Ultra-light 3D fabric Reinforced Composite with Distinct Thermal Insulation and Superior Sound-absorbing Properties

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Abstract. Research on lightweight advanced materials that combine heat insulation and sound isolation becomes more attractive day by day. In this study, a 3D spacer structural Kevlar/polyimide composite (3DSSK/PIC) with light weight, heat insulation and sound absorbing properties was prepared by a combination of structural design, hand paste resin method and hot-pressing process. The fabricated 3DSSK/PIC possesses more than 80% of void as well as the ultra-light density (0.2 g/cm\(^3\)). Consequently, the thermal insulation performance of 3DSSK/PIC (34%) is superior to that of polystyrene foam (adiabatic ratio $\Delta T \sim 20\%$) and similar to that of wood block ($\Delta T \sim 35\%$). Furthermore, the sound absorption coefficient of the 3DSSK/PIC is higher than 0.2 in the range of 600 – 2500 Hz, demonstrating its super sound absorption performance. In addition, compressive tests and SEM images were conducted to characterize the mechanical and structural performance. Therefore, the ultra-light 3D fabric reinforced composite with ultra-high thermal insulation and sound-absorbing properties justify a great potential in a wide variety of applications in the industry engineering, automobile, or aerospace.

1. Introduction

In these decades, with the rapid development of transportation, construction and electronic information industry, a variety of large-scale and high-speed machinery comes with the production of noise and heat. As one of the major pollution problems, noise pollution will affect the normal work and life of human beings, even harm human health [1]. In addition, it is necessary to insulate the large amounts of undesirable heat generated by high-speed friction that will affect the function of material and electronic equipment. On the contrary, preventing the loss of beneficial heat and improving energy efficiency, such as heat in cabins and buildings in winter, are crucial for the conservation of energy and greenhouse gas emission [2]. Therefore, obtaining multifunctional material with a variety of comprehensive properties such as lightweight, effectively eliminating noise and isolating heat has become a research hotspot in recent years.

In recent decades, one of the most effective methods to prevent noise is using sound absorbing materials [3]. Those materials usually have high porosity to convert sound energy into kinetic energy and internal energy to be consumed [4]. For thermal insulation materials, the higher internal porosity also contributes to the improvement of thermal insulation performance, mainly due to the low thermal conductivity of air, and the small pores confine air in a small space to prevent thermal convection [5]. In fact, there are not many types of materials that can be simultaneously light weight, heat insulation and sound absorption properties.
Polyurethane foam and polystyrene foam are often used for sound-absorbing and thermal insulation materials due to their light weight and ease of cutting and installation [6]. However, such polymers have poor thermal stability, and hidden safety risks. Metal foam with the characteristics of high temperature resistance and good corrosion resistance has also been used in the field of sound absorption collars in recent years [7]. However, metal foams are generally heavy and cannot have thermal insulation properties at the same time. Traditional organic fiber, such as jute, bamboo, and wood fibreboard, can be used as sound absorption materials and have good sound absorption performance, but these materials with the characterization of sensitivity to ambient humidity, poor thermal stability, and low flame resistance apart from the relatively poor thermal insulation properties [1]. Inorganic fiber, mainly include glass wool, mineral wool, etc. could be used as sound-absorbing and thermal insulating materials and has better sound absorption coefficient and thermal insulating performance compared with organic material. However, these fibers are fragile and brittle, forming powders that can interfere with breathing and cause itching.

Three-dimensional woven fabrics are woven by three-dimensional looms, with integrated structure and overall performance, which have a great potential to be applied in aerospace, marine, military, and other fields [8]. Reasonable structural design can make the 3D fabric reinforced composite light-weight and have a large void which can expand its application in the field of sound absorption and heat insulation [9]. However, there are few researches on the sound absorption and heat insulation of 3D fabric reinforced composites.

A high-performance fiber, Kevlar, with high temperature and corrosion resistance, can be used to prepare three-dimensional fabrics and combined with resins to make multifunctional composites. In this paper, a 3D spacer structural Kevlar/polyimide composite (3DSSK/PIC) with light weight and integrate structure was prepared by structural design combined with hand paste method and hot-pressing process. The compression performance of the composite was studied by means of an INSTRON test machine. The compression failure mode of the composite was investigated by means of XK-ST900 Continuous Variable Ploidy Microscope and Scanning electron microscope (SEM). The thermal insulation properties of the composites were analysed by infrared thermal imager. SW230 impedance tube was used to test the sound absorption performance.

