Design and mechanical analysis of shear thickening fluid/polyurethane composite sandwich

Hua Cong, Mingmei Zhao*, Jinqiu Zhang and Yile Liu
Army Armored Forces Academy, Beijing, China

Abstract. In this paper, high density rigid polyurethane foam is used as sandwich skeleton and shear thickening fluid as material core. A shear thickening fluid/polyurethane sandwich structure with light impact resistance was designed and fabricated. High strain rate impact test was carried out. It was found that STF-2/PU reached the peak load of 4978 N in 13 ms after receiving 20 J impact energy, and the energy absorption ratio was as high as 43%. The shear thickening fluid/polyurethane honeycomb sandwich foam prepared by secondary foaming process has stable structure and can effectively absorb impact energy to achieve good protection effect.

key word: shear thickening fluid; polyurethane; sandwich structure.

1. Introduction

Shear thickening fluid (STF), as a kind of intelligent material, has a significant increase in apparent viscosity under the condition of applying shear stress or increasing shear rate, which can increase from several times to dozens of times. It is characterized by simple preparation, fast response and reversible repetition [1]. With the deepening of the research, people realize that the shear thickening phenomenon has great application potential in the industrial field. It not only gradually solves various problems caused by shear thickening phenomenon, but also finds that STF has a good application prospect in damping device development [2, 3], vibration reduction, energy absorption and individual protection [4-7] based on its characteristics. Moreover, fruitful achievements have been made in the microscopic mechanism of shear thickening [8-10], rheological properties and their influencing factors [11-14], STF-based development and application [15-17], and other research fields. Due to the fluidity of shear thickening fluid materials, most of its composite forms are impregnated or coated. In the shear thickening fluid/Kevlar material, the Kevlar fiber is used as the skeleton structure to provide support for the shear thickening fluid. In the face of more complex and violent impact environment, new shear thickening fluid composite forms and skeleton materials need to be proposed. To this, scholars have carried out a lot of research. Albuja et al. [18] filled STF/aramid fabric between two aluminum alloy plates and conducted ballistic firing tests based on NIJ 0108.01 standard. The results show that the target containing STF has better stability after multiple shots. Cwalina et al. [19] replaced the neoprene nylon absorbent layer in the space suit with shear thickening fluid arylon fabric, and conducted impact tests with spherical aluminum projectiles at 4-8 km/s. They found that EVA suits containing STF/fabric provide reasonable micrometeoroid and orbital debris (MMOD) puncture protection while being lighter than standard EVA suits. Pinto et al. [20] filled the shear thickening fluid into the carbon fiber reinforced polymer (CFRP) sandwich plate and found that the energy absorption capacity of STF-CFRP sandwich structure increased with the increase of impact velocity. Jeddi et al. [21] studied the energy absorption characteristics of three-dimensional fabric-core aluminum sandwich plates containing shear thickening fluid (STF) under different loading conditions. The dynamic compression test shows that STF is helpful to improve the impact absorption and compression performance of sandwich plate. Gu et al. [22] filled the shear thickening fluid into the lattice truss sandwich plate (SPLTC-STF) and carried out experiments and numerical simulations at high strain rates. The influence of the shear thickening effect of STF on the dynamic response of SPLTC-STF is predicted, which provides an idea for dynamic energy absorption optimization design of STF-filled sandwich plate under high impact load. The above research shows that the shear thickening fluid can be recombined not only by dipping. When the thickening fluid is shear as the inner core of the sandwich material, the energy absorption capacity of the material can also be improved. On the whole, there are few studies on shear thickening fluid composite sandwich structure at present, most of which are compounded with aluminum plate, steel plate and other materials, and there are some problems in the sealing in the process of composite. On the other hand, the shear thickening fluid composite sandwich structure has a different energy absorption
mode than the shear thickening fluid/Kevlar fiber. In the latter, not only the shear thickening behavior can absorb the impact energy, but the use of STF also increases the coupling force and friction between Kevlar yarns, which can also dissipate the impact energy. However, the interaction between non-Newtonian fluid and solid in the shear thickening fluid composite sandwich is mainly the interaction between non-Newtonian fluid and sandwich skeleton, and the interaction between non-Newtonian fluid and sandwich skeleton is worth further study.

