Mechanical Response of Honeycomb Structures Under Impact

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Abstract: A honeycomb structure with a negative Poisson's ratio (NPR) was designed, fabricated, and analyzed for utilization in personal protective clothing (PPC). The mechanical properties were investigated using a quasi-static mechanical testing and the Hopkinson pressure bar experimental system, and results were compared with similar samples containing regular hexagonal and regular quadrilateral honeycomb structures. The experimental results showed that under quasi-static loadings, the concave honeycomb structure had the highest compressive modulus and yield strength, which produced the highest strain absorption energy, anti-deformation performance and energy absorption. When exposed to a dynamic load at a high strain rate, the concave honeycomb also exhibited the highest dynamic compression modulus, the best impact resistance and best energy absorption among the three structures. In summary, the concave honeycomb structure was more resistant to deformation and had higher impact resistance than the regular hexagonal and regular quadrilateral honeycombs, and exhibited better energy absorption, which makes it a good candidate for application as a personal safety protection material.

Key words: negative Poisson's ratio effect; quasi-static; dynamic analysis; energy absorption
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The probability of death or injury of emergency first responders in the dangerous chemical explosion accidents is 1.2×10^7 times greater than in fire-fighting and 3.4×10^7 times greater than in social relief and assistance activities[1-2]. One of the leading causes of heavy casualties in the emergency rescue workers are the absence of appropriate explosion-proof suits for the rescuers. The common clothing worn by the rescuers is completely incapable of protecting the wearer from the effects of explosion. Therefore, a study of the structural and materials properties of explosion-proof suits can play a significant role in reducing the casualties of the emergency rescue workers.

Multilayer composite materials have attracted more and more attentions from numerous researchers both domestically and abroad due to their excellent explosion-suppression, energy-absorption performances. For example, Tedesco et al. analyzed the attenuation of an explosive shock wave in a multilayer composite structure[3]. Their results showed that this layered structure played a strong role in suppressing the explosive shock wave. Lee et al. studied the role of an open foam structure in air in weakening an explosive shock wave[4]. Kleine et al. studied the behavior of open foam and closed foam of various densities in attenuating explosive shock waves[5]. Yang et al. studied the shock wave suppression effect of armored steel of different structures and aramid fiber multilayer composite structures[6]. Zhou et al. experimentally studied the interactions between the shock wave and open and closed foaming structures[7]. Some multilayer structures can be used to manufacture protective suits, due to their excellent performance in energy absorp-

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tion and shock absorption as well as their ability to attenuate shock waves.

Indented honeycomb structures have a negative Poisson's ratio and this can be applied to the development of new materials with a negative Poisson's ratio. Overaker et al. studied the effects of the expansion angle of the cells of traditional honeycomb structure on the elastic mechanistic performance of the structure[8]. Their research showed that the mechanical response of this foam with a negative Poisson's ratio was influenced by the honeycomb unit structure. Wan et al. discussed the effect of indented honeycomb unit cells of various geometric sizes on the overall honeycomb structures with a negative Poisson's ratio[9]. Horrigan et al. proposed two methods to optimize the negative Poisson's ratio honeycomb structure to enhance the mechanical performance of the structure[10]. Grima et al. studied the foam structure and reinterpreted the effect of the negative Poisson's ratio[11]. Zhang et al. studied the dynamic mechanical response of the negative Poisson's ratio honeycomb structure subjected to an in-plane shock using shock dynamics finite element software ANSYS/LS-DYNA[12].

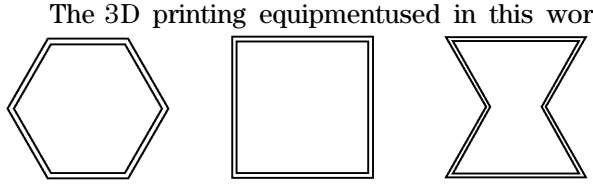
The honeycomb structure has an excellent impact energy absorption performance, a high strength-to-weight ratio and excellent mechanical properties with broad application prospects in energy absorption. Therefore, several typical honeycomb structures are selected as research objects. In this paper, we examined the differences in the quasi-static and dynamic mechanical response and the energy-absorption characteristics of different honeycomb structures using the 3D printing to rapid prototypes of the materials. First, an indented honeycomb structures with a negative Poisson's ratio that had a regular hexagon honeycomb, and a regular quadrangular honeycomb of the same unit size were designed, and processed using the 3D printing technique. Second, a quasi-static mechanical test was conducted to compare the basic mechanical parameters of the honeycomb structure with a negative Poisson's ratio and other typical honeycomb structures. An analysis of the test results compared the differences in quasi-static compressive mechanical performance of the several structures, as well as the mechanical response characteristics of the negative Poisson's ratio structures. Finally, a dynamic mechanical test was conducted to compare the stress-strain curves of the different materials under the same strain rate to determine the mechanical response and energy-absorption characteristics of the different honeycomb structures under a high strain rate.