2. Materials and Methods

2.1 Kevlar fibers and the three-dimensional woven spacer fabrics

In this study, Kevlar-129 fiber (Type964c) was provided by DuPont Co, Ltd. and was used to fabricate the three-dimensional woven spacer fabrics in a 3D weaving loom. As shown in Figure 1(a), the 3D woven spacer composite consists of three layers namely top, core and bottom. The top and bottom face

Figure 1. Structure diagram of the 3D Integrated Woven Spacer Composites. (a) 3DSSK/PICs; (b) Cross-section of the warp direction; (c) Cross-section of the weft direction.
Sheets, which were woven by the warp and weft yarns into a plain pattern, were integrated by the interpenetrated pile yarns. In the core layer, the single pile can be viewed as the form of a “goblet” shape in the warp direction, and the adjacent piles constitute an “8” shape, as shown in Figure 1(b), while the piles are regarded as a “1” shape in the weft direction as shown in Figure 1(c). The precursor of polyimide (PAA), used as the matrix, was purchased from XinFeng Plastic Co. LTD.

2.2 Preparation of Kevlar/PI composites

First, the three-dimensional spacer fabric is manufactured by a three-dimensional loom, then the PAA was transferred to the 3D fabric by hand lay-up method. Once the liquid fully infiltrated the fabric, the gradient temperature control method was used to gradually convert the PAA into polyimide to obtain Kevlar/polyimide composites.

2.3 Compressive test

Compression experiments were carried out according to the ASTM C365/C365M-11a test standard through an INSTRON test machine (model 5967). 3DSSK/PICs were tested in the flat direction, and the speed of the cross-head was set at 0.5 mm/min. During the measurements, the loads and cross-head displacement were recorded automatically by the computer. Five specimens were verified for each type of 3DSSK/PICs with identical dimensions, and the mean values of experimental results were calculated.

2.4 Thermal insulation and Sound-absorbing tests

Thermal insulation properties of 3DSSK/PICs were examined by infrared thermal imager (Fotric, model 225). The bottom surface is heated by a constant temperature heat source, and the temperature of the upper surface of the sample was captured by an infrared camera, from which the thermal insulation efficiency of the sample can be calculated. The sound absorption coefficient is automatically calculated by the sound absorption test system using the SW230 impedance tube of Beijing Shengwang Co., Ltd. according to GB/T 18696. 2-2002. The sound absorption test system finds the normal incident sound pressure reflection coefficient $r$ according to the recursive function, and calculates the sound absorption coefficient by the following formula:

$$a = 1 - r^2$$

where $a$ is sound absorption coefficient, $r$ is the normal incident sound pressure reflection factor [10].

2.5 Characterizations

Fourier transform infrared spectroscopy (FT-IR): FT-IR was carried out using a Perkin-Elmer FT-IR (Spectrum100, Waltham, MA, USA) in the range of 400 $\sim$ 4000 cm$^{-1}$ range to observe whether PI is bonded on the surface of aramid fiber.

The surface morphology of the pile yarns was investigated after compression using XK-ST900 Continuous Variable Ploidy Microscope, and a scanning electron microscope (SEM) (Model JSM-5600LV, JEOL, Japan) at a voltage of 10 KV was used for observation at a greater magnification. The samples were coated with gold before the measurement to induce conductivity.

3. Results and discussion

3.1 Mechanical properties of K/PICs

The FTIR spectrographs of 3DSSK/PICs indicate the existence of carbonyl and imide at the peak of 1710 cm$^{-1}$ and 1370 cm$^{-1}$ as shown in Figure 2(a). In addition, FTIR spectrograph of Kevlar fiber demonstrated the formation of PI in the fabric. The density of 3DSSK/PICs is about 0.20g/cm$^3$, which is approximately two times lower than the wood (Willow) density (0.5 g/cm$^3$). The compressive results
in Figure 2 (b) show that the compressive strength is 520 KPa with the strain of 6%. The elastic buckling of the material occurs before the elastic deformation of the structure reaches the peak load. After the buckling failure, the load will suddenly drop, followed by a longer deformation platform and the curve remains flat and parallel to the deformation axis.

![Figure 2.](image)

**Figure 2.** (a) FT-IR spectra of Kevlar and 3DSSK/PICs; (b) Stress-strain curve of compression properties of 3DSSK/PICs.