Weight, hardness, impact resistance and cost need to be taken into account when choosing the skeleton structure of shear thickening fluid. Polyurethane foams (PU) have significant characteristics such as lightweight, environmental protection, low density, impact resistance, workability and excellent elasticity. Polyurethane foams (PU) are the most widely studied and developed materials in the polymer family [23-25]. By using different polyols and isocyanates as raw materials, polyurethane foams of various physical states such as viscous fluid, low-density soft foam, flexible and semi-flexible foam and hard foam are prepared according to the application requirements of different industries [26]. The density of polyurethane foam can range from 10 kg/m³ to 800 kg/m³ [27]. Its excellent characteristics and low cost make it widely used in automobile protection, furniture manufacturing, sports buffering, transportation, insulation and other fields [28].

Subhash et al. [29] conducted an experimental study on the behavior of polymer PU foam with different porosity under quasi-static and high strain rate loading. Linul [30] et al. studied the mechanical response of rigid polyurethane foams with different densities under impact. In many applications, polyurethane foam is often used as a sandwich structure in aerospace, ships, automobiles, insulated sandwich panels, shipbuilding and construction industries [31]. Liu et al. [32] proposed a composite sandwich structure consisting of fiber-reinforced polymer (FRP), polyurethane foam and ceramic particles, which can effectively protect piers from ship collisions. Chen et al. [33] studied the impact resistance of PU foam sandwich structure under vehicle collision through finite element analysis. Shan [34] proposed a composite protective structure composed of steel plate and polyurethane foam, and found through tests that the modified composite structure had good energy absorption performance. It is not difficult to find that polyurethane foam, a multifunctional material, is suitable for the sandwich skeleton support of shear thickening fluid.

Based on the above discussion, this paper uses high density rigid polyurethane foam as sandwich skeleton and shear thickening fluid as filling material. A shear thickening fluid/polyurethane sandwich structure with high impact resistance was designed and fabricated. The high strain rate impact test was carried out to lay a foundation for the optimization and development of shear thickening fluid sandwich in the future.

2. Shear thickening fluid/polyurethane sandwich structure design

2.1 Raw material

The materials used to prepare STF in this study included nano silica particles (12nm, 99.5%, Aladdin Biochemical Technology) and polyethylene glycol (200g/mol, Aladdin Biochemical Technology). Firstly, the mass of each part is calculated according to the concentration of the fluid. Secondly, nano silica particles were dispersed into polyethylene glycol solvent by agitator dispersing instrument (AD500S-H) and stirred for 1 h at 2000 r/min. Since the system is easy to agglomerate, ultrasonic dispersion instrument (GS-010A) was used to vibrate the stirred samples in order to ensure the uniform dispersion of silica particles. Then the samples were placed in a vacuum drying oven for 24 h to remove the bubbles, and finally a stable dispersion system was obtained. The schematic flowchart of preparation is shown in Figure 1. Two shear thickening fluids as shown in Table 1 were prepared by the above process. The rheological characteristics of the two shear thickening fluids are shown in Figure 2.

