Short Note

Mechanical Properties and UV Reliability of Microlattice with Urethane Elastomers for insole

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Abstract: We investigated the properties of architected materials made from UV-cured urethane elastomers and the use of such materials for insoles. The durability and reliability of various materials currently used in medical insoles were compared with those of architected materials with microlattice. The results show that architected materials made from UV-cured urethane elastomers have high impact resilience and grip, and the hardness can easily be changed by adjusting the column diameter of the unit cell. Compared with the foam materials used for medical insoles today, these architected materials also demonstrate superior UV resistance, suggesting that, after being washed in water, they can be air-dried outdoors.

Keywords: 3D Printing; Lattice; Architected Material; Metamaterial; Elastomer; Insole; Durability; Reliability; Asker Hardness

1. Introduction

3D printing is known to achieve rapid shape prototyping because the 3D shapes can be designed and manufactured directly without the need for 2D drawings and mold fabrication [1]. Particularly in the medical field, 3D printing can be tailored to meet individual needs, e.g., for manufacturing personalized jigs and orthotics [2]. This makes it preferable to the traditional process of using plaster molds in areas such as orthopedic medicine [3]. This new potential use is also expanding the business model from prototyping to manufacturing, especially for "personalized manufacturing" applications [4]. In recent years, by applying 3D printing technology using the laser sintering of metal powders [5,6], researchers have studied architected materials that exhibit unique nonlinear properties, such as structure-derived energy absorption, from a single material by forming a microstructured periodic lattice structure [7,8]. In addition, some researchers have attempted to apply architected materials to polymer materials to produce nonlinear properties [9,10]. Microstructures have been fabricated using UV curable elastomers, and the relationship between 3D design parameters, deformation behavior, and mechanical properties of flexible lattice structures has been investigated [11-13]. One experiment assigned these elastomer microlattices to the shape of a wearable device in an attempt to use architected materials while controlling the external shape and local hardness [14].

It remains unclear, however, if the durability and reliability of such microlattice structures are sufficient compared with those of materials currently used for medical insoles. Traditionally, foam polymer materials such as polyethylene (PE) foam, ethylene vinyl acetate (EVA) foam, and polyurethane (PU) foam have been used for medical insoles [15-17]. The properties of these foam materials depend on whether the cell bubbles are continuous or closed bubbles [18]. For medical insoles, it is important to consider the many ways they might be used [19]; continuous-cell foam materials have a soft structure but lack durability and reliability, whereas closed-cell foam is more durable, but too hard [20]. Furthermore, the degradation of materials due to heat, UV light, and moisture must also be considered [17,21].

In this study, we investigate the properties of architected materials made from UV-cured urethane elastomers and the use of such materials for insoles. The lattice structure has a specific volume of hollow space, so it is expected to have a soft structure similar to that of a continuous bubble. Unlike continuous bubbles, however, elastomers can be used to achieve high durability. The durability and reliability of various materials used in existing medical insoles were compared with those of the architected materials.

2. Materials and Methods

2.1. Materials

2.1.1. Architected Materials

OpenSCAD [22] can generate 3D structures by scripting, and the structures can be designed parametrically. In this study, columns were placed on the unit cell based on the body-centered cubic structure and the pattern shown in Figure 1(a). The size of the unit lattice was 4 mm on each side, and a cubic structure with a periodic structure (5 × 5 × 5 unit) was designed, as shown in Figure 1(b); in the architected material, the diameter of the columns of the unit lattice was changed from 0.80 to 1.52 mm. To make the contact area uniform, each cube had a 0.7-mm-thick bottom and top plate. To maintain ventilation, 1.7-mm square holes were periodically placed on each side of the bottom and top plates. UV-cured urethane elastomer EPU41 (Carbon Inc.) was used for UV modeling using a photo-curable 3D printer L1 (Carbon Inc.). Finally, the structures made of architected materials were created via heat treatment at 120 °C for 8 h. In particular, the physical properties and UV resistance of the samples with column diameters of 0.80 mm (AM-1), 1.20 mm (AM-2), and 1.52 mm (AM-3) were compared with those of the foam materials. Three different sample sizes were fabricated: 20 × 20 × 20, 110 × 60 × 5, and 50 × 20 × 5 mm.