1 Methodology

1.1 Design and processing of the honeycomb structure

An indened hexagon honeycomb structure with a negative Poisson's ratio was designed based on the traditional, natural honeycomb structure. The three-dimensional mapmaking software Solidworks was used to plot the normal hexagonal, normal quadrangular, concave, hexagon honeycomb units and protective baseplate CAD models. The unit cells and overall arrangements of the three structures are shown in Fig. 1. The unit cell of each of the designed three honeycomb structures was 3.4 mm long and high with a wall thickness of 0.1 mm. The interior angle of the orthohexagonal honeycomb structure was 120°. The interior angle of the quadrangular honeycomb structure was 90°. The concave angle of the negative Poisson's ratio, indented honeycomb structure was 30°. The dimensions of each of the three protective baseplates were 60 mm × 60 mm × 10 mm. There were 3 units in the vertical direction and 18 units in the horizontal direction, as shown in Fig. 2.

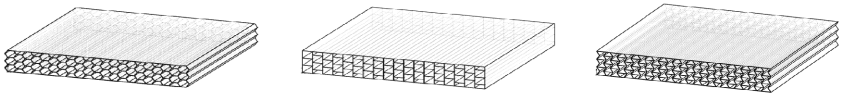
The 3D printing equipmentused in this work



(a) Regular hexagon (b) Regular quadrangle (c) Indent hexagon

Fig. 1 Three honeycomb unit structures

was a BLT-S310 metal 3D printer, with technical specifications shown in Tab. 1.



(a) Regular hexagon (b) Regular quadrangle (c) Indent hexagon

Fig. 2 Three types of honeycomb type protective baseplates

Tab. 1 Technical specifications of the BLT-S310 metal 3D printer

Index	Parameter
Printable material	Titanium alloy, aluminum alloy, high-temperature aluminum
Laser power	500 W
Accuracy of Z axis repositioning	0.005 mm
Powder scraping mechanism	Two-way powder application
Parts layer thickness	20 – 100 μm
Powder application accuracy	10% within the layer thickness
Scanner scanning speed	1 m/s
Maximum positioning speed of scanner	12 m/s
Highest preheating temperature	200 ℃
Effective forming dimension of equipment	250 mm × 250 mm × 400 mm
Overall dimension	2 750 mm × 1 160 mm × 2 185 mm

TC4 has a density of only 60% of steel with higher strength. It has strong corrosion resistance and meets the lightweight and durable performance requirements of protective clothing. The raw material used in the 3D printing was a TC4 titanium alloy powder with high specific strength and excellent toughness and corrosion resistance and the physical characteristic parameters of this material are listed in Tab. 2.

Tab. 2 Performance parameters of the TC4 titanium alloy powder

Parameter	Numerical value
Poisson's ratio	0.325
Density/(g·cm^{-3})	4.45
Volume sound velocity/(m·s^{-1})	4 990
Melting point/℃	1 660
Young modulus/GPa	117
Shear modulus/GPa	44
Volume modulus/GPa	111
Percentage reduction of area/%	25

1.2 Quasi-static compression test

A MTS universal material tester (MTS LANDMARK) was used to determine the mechanical behavior and energy-absorption characteristics of the various honeycomb structures under quasi-static compression conditions (Fig. 3). The loading rate of the material tester was set to 3.0 mm/min. The rated loading strain rate was 0.005 s^{-1}. The corresponding sampling rate was 50 Hz. The processed protective baseplates were cut into Φ10 mm × 10 mm cylindrical test pieces. The test pieces of each honeycomb structure were tested three times. Test pieces were grouped, numbered and measured to obtain the diameter and height using an electronic vernier caliper (LT-MT518) before testing. The test pieces in the quasi-static compression test and the loading processes are shown in Fig. 4.