![Figure 1. Schematic diagram of preparation of shear thickening fluid](image)

**Table 1. Composition of sample of shear thickening fluid**

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Silica particle size (nm)</th>
<th>Silica mass fraction wt.%</th>
<th>Polyethylene glycol Average molecular weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>STF-1(12nm +15wt%SiO2/PEG200)</td>
<td>12</td>
<td>15</td>
<td>PEG 200</td>
</tr>
<tr>
<td>STF-2(12nm +30wt%SiO2/PEG200)</td>
<td>12</td>
<td>30</td>
<td>PEG 200</td>
</tr>
</tbody>
</table>
The materials used to prepare polyurethane foam include polyether polyols (Jining Huacai Resin Co., LTD., LDT-02A, density 1.05 g/cm³) and polyisocyanate (Wanhua Group Co., LTD., 450C, density 1.25 g/cm³). According to the mass ratio of polyether polyol and polyisocyanate at 3:1, the mixture fluid was stirred at 500 r/min by homogenizing stirring dispersion instrument (AD500S-H). The fluid is then mixed and foamed to form polyurethane foam. By controlling the quality of mixed fluid of polyether polyols and polyisocyanate, the density of polyurethane foam is 200 kg/m³. Scanning electron microscopy was used to observe the prepared polyurethane foam, as shown in Figure 3. As a kind of porous material, polyurethane foam contains closed pores. The compressibility of polyurethane foam was prepared for further testing. The stress and strain of PU material under quasi-static condition was tested by universal testing machine. A number of cubic polyurethane samples (2cm×2cm×2cm) were cut out, and a compression test of 20 mm/min was conducted at room temperature 25°C. The data results of multiple cubic polyurethane samples were averaged, and the results as shown in Figure 4 were obtained.

2.2 Honeycomb sandwich structure design

The main considerations in the design of sandwich structure are as follows: (1) structural stability. As a fluid, shear thickening fluid needs to be stored stably in a confined space. (2) Light quality. Whether in the field of personal protection, automotive, aviation and industrial manufacturing, it is necessary to reduce the weight of materials as much as possible to achieve the purpose of reducing the load. (3) strong complex integrity. The sandwich structure needs to withstand large deformation in the impact, which requires higher reliability of materials.

Among many sandwich structures, honeycomb sandwich structure is the most widely used and mature [35]. Honeycomb interlayer is produced by imitating the hexagonal honeycomb of bees from the perspective of bionics. This structure has large internal space and strong compressive and bearing capacity [36]. Scholars have carried out a lot of research based on honeycomb sandwich structure. Duan et al. [37] conducted experimental tests and numerical simulation on honeycomb sandwich structure of carbon fiber reinforced polymer, established an oblique impact model, and verified the reliability of the model through the oblique impact test. Rathod et al. [38] studied the mechanical properties and perforation of aramid and aluminum honeycomb sandwich structures under high-speed impact. Through ABAQUS/Explicit modeling, the influence of different geometric parameters on the impact response of sandwich structure was studied. Huang et al. [39] filled honeycomb sandwich with magnetic shear thickening gel, designed and optimized the wave-absorbing honeycomb sandwich structure (MAHSS) by simulating the content of carbonyl iron particles (FCIP) and the properties of magnetic shear thickening gel. Inspired by leaf texture, Lv et al. [40] innovatively added rectangular mesh to honeycomb to form a mesh-honeycomb hybrid sandwich. The low speed impact response of grid-honeycomb composite sandwich structures is studied by means of experiments and numerical simulation. All the above studies indicate that honeycomb sandwich structure can provide stable structure during dynamic impact process. Therefore, in this study, the polyurethane foam was designed as a honeycomb sandwich structure. Considering the operability of the actual foaming process and preparation process, the honeycomb sandwich structure is designed as shown in Figure 5. The honeycomb structure consists of regular hexagons. The yellow part is polyurethane PU foam, and the hexagonal side length is 2 cm. The blue part is the shear thickening fluid filling part. The side length is 1.5 cm. The overall thickness of the sandwich is 2 cm, and the thickness of the shear thickening fluid is 1 cm.
3. Shear thickening fluid/polyurethane interlayer synthesis