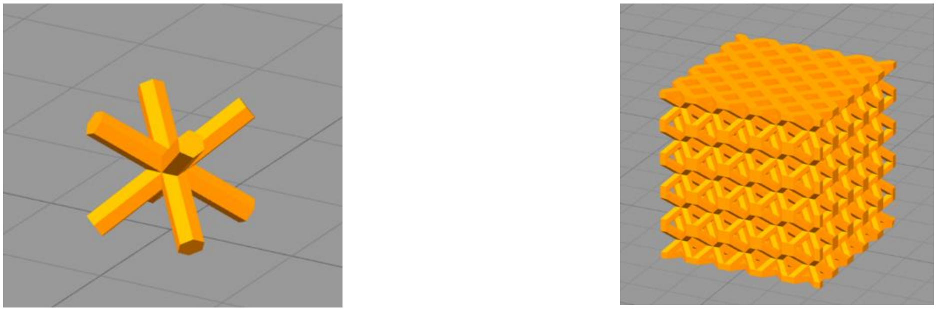

(a) (b)

Figure 1. 3D structure made of architected materials designed in OpenSCAD: (a) unit cell structure; (b) 5 × 5 × 5 lattice cube structure.

2.1.2 Polymer Foam

Foam materials with different densities (EVAfoam-1, EVAfoam-2, EVAfoam-3, PEfoam, and PUfoam) were obtained, and their bulk density and Asker C hardness were measured. For EVAfoam-1, EVA foam with a hardness of 70 was purchased from Benkyodo Co; the bulk density of a 20 × 20 × 20-mm cube was 0.28 g/cm^3. For EVAfoam-2, EVA foam P-E Lite (A-20) was purchased from INOAC Corp.; the bulk density of a 20 × 20 × 20-mm cube was 0.18 g/cm^3. For EVAfoam-3, EVA foam nora® Lunairmed was purchased from Nora Systems, Inc.; the bulk density of a 20 × 20 × 20-mm cube was 0.09 g/cm^3. For PEfoam, PE foam AZOTE® (LD-45) was purchased from INOAC Corp.; the bulk density of a 20 × 20 × 20-mm cube was 0.05 g/cm^3. For PUfoam, PU foam X2 SOFT/MAROON was purchased from Henry Schein, Inc.; the bulk density of a 20 × 20 × 20-mm cube was 0.05 g/cm^3.

2.2. Methods

2.2.1. Hardness

The hardness (Asker C) was measured using an automatic rubber hardness tester (P2-C type) manufactured by Polymer Instrument Co. The hardness was considered to be the peak value of a 20 × 20 × 20-mm sample pressed against a hardness tester at a speed of 3.2 mm/min.

2.2.2. Impact Resistance

A shovel-type repulsive elasticity tester (RT-90) manufactured by Polymer Instrument Co. was used to strike a 20 × 20 × 20-mm sample with a pendulum six times, and the average of the three repulsive moduli from the fourth strike onward was considered the impact resistance.

2.2.3 Frictional Force

The frictional force was measured using the Tribo Station (Type:32), a surface property measuring instrument manufactured from Shinto Scientific Co., Ltd. A 30 × 30-mm flat indenter laminated with a non-woven waste cloth was pressed against a 110 × 60 × 5-mm specimen at a load of 200 g. The dynamic frictional force was evaluated when the specimen was scanned at a moving speed of 500 mm/min and a reciprocating distance of 40 mm.