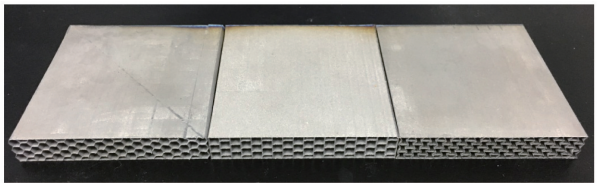


Fig. 3 Processed honeycomb type protective baseplates: regular hexagon, regular quadrangle, indent hexagon (from left to right)

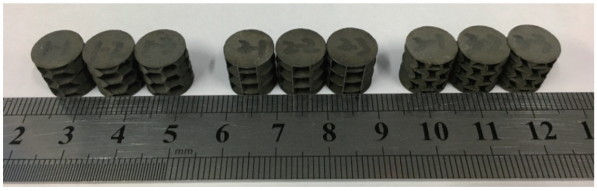


Fig. 4 Test pieces for quasi-static compression test: regular hexagon, regular quadrangle, indent hexagon (from left to right)

1.3 Dynamic compression test

A split-Hopkinson pressure bar driven by compressed gas was utilized to measure the dynamic mechanical response of the different honeycomb structures under a various high strain rates ($500 - 1\,500\ s^{-1}$) to obtain the stress-strain curves of the different structures under a high strain rate. The mechanical properties of different structures under the same strain rate were compared. Based on the test piece size and the test requirements, a 14.5 mm diameter split-Hopkinson pressure bar was used. The collision bar, incident bar, transmission bar, and absorption bar were composed of TC4 titanium alloy. The Young's modulus was 117 GPa. The collision bar was 200 mm long. The incident bar and the transmission bar were 1 200 mm long and the absorption bar was 600 mm long.

Two different strain rates, 700 s^{-1} and 1 000 s^{-1} were selected for this test. Using these two strain rates, each test piece was tested five times. The test data, i. e. the strain signal acquired by the strain meter, was stored using the dynamic strain meter. The dimension of each test piece was Φ10 mm × 10 mm, as shown in Fig. 5. The diameter and height of each test piece were measured with an electronic vernier caliper (LT-MT518) during the test. The incident signal and transmission signal were recorded. Two sets of data with a good repeatability were selected from each set of tests and recorded data.

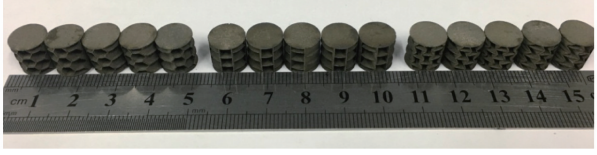


Fig. 5 Test pieces for dynamic mechanical test: regular hexagon, regular quadrangle, indent hexagon (from left to right)

2 Results and Discussion

2.1 Quasi-static compression test

The results of the quasi-static compression test are shown in Fig. 6. Each curve was the result of the averaging of three test results and showed a good repeatability. The median elastic segment of the stress-strain curve was linearly fitted to obtain the straight slope, which was the compression modulus of the corresponding honeycomb structure. The vertical coordinate of the first inflection point on the strain curve was the yield strength of the corresponding honeycomb structure. The mechanical performance parameters are shown in Tab. 3.

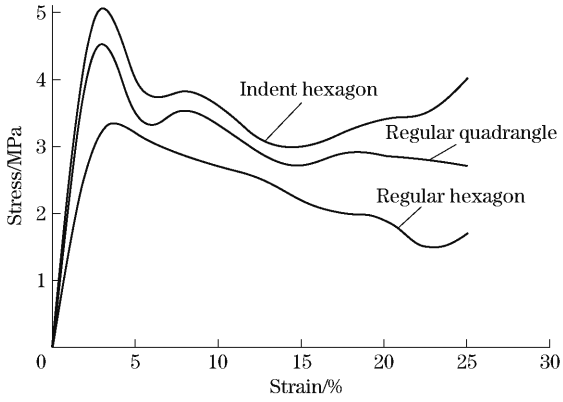


Fig. 6 Quasi-static compression stress-strain curves of three honeycomb structures

Tab. 3 Mechanical properties of three types of honeycomb structures MPa

Parameter	Regular hexagon	Regular quadrangle	Indent
Compression modulus	0.88	1.36	1.86
Yield strength	3.18	4.36	4.87