![Figure 3.](image)

**Figure 3.** Failure pattern of 3DSSK/PICs being compressed. (a) and (d): Cross-section of the composite in the warp direction and weft direction after the sample was compressed and destroyed, respectively; (b) and (e) are the enlarged view of broken pile yarns in warp and weft cross-section under XK-ST900 Continuous Variable Ploidy Microscope, respectively; (c) and (f) is the SEM of the broken pile yarns in the cross-section in the warp direction and weft direction, respectively.

As showed in Figure 3, (a) and (d) was the cross-section of the composite in the warp direction and weft direction after the sample was compressed and destroyed, respectively. It can be found that after compress the pile yarns were not broken, but becomes relatively fluffy, as shown in Figure 3(b) and (e). When observed under higher magnification, it can be found from the SEM images Figure 3(c) and (f) that the resin and the yarn were separated, the binding of the resin on the yarns were weakened, and the single fiber in the core yarn was separated from each other. It can be speculated that, taking measures to increase the interface bonding strength of aramid fiber and resin will become the possibility of improving the compression performance of the composite material. This will be next part of our work to explore.

### 3.2 Thermal insulation properties

The heat insulation performance of the material was tested in the environment where the temperature of the heat source is maintained at 90 °C, and the results are shown in Figure 4. It can be seen from Figure 4(a) that the surface temperature of 3DSSK/PIC was basically maintained at 59 (±1) °C when the stable state was reached, and the heat insulation degree was close to 35%, which was lower than 69 (±1) °C of
the polystyrene foam material with the heat insulation degree of 23% (Figure 4(b)) and basically achieved the same thermal insulation performance as the wood block (Figure 4(c)). It can be concluded that the heat insulation performance of the composite material is superior than that of the foam material under the same conditions. Like wood structure, the excellent thermal insulation behavior of 3DSSK/PICs contributed to its high percentage of hollow structure. Due to the hollow core layer composed of pile yarns in the 3DSSK/PICs as shown in Figure 4(d), the heat transfer from the bottom to the top face sheet was blocked by many voids so that the heat was mainly transferred from the pile yarns and few infrared radiations by air.

![Figure 4](image)

**Figure 4.** Thermal insulation of materials: (a) Surface temperature and time curve of polystyrene foam, 3DSSK/PICs and wood during heating; (b) Schematic diagram of heat conduction form of 3DSSK/PICs.

### 3.3 Sound-absorbing performance

The installation diagram of the instrument is shown in Figure 5(a). The sound absorption coefficient and frequency curves of the composite material are shown in Figure 5(b). It can be seen from the figure that the sound absorption coefficient of the composite lower than 0.2 within the range of 100–650 Hz. However, in the range of 650 ~2500Hz, the sound absorption coefficient of the composite material is higher than 0.2, and with the increase of frequency, the sound absorption coefficient of the material as a whole tends to increase gradually, with the maximum value of about 0.96, indicating excellent sound absorption performance.

![Figure 5](image)

**Figure 5.** (a) Assembled diagram of measurement sound absorption system with SW230 impedance tube; (b) Acoustic absorption coefficient and frequency curves of 3DSSK/PICs; (c) Schematic diagram of sound absorption principle of 3DSSK/PICs.
As shown in Figure 5(c), based on the structural characteristics of the three-dimensional spacer fabric composite material, when sound waves enter the interior of the material, due to the presence of pile yarns and the air channels formed by the large voids in the material, the vibration speed of sound waves near the column yarns and between the gaps is different. Consequently, the internal friction was generated, so that the sound wave vibration energy is converted into heat energy and absorbed.

4. Conclusions
In this paper, an ultra-light 3D spacer structural Kevlar/polyimide composite (3DSSK/PIC) with heat insulation and sound absorbing properties was prepared by structural design combined with hand paste method and hot-pressing process. The as-produced integrated 3DSSK/PIC possesses more than 80% of the void as well as the super small density of 0.20g/cm³. Consequently, the 3DSSK/PIC showed better thermal insulation performance (34%) than the polystyrene foam (20%) and similar with wood block (35%). Furthermore, the value of the sound absorption coefficient of the 3DSSK/PIC is higher than 0.2 in the range of 600 ~ 2500 Hz, demonstrating the super sound absorption performance. This kind of composite material will have a great application potential in the fields that require materials with comprehensive properties such as light weight, heat insulation and sound absorption.

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