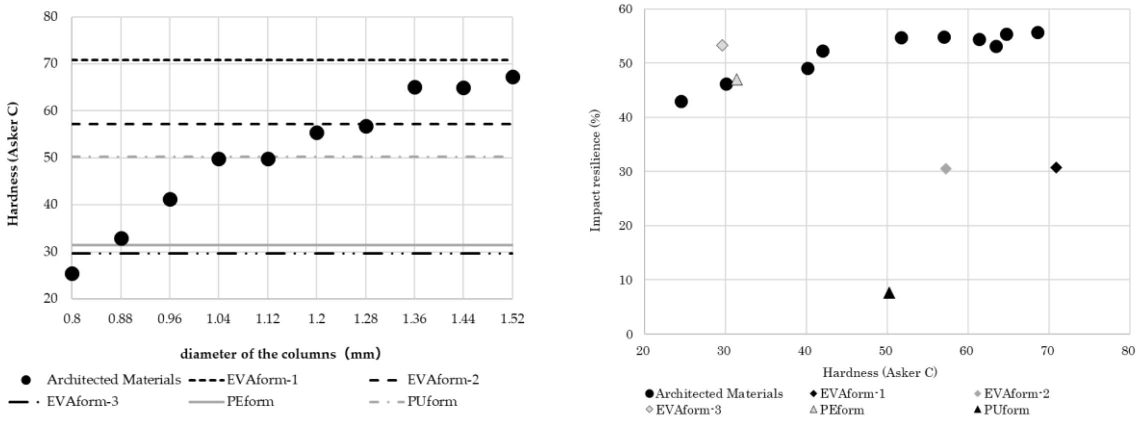
2.2.4. UV Resistance

Specimens of 50 × 20 × 5 mm were irradiated for 48 h at 63 °C in the chamber using a Suga Testing Machine ultraviolet Carbon Arc fade meter (U48). The color change after irradiation and the presence of cracks when the specimen was bent by hand were visually observed.

3. Results and Discussion

The hardness (Asker C) of the lattice cube after the column diameter of the unit lattice was changed from 0.80 to 1.52 mm is shown in Figure 2(a). The hardness increased as the diameter of the pillars increased, and it was confirmed that the hardness can be freely controlled so that it is similar to that of commercial insole materials. However, when the relationship between the hardness and impact resistance of each material was investigated, it was found that the lattice cube structure is a material with low hardness and high rebound coefficient, as shown in Figure 2(b). This is due to the characteristics of the elastomer material and the low energy dissipation of the structured material when a body-centered cubic lattice is used for the unit lattice—it shows a load displacement curve without buckling of the structure [14].

After 48 h of carbon arc testing, the PU foam became discolored, and the PE foam shrunk, as shown in Figure 3. In addition, when the samples were bent after the test, cracks occurred in the PU foam, as shown in Figure 4. The AM samples did not show any abnormality in appearance or bending after the test.



(a) (b)

Figure 2. Comparative results of mechanical properties: (a) relationship between the diameter of pillars in the unit cell and hardness of the lattice structure; (b) relationship between hardness (Asker C) and impact resistance.