As shown in Fig. 6, within a range of 0 – 25% of the strain during the quasi-static loading process, the variation in the stress-strain curves of the three types of honeycomb structures was consistent and can be divided into three stages: ① elastic stage, at the beginning of loading, the material's stress increases linearly with the strain so that the stress-strain curve approximates a straight line. During this stage, the test piece de-

formation was elastic deformation. The test piece was restored after unloading; ② instability stage, where the stress of the test piece decreased rapidly after the curve attained the first wave crest point, i. e. yield point. In this stage, some honeycomb units suffered instability and plastic deformation. The stress was small, but the strain is large; ③ yield stage, as the strain increased, the stress in the material piece no longer decreased and fluctuated within a set range. At this point, the stress varied little while the strain increases continuously, which indicated that plastic deformation had occurred in the overall structure.

In the linear elasticity stage, the compression moduli of the regular hexagon, regular quadrangle, and indent honeycomb structures were: 0.88 MPa, 1.36 MPa, 1.86 MPa; the yield strengths were: 3.18 MPa, 4.36 MPa, 4.87 MPa. The compression modulus of the indent honeycomb was 1.37 and 2.11 times greater than the regular quadrangle and the regular hexagon. The yield strength of the indented honeycomb was 1.12 and 1.53 times greater than the regular quadrangle and the regular hexagon. The stress-strain curves of the indented honeycomb structure were the steepest and its inflection point was the highest in the linear elasticity stage. The compression modulus and the yield strength were significantly larger than that of the regular hexagon and regular quadrangle honeycombs, indicating that it had the best anti-deformation properties and mechanical properties under the action of the quasi-static loading.

As shown in Fig. 7, the indented honeycomb unit contracted in the force direction under the action of the quasi-static compression load and also contracted in a direction that was perpendicular to the direction of the applied force. The regular quadrangle honeycomb unit deformed into parallelogram shapes that were perpendicular to the direction of the applied force. These changes in dimension were insignificant. The regular hexagon honeycomb unit expanded in the direction perpendicular to the direction of the applied force. Thus, when the same strain occurred, the indented honeycomb had the highest equivalent density. The structure with a higher equivalent density had a higher compression modulus and yield strength. Thus, the indented honeycomb structure exhibited is excellent anti-deformation capacity.

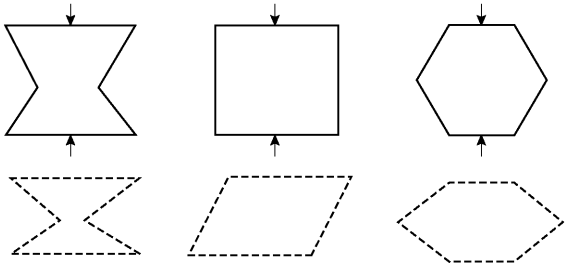


Fig. 7 Schematic diagram of the three types of honeycomb units under the action of the compression load

2.2 Dynamic compression test result

A split-Hopkinson pressure bar test was conducted to investigate the dynamic stress-strain behavior of the three types of honeycomb structures. The signal from the apparatus was processed to produce the dynamic stress-strain curves of the various structures tested at different strain rates as shown in Fig. 8 and Fig. 9. Each curve was obtained by averaging the several results with good repeatability from five tests. Similar to the quasi-static test, the dynamic stress-strain curve was analyzed to obtain the dynamic yield strength of the three types of honeycomb structures under different strain rates, as shown

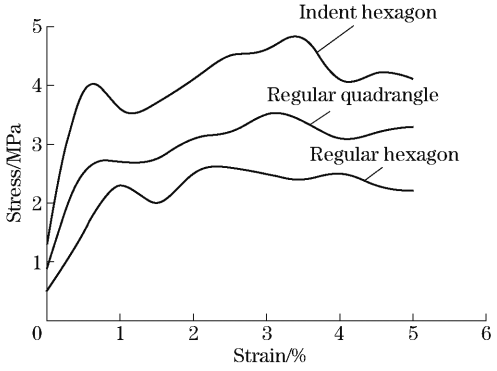


Fig. 8 Stress-strain behavior of three honeycomb structures at a strain rate of 700 s^{-1}

in Tab. 4.

