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Parameter control in selective laser sintering for elastic lattice structures of functionally graded seat cushion

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Lattice structures have been widely applied in many fields, including aerospace and automotive, due to its superior capabilities on energy absorption and weight reduction. However, with their complex shapes, it is often difficult to realize lattice structures with conventional manufacturing methods. In this sense, additive Manufacturing (AM) can provide with an excellent solution for implementing complex shapes of lattice structures due to the high design flexibility. Therefore, researchers and engineers have shown an increased interest in designing and applying lattice structures using AM. Especially, a lattice structure which is AM printed with an elastic material (e.g., a thermoplastic polyurethane (TPU)) provides flexibility and elasticity to the parts and functional designs. Previous studies of AM printed lattice structures have focused on energy absorption efficiency and packaging for product protection. However, far too little attention has been paid to applying additive manufacturing to seat cushions such as automobile seats. In this research, the effects of the process parameters on the sag factor and hysteresis loss rate of a Kelvin lattice structure produced through Selective Laser Sintering (SLS) process were investigated. The sag factor and hysteresis loss rate are properties quantitively defined to represent the comfort of the seat cushion. A design of experiment is designed with three main process parameters (i.e., Laser Power, Hatching Distance, and Scan Speed). The effects of the parameters on the cushion properties were assessed using analysis of variance (ANOVA). The optimal process parameter combination for the cushion properties that shows similar performances to existing automobile seat cushion was obtained using the response surface methodology (RSM). A confirmation test was conducted to verify the optimal process parameters by manufacturing a prototype of the seat cushion. It is shown that a seat cushion additively manufactured with a single material and SLS has multiple cushion areas by applying the combination of various process parameters.

1. Introduction

Additive manufacturing (AM) provides great opportunities for designing a flexible and automatic 3D component in many fields such as aerospace, biomedical, and automobile manufacturing [1,2]. It could make complex structures that are unfeasible by conventional manufacturing methods.

A lattice structure is a porous foam structure composed of an array of unit cells repeated periodically with edges and faces, which have many superior properties of energy absorption, heat transfer efficiency, and lightweight [3]. Although lattice structures could give an unprecedented solution in many applications, their entangled struts are a challenge to fabrication. However, the high design flexibility of additive manufacturing makes lattice structures have uniform porosity.

The additively manufactured lattice structure has been widely used with various materials such as metals, polymers, and composites. Elastomer materials such as thermoplastic polyurethane (TPU) attract the attention of researchers with outstanding flexibility and resilience like soft foam. The studies of TPU additive manufactured lattice structures have shown that their great energy absorption and dissipation depend on the type of unit cell, relative density, and process parameters of AM machine [4,5,6]

[4] studied the mechanical properties of additively manufactured TPU lattice structures depending on the geometric and process parameters of fused filament fabrication (FFF) by finite element simulation of a compression process. The printing temperature, orientation angle, unit cell size, and unit cell types affect the stiffness of lattice structures. This study showed that the relative density of structures and the geometry complexity of each cell type have a strong influence on their mechanical properties. By controlling the parameters, it offers an opportunity for energy absorption applications demanding customized mechanical properties.

Flexible additively manufactured gyroid structures are fabricated by FFF in [5]. The relative density, called solid volume fraction in this paper, was varied with two different types of TPU filaments. The mechanical behavior of three conventional polyurethane foams was compared with gyroid structures during the compressive test and fatigue test. This study shows that the tailored changes in structure lead to control of their cushioning behaviors. Therefore, the customized cushioning can be additively manufactured for specific demands and can be a substitution for conventional polyurethane foam.

However, most studies have focused on their energy absorption and have not quantitatively represented the cushion properties felt when the user is directly contacted. In this study, to replace the automobile seat with flexible additively manufactured lattice structures, the cushion properties such as sag factor and hysteresis loss rate are used to express the cushion feeling quantitatively, which are used for actual automobile seat test. Although previous studies show the possibility that additively manufactured TPU lattice structures could replace cushion foam by using FFF, it is not suitable in terms of time and quality to manufacture large parts such as automobile seats. Therefore, in this study, the TPU kelvin structures are fabricated via the SLS machine by varying the process parameters such as laser power, scan speed, and hatching distance to find the correlation with the cushion properties. The conventional polyurethane foam used in the automobile seat is compared and the optimal process parameters that additively manufactured structures have similar cushion properties to polyurethane foam are chosen. Finally, the optimal process parameter is applied to the fabrication of a seat prototype to verify the results.

2. Background and Experiment Setups

2.1 Kelvin structure

The Kelvin cell consists of 6 squares and 8 hexagon faces, which is a tetrakaidekahedral cell for the structure of soap foams with equivalent bubble size. The edges of the square and hexagon faces have the same struts and edges and meet at the tetrahedron vertices. The Kelvin cell is known that it has minimum surface energy [6].