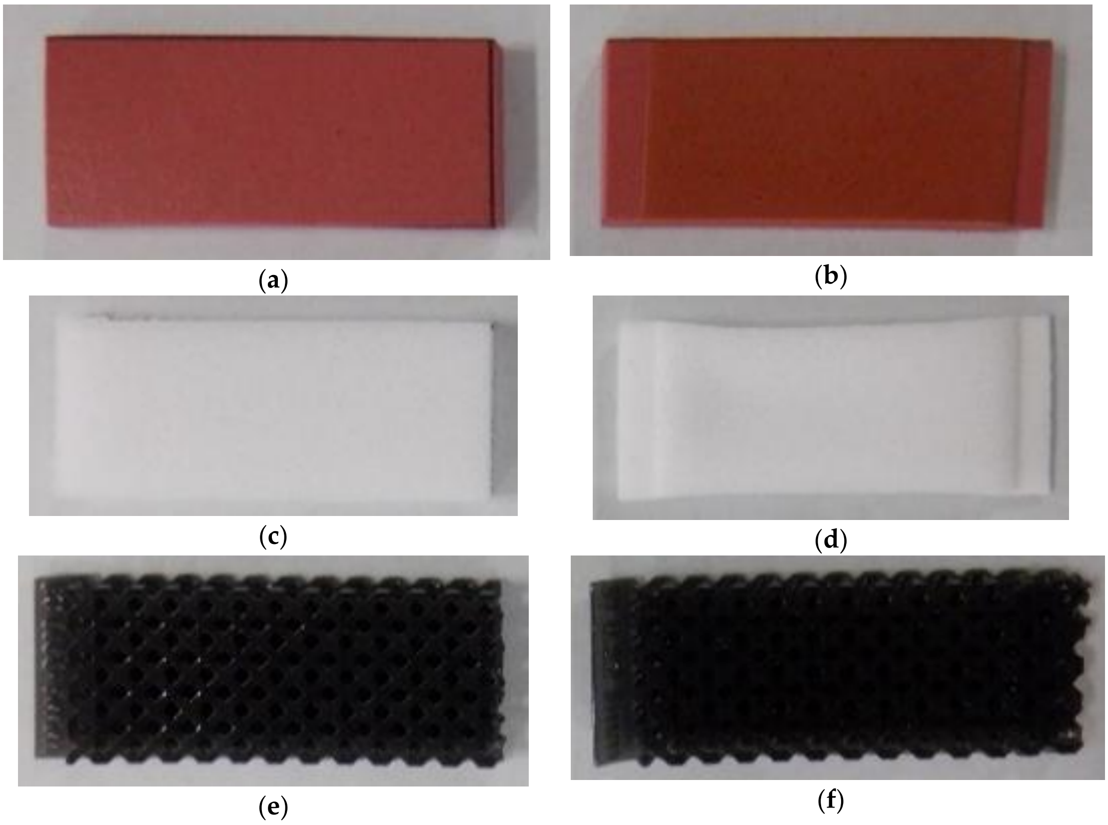

(a) (b)
(c) (d)
(e) (f)

Figure 3. Appearance of samples before and after carbon arc testing: (a) PU sample before carbon arc testing; (b) PU sample after carbon arc testing (discoloration occurred); (c) PE sample before carbon arc testing; (d) PE sample after carbon arc testing (shrinkage occurred); (e) AM sample before carbon arc testing; (f) AM sample after carbon arc testing.

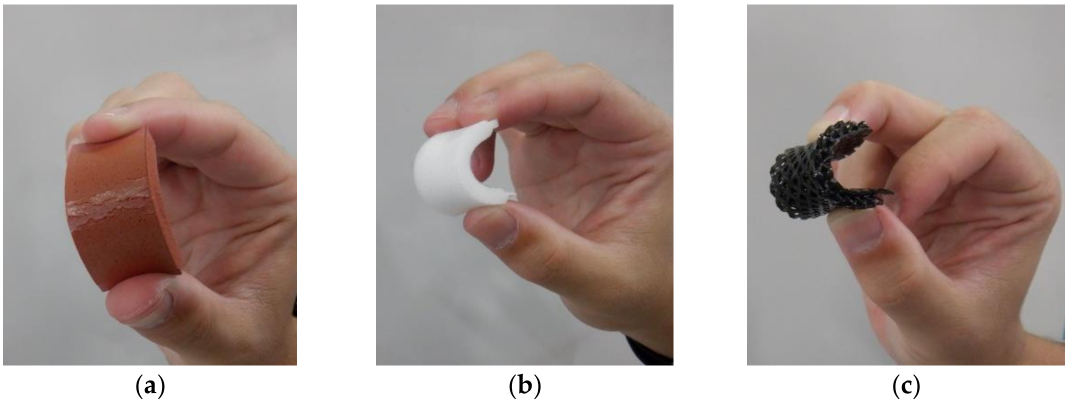

(a) (b) (c)

Figure 4. Appearance of samples after bending: (a) PU sample (cracking occurred); (b) PE sample; (c) AM sample.

The physical properties and UV resistance test results for each material obtained in each test are shown in Table 1. Although the Asker C hardness could be changed at will, the architected materials made of a single elastomer showed no significant change in impact resistance, and the coefficient of friction tended to remain constant. In addition, the carbon arc test confirmed that, compared with currently used foam materials, the architected materials were more reliable in the UV environment.

Table 1. Physical Property and Reliability of Architected Materials.

Material	Bulk Density (g/cm^3)	Hardness (Asker C)	Impact resilience	Coefficient of Friction	Carbon Arc Test (48h)
AM-1	0.25	31	49	208	OK
AM-2	0.41	56	54	208	OK
AM-3	0.55	68	56	208	OK
EVA-1	0.28	71	31	112	Shrinking
EVA-2	0.18	57	31	143	Shrinking
EVA-3	0.09	30	53	204	Shrinking
PE	0.05	31	47	148	Shrinking
PU	0.05	50	8	46	Discoloring/Cracking

4. Conclusions

The durability and reliability of various foam materials currently used in medical insoles were compared with those of architected materials. It was shown that architected materials made of UV-cured urethane elastomers had high resilience and grip, and the hardness could easily be changed by adjusting the pillar diameter of the unit cell. Architected materials were also shown to be more UV resistant than existing foam materials, suggesting that, after being washed with water, they can be air-dried outdoors.

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