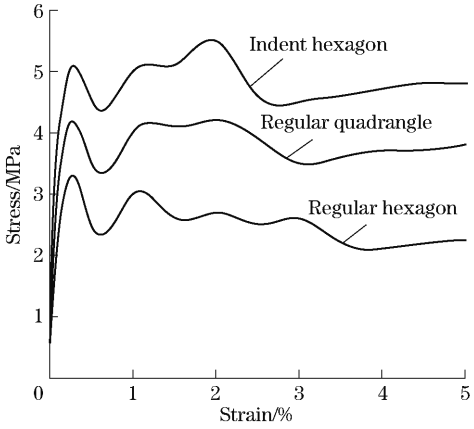


Fig. 9 Stress-strain curve of three types of honeycomb structures at a strain rate of 1 000 s^{-1}

Tab. 4 Dynamic yield strength of three honeycomb structures under different strain rates

Strain rate/ s^{-1}	Regular hexagon/MPa	Regular quadrangle/MPa	Indent/ MPa
700	1.56	2.81	3.77
1 000	2.16	3.13	3.87

As shown in Fig. 8 and Fig. 9, the variations in the stress-strain curves of the three types of honeycomb structures were similar and could be divided roughly into two stages: ① linear elasticity, when the dynamic shock load was applied on the test piece, it experienced an extremely small elastic deformation and its stress increased rapidly; ② plasticity segment, in contrast to static compression, the stress-strain curve of the honeycomb structure subjected to a high strain rate had no significant instability segment and rapidly entered the plastic deformation stage after yield occurred. In this stage, the stress of the test piece did not rapidly attenuate, but fluctuated within a range of high level. The cause of fluctuation was of a substantial plastic failure within the honeycomb structure. The honeycomb unit was severely deformed, crushed, and squeezed, producing significant resistance.

According to Tab. 4, the strain rate increased and the dynamic yield strength increased in each honeycomb structure. This was due to the strain rate strengthening effect. When the strain rate was increased, the loading rate was higher; so the structural deformation was quicker and the time required for development of the same strain was shorter. When the deformation rate was higher, the structural response time became shorter and the mutual squeezing action was stronger, so the resistance was larger and the yield strength also improved accordingly. As the strain rate was increased to 1 000 s^{-1} from 700 s^{-1}, the dynamic yield strength of the regular hexagon honeycomb increased by 38.4%. Under the same conditions, the dynamic yield strength of the regular quadrangle material increased by 11.4% and the dynamic yield strength of the indented honeycomb increased by 2.65%.

Based on the results shown in Figs. 8 – 9 and Tab. 4, the stress-strain curves of the indented honeycomb structure were always higher than those of the regular quadrangle and the regular quadrangle, indicating that the indented honeycomb structure experienced the highest structural stress with the same strain in a dynamic shock load. The dynamic yield strength of the indented honeycomb was also the highest when the strain rate was 700 s^{-1}, 1 000 s^{-1} and was recorded to be 1.34, 1.23 times greater than the regular quadrangle honeycomb, 2.41, 1.79 times greater than the regular hexagon honeycomb. This indicated that the indented honeycomb structure had the strongest anti-deformation and anti-shock properties in a dynamic shock load.

The indented honeycomb contracted, but the changes in the dimension of the regular quadrangle honeycomb was insignificant, but the regular hexagon honeycomb expanded. As a result, the indented honeycomb had the highest structural equivalent density, the most significant mutual squeezing effect, the largest stress and yield strength at the macroscopic level when the same strain occurred. Thus, the indented honeycombs had the largest anti-shock and anti-deformation capacity when subjected to the dynamic load.

In contrast to the quasi-static compression,

the energy absorption of the honeycomb structure during dynamic compression occurred primarily in the plasticity segment. The major forms of the consumption and absorption of energy by the structures were, dynamic load working, honeycomb unit deformation and mutual squeezing and heating. The analysis and comparison of the three types of honeycomb structures under a shock load helped in the selection of the optimum protective structure. Similar to the energy-absorption analysis under the quasi-static conditions, the diagrams of the energy absorption values and the energy-absorption points of the three types of honeycomb structures subjected to different strain rates, are shown in Fig. 10 and Fig. 11.