However, the kelvin structures were mainly focused on mechanical properties such as stiffness and energy absorption [7], not cushion properties.

2.2 Cushion properties

Because the automotive seat is always in contact with the driver's body, it directly affects the comfort of the driver. As the user experience inside vehicles is drawing attention due to the recent trend of autonomous driving, the comfort of seats has become more important. In this study, to quantitatively compare comfort, some cushion properties composed of compressive loads are used as shown **Fig. 1**.

A sag factor (SAG) is one of the cushion properties representing the feeling of support of cushion foam and is measured by dividing a 65% compression load by a 25% compression load. The hysteresis loss rate (HLR) is the ratio of the compressive energy to the released energy, which is related to the resilience of the sheet. These cushion properties can be calculated each by the equation (1) and (2).

$$SAG = \frac{65\%\ compressive\ load}{25\%\ compressive\ load} \tag{1}$$

$$HRL = \frac{Loading\ energy - Unloading\ energy}{loading\ energy} \tag{2}$$

The cushion properties including the sag factor and hysteresis loss rate should be sensitively pursued for the comfort of drivers and passengers.

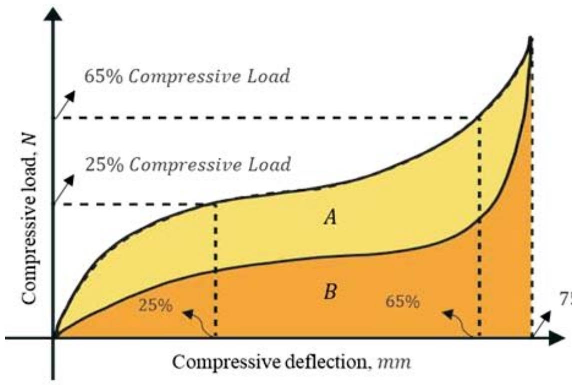

Fig. 1. Load-deflection curve of TPU Kelvin structure

2.3 Material and machine

The WAFAB-PU95AB (Wanhua Chemical Group Co., China), which is a Polyester-based grade TPU 3D powder with excellent flowing, was used as raw material. Material properties provided by the manufacturer of the used TPU powder are shown in **Table 1**. The Kelvin lattice cube-shaped specimens were fabricated by the SLS 3D printer Farsoon Flight 403P (Farsoon, Inc, China). The specimen size is 40 x 40 x 40 mm, and the Kelvin unit cell is 8 x 8 x 8 mm. It means the total of 125-unit cells (5x5x5 unit cells) are in lattice cube-shaped specimens patterned along the coordinates. Kelvin lattice printed through the above arrangement is shown in **Fig. 2.**