Shear thickening fluid/polyurethane sandwich structure was prepared by secondary foaming process. As shown in Figure 6(a), polyether polyols and polyisocyanate were mixed, quickly stirred, and quickly poured into the honeycomb mold. After the formation of polyurethane foam, foaming was completed in about 25 minutes. According to the thickness setting of the sandwich structure, the thickness of the excess polyurethane is removed to complete the lower half of the STF/PU sandwich, as shown in Figure 6(b). Secondly, pour the prepared shear thickening fluid into the honeycomb space under the same process, as shown in FIG. 6(c) and (d). Then the polyurethane foam loaded with STF fluid was placed into the mold again for secondary foaming and excess thickness was removed, as shown in Figure 6(e). Finally, a cellular polyurethane sandwich foam containing shear thickening fluid is formed, as shown in Figure 6(f). The overall production process and technology is shown in Figure 6.

![Figure 6. Production process of shear thickening fluid/polyurethane composite sandwich](image)

4. Mechanical characteristics analysis of shear thickening fluid/polyurethane sandwich structure

Considering the small volume and elastic modulus of the shear thickening fluid/polyurethane foam, in order to make the composite sandwich under uniform stress, DYNAUTUP 8200 drop weight impact testing machine was used in the mechanical test, and a disc-shaped plate with a diameter of 70 mm and a mass of 5 kg was used as the impact object, as shown in Figure 7. By changing the height of the impact plate, the impact kinetic energy of the disc drop hammer is adjusted. The load curves and energy absorption of STF-1/PU and STF-2/PU sandwich structures were tested under the impact of 10J, 15J and 20J respectively (corresponding impact velocities of 2 m/s, 2.45 m/s and 2.83 m/s). In order to reduce sample error, three samples of each type of STF/PU interlayer were tested with an average value.

![Figure 7. Schematic diagram of shear thickening fluid/polyurethane impact testing equipment](image)

![Figure 8. STF-1/PU impact test result](image)
According to the law of conservation of energy, the expression of energy absorption in the impact process is shown as follows. Where \( m_a \) is the weight of the drop weight, \( h \) is the height of the free fall, \( F \) is the load force recorded by the sensor below the sandwich, and \( z \) is the penetration depth.

\[
E_{\text{Absorption}} = m_ah - \int Fdz \quad (1)
\]

According to Figure 8 and 9, as the impact energy increases, the peak load of the same STF/PU sandwich increases, the reaction time shortens, and the corresponding absorbed energy increases. Among them, STF-1/PU reached the peak load of 5469N in 11.9ms after receiving 20J impact energy, and the energy absorption ratio was as high as 36.1%. After receiving 20J of impact energy, STF-2/PU reaches the peak load of 4978N in 13 ms, and absorbs 8.6J of energy, with energy absorption ratio up to 43%. It can be seen that the shear thickening fluid/polyurethane sandwich structure can effectively absorb impact energy and achieve good protection effect.

5. Conclusion

As a typical non-Newtonian fluid, STF has been widely used in the field of shock resistance. But the action mechanism of the composite sandwich structure still needs to be further explored. In this paper, high density rigid polyurethane foam as sandwich skeleton, shear thickening fluid as the material core, design and manufacture a lightweight impact resistant shear thickening fluid/polyurethane sandwich structure. High strain rate impact test was carried out.

It was found that the shear thickening fluid/polyurethane honeycomb sandwich foam prepared by secondary foaming process has stable structure. With the increase of impact energy, the peak load at the bottom of STF/PU honeycomb sandwich increases, the reaction time shortens, and the corresponding absorbed energy increases. Among them, STF-1/PU reached the peak load of 5469N in 11.9ms after receiving 20J impact energy, and the energy absorption ratio was as high as 36.1%. After receiving 20J of impact energy, STF-2/PU reaches the peak load of 4978N in 13 ms, and absorbs 8.6J of energy, with energy absorption ratio up to 43%. It can be seen that the shear thickening fluid/polyurethane sandwich structure can effectively absorb impact energy and achieve good protection effect.

Acknowledgments

This work was funded by the National Natural Science Foundation of China [No. 51605490].

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