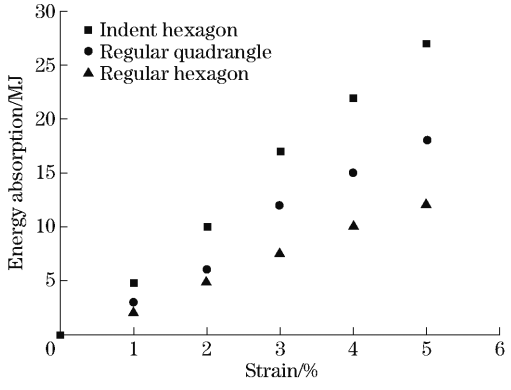


Fig. 10 Energy absorption of three types of honeycomb structures under a strain rate of 700 s^{-1}

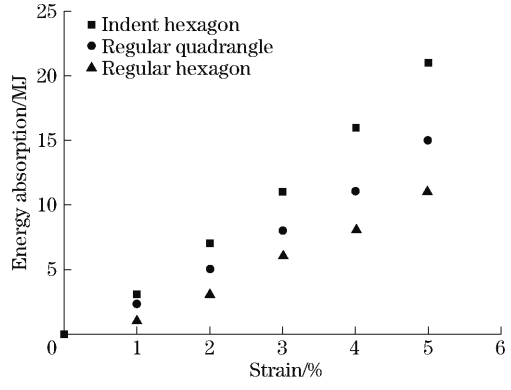


Fig. 11 Energy absorption of three types of honeycomb structures under a strain rate of 1 000 s^{-1}

Based on an analysis of Figs. 10 – 11 and a comparison of the energy-absorption results for the honeycomb structures, the strain rate was found to increase and the energy absorbed at the same strain increased in the case of the same honeycomb structure. The strain rate was increased from 700 s^{-1} to 1 000 s^{-1}. The results showed that when the strain was within the range of 0 – 5%, the energy-absorption value of the indented honeycomb increased by 17.2%, the energy-absorption value of the regular quadrangle increased by 18.23% and the energy-absorption value of the regular hexagon increased by 7.98%. These results were considered to be related to the strain rate strengthening of the materials. The energy absorbed by the indented honeycomb was 1.33 or 1.24 times greater than the energy absorbed by the regular quadrangle and 1.72 or 1.86 times greater than the energy absorbed by the regular hexagon, indicating that the indented honeycomb structure produced the optimum energy-absorption result when subjected to a dynamic shock load.

3 Summary and Conclusions

The paper is focused on the design of an indented honeycomb structure with a negative Poisson's ratio and its fabrication using the SLM technique. To compare the advantages and disadvantages of this structure with the regular hexagon, and the regular quadrangle honeycomb structures, a quasi-static compression test and a dynamic compression test were conducted to obtain the stress-strain curves of the three structures under the quasi-static and high strain rates. The results were used to analyze and compare the mechanical responses and energy-absorption behavior of the three structures under the stated test conditions. The experimental results indicated that the indented honeycomb structure had the best anti-deformation capacity and energy-absorption behavior. Explosion-proof clothing can resist the impact of overpressure shock waves through the efficient anti-explosive structure. The indented structure has high energy absorption characteristics and impact resistance with the advantages of strong corrosion resistance. The indented structure can strongly meet the performance requirements of explosion-proof clothing, but fur-

ther improvements are needed in practical applications to better meet the needs of personnel wear. The main conclusions of this study are presented as follows:

① During the process of quasi-static compression in the linear elasticity stage, the indented honeycomb structure exhibited a larger compression modulus and yield strength, that is to say that its anti-deformation capacity was better than the regular hexagon and regular quadrangle structures.

② During the process of quasi-static compression, the energy-absorption results for the indented honeycomb were better than those for the regular hexagon and regular quadrangle honeycombs.

③ When subjected to a dynamic shock load, the strain rate increased and the dynamic yield strength increased in all the honeycomb structures. The indented honeycomb exhibited the largest dynamic yield strength and the optimum anti-shock performance under the same strain rate.

④ When subjected to a dynamic shock load, the strain rate increased, and the energy absorbed at the same strain increased in the case of the all the honeycomb structures. However, the indented honeycomb exhibited the best energy-absorption result under the same strain rate.

⑤ The surface densities of the indented hexagonal, regular hexagonal, and regular quadrangle honeycomb structures are 1.80, 1.30, 1.75, respectively. The regular quadrangle honeycomb has the smallest surface density but much lower impact resistance than the other two structures. There seems to be no significant differences between the indented structure and regular hexagonal structure on the surface density, but the impact resistance of the indented structure is significantly higher than that of the regular hexagon.

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