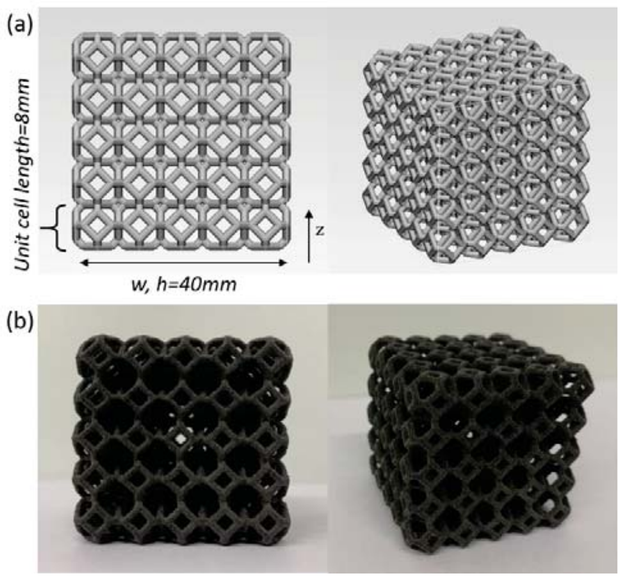

Fig. 2 Kelvin lattice cube-shaped of (a) CAD, (b) as-printed specimen

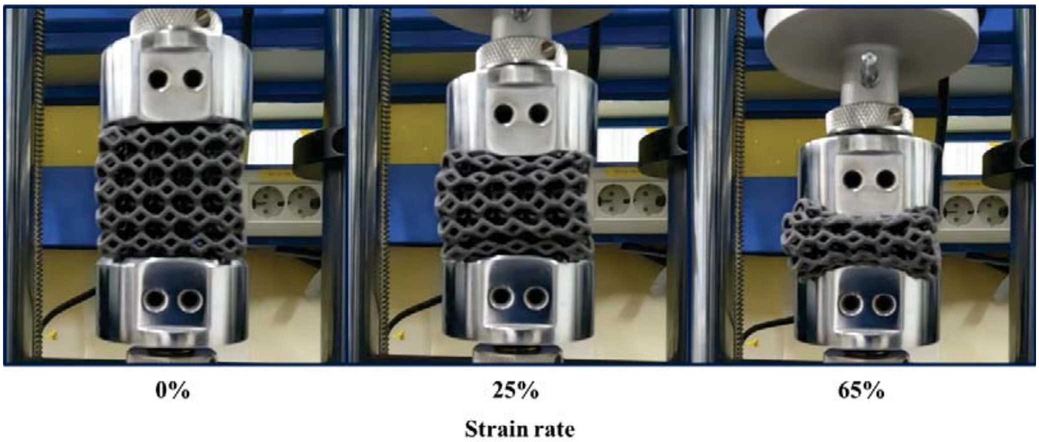

Fig. 3. Compressive deformation images of compression test with specimen No. 25

Table 1 Material properties of TPU powder (WANFAB-PU95AB) used for specimen manufacturing.

Shore hardness	Ultimate Elongation	Bulk Powder Density	Sintering parts Density	Tensile Strength
95A	310%	0.5 g/cm3	1.15 g/cm3	21 MPa

2.4 Orthogonal experiment

In this experiment, the effects of three main process parameters on cushion properties were examined by orthogonal experimental design. The layer thickness was fixed to 0.1 mm, the powder bed temperature was 112℃ and each factor has five levels in **Table 2**. an orthogonal table is established in **Table 3** to study the influences of process parameters on the cushion properties which were extracted from load-deflection curves.

Table 2. A summary of the process parameters for the SLS printer.

Process parameters	Values
Laser power	200-400 W (intervals of 50 W)
Laser scan speed	10000-30000 mm s^{-1} (intervals of 5000 mm s^{-1})
Laser hatching distance	0.09-0.21 mm (intervals of 0.03 mm)
Layer Thickness	0.1 mm
Powder bed temp.	116 ℃

2.5 The quasi-static compression tests

The quasi-static compression tests were carried out with an Instron universal testing machine (Instron 5948) with the 100kN load cell at room temperature. The compressive loads were applied to every sample until 75% load deflection (30mm) with the constant strain rate of $0.03s^{-1}$ (1.2mm/s). The number of compression cycles, which means the number of repeating the compression and release is fifty times and all tests end up at 75% load compression. Therefore, intuitively said, the total number of compression cycles is 50.5.

Images of a cyclic compression test for one of the Kelvin lattice samples are shown in **Fig. 3.** The load-deflection curves were extracted from the Kelvin lattice cube-shaped samples by conducting the quasi-static compression tests. The relationship between process parameters and cushion properties was determined from the load-deflection curves.

Table 3. Orthogonal table $L_{25}(3^5)$ for experiment design of SLS processing.

No.	Laser power (W)	Scanning speed (mm s^{-1})	Hatching distance (mm)
1	200	10000	0.09
2	200	15000	0.12
3	200	20000	0.15
4	200	25000	0.18
5	200	30000	0.21
6	250	10000	0.12
7	250	15000	0.15
8	250	20000	0.18
9	250	25000	0.21
10	250	30000	0.09
11	300	10000	0.15
12	300	15000	0.18
13	300	20000	0.21
14	300	25000	0.09
15	300	30000	0.12
16	350	10000	0.18
17	350	15000	0.21
18	350	20000	0.09
19	350	25000	0.12
20	350	30000	0.15
21	400	10000	0.21
22	400	15000	0.09
23	400	20000	0.12
24	400	25000	0.15
25	400	30000	0.18

3. Conclusions

This study aims to express cushion properties from the compressive tests of additively manufactured Kelvin structure fabricated by metamaterial, TPU. The Kelvin cube samples were compressed until 75% deflection and released repeatedly. The cushion properties such as SAG and HLR will be extracted from the load-deflection curves of

Kelvin samples. Depending on the process parameters, the deflection loads at different strain rates show significant variance in cushion properties. It means that the process parameters of SLS printing may have a worthwhile effect on the performance of lattice structures and could realize a TPU lattice customized seat cushion by using additive manufacturing.

A regression equation for predicting the cushion properties according to the process parameters will be derived after reproducing the number of repetitions of the specimen to increase the reliability of the data. The Kelvin lattice specimen will be compared with the polyurethane seat of the automobile seat and the response surface method (RSM) suggests the optimal process parameters which make the kelvin structure has similar cushion properties to the automobile seat. The optimal process parameters will be verified by applying them to a seat prototype.

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