

Study of the flexural properties of polyurethane-foam-core composites reinforced with warp-knitted spacer fabric

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ABSTRACT – REZUMAT

Study of the flexural properties of polyurethane-foam-core composites reinforced with warp-knitted spacer fabric

In this paper, novel ternary composites consisting of polyurethane-foam-core, warp-knitted spacer fabrics and polyurethane resin were involved. The composites obtain unique three-dimensional structures, high strength and a variety of surface structures. The aim of this study was to investigate the flexural properties of the composites. First, the warp-knitted spacer fabrics with different structural parameters were laminated with polyurethane foam to produce the foam-core materials. Meanwhile, two types of microspheres were incorporated into the polyurethane foam. Then the prepared foam-core materials were combined with polyurethane resin to fabricate the polyurethane composites. A flexural test was conducted to investigate the effects of the surface structure of spacer fabrics, microspheres types and contents on the flexural properties of the polyurethane composites. The findings show that the composites had excellent flexural properties and the flexural performance can be significantly improved by varying the surface structure of the fabric and the type of microspheres to meet specific end-user requirements.

Keywords: Polyurethane-foam-core, warp-knitted spacer fabric, polyurethane resin, microspheres, flexural properties

Studiul proprietăților de încovoiere ale compozitelor cu miez din spumă poliuretanică armate cu tricot din urzeală ca distanțier

În această lucrare, a fost analizat un nou compozit ternar constând din miez de spumă poliuretanică, tricot din urzeală ca distanțier și rășină poliuretanică. Compozitele dețin o structură tridimensională unică, o rezistență ridicată și o varietate de structuri de suprafață. Scopul acestui studiu a fost de a investiga proprietățile de încovoiere ale compozitelor. În primul rând, tricaturile din urzeală distanțiere cu diferiți parametri structurali au fost laminate cu spumă poliuretanică pentru a produce materialele cu miez de spumă. Între timp, două tipuri de microsferă au fost încorporate în spuma poliuretanică. Apoi, materialele preparate din miez de spumă au fost combinate cu rășină poliuretanică pentru a fabrica compozitele poliuretanică. A fost efectuat un test de încovoiere pentru a investiga influența structurii suprafeței tricoturilor distanțiere, tipurile și conținutul microsferelor asupra proprietăților de încovoiere ale compozitelor poliuretanică. Rezultatele arată că materialele compozite au proprietăți de încovoiere excelente și performanța la încovoiere poate fi îmbunătățită semnificativ, prin modificarea structurii suprafeței tricotului și a tipului de microsferă pentru a îndeplini cerințele specifice utilizării finale.

Cuvinte-cheie: miez din spumă poliuretanică, tricot din urzeală distanțier, rășină poliuretanică, microsferă, proprietăți de încovoiere

INTRODUCTION

Textile composites have the advantages of high strength and specific modulus and low density, so they are gradually replacing traditional metallic materials in many fields. Warp-knitted spacer fabric, as one of the reinforcements used in textile composites, is compared with the traditional sandwich composites. It has obvious advantages in terms of delamination resistance, fracture toughness, and impact damage tolerance [1]. Textile composites as lightweight and high-strength composites, their main applications are in the form of various artificial stone panels for construction and plate materials such as ship hulls and automobile shells [2, 3]. For example, textile composites in the aerospace field are generally used in wing beams, tail structures, engine nacelles

(especially jet engine nacelles), external culverts, seats and access panels [4]. In the construction field, it can be used in woven sound insulation panels, roof panels, etc. [5]. In the automotive field, it can be used for drive shafts, bodies, cantilever beams, etc. [6, 7]. It also can be used for hull bulkheads, interior walls, ship interior decoration materials, etc. [8, 9]. The form of application determines that the length of composite fabricated parts is generally much greater than their thickness [10]. Ma and Qin [11] prepared glass/unsaturated polyester resin composites and explored the tensile and flexural properties of the composites and found that Warp-knitted spacer fabric composites revealed good flexural mechanical properties. Chen et al. [12] prepared glass/unsaturated polyester resin composites and explored the tensile and flexural properties of the composites and found that Warp-knitted

spacer fabric composites revealed good flexural mechanical properties. Therefore, the specific form of the parts determines that the flexural property is a very important mechanical property for composite materials, and the poor flexural property can seriously restrict the application field of composite materials and even produce safety hazards. Therefore, it is necessary and valuable to investigate the flexural properties of warp-knitted spacer fabric-reinforced composites [13, 14]. For these reasons, the flexural properties of warp-knitted spacer fabric-reinforced composites are systematically investigated in this chapter. First, three-point flexural tests were performed on composite samples, then the displacement-load images obtained were recorded and analysed, and finally, the effects of different spacer fabrics and microspheres parameters on the flexural properties of warp-knitted spacer fabric-reinforced composites were discussed in detail.

In this research, novel ternary composites consisting of polyurethane-foam-core, warp-knitted spacer fabrics and polyurethane resin were involved. And the flexural properties of the polyurethane composites were investigated. Furthermore, the effects of the surface structure of spacer fabrics, microspheres types and contents on the flexural properties of the polyurethane composites. In addition, the characteristics of polyurethane composites under flexural load were investigated by macroscopic observation and scanning electron microscopy (SEM).

MATERIALS AND METHODS

Materials

Three warp-knitted spacer fabrics (purchased from Wuyang Co. Ltd., Jiangsu, China) with different outer structures were selected in this paper, as shown in figure 1. The surface structures of the spacer fabrics are Chain, Rhombic mesh and Hexagonal mesh, respectively. It can be seen that the size is continuously increasing. The types of yarns and the structural parameters of the spacer fabrics are shown in table 1. The PET multifilament yarn of 300D/96f was used for the surface layers, while the PET monofilament with 0.2 mm diameter was used for the spacer yarn. Despite the same warp and weft setting machine, the actual thickness of all three samples is near 7.4 mm, so it can be considered that the thickness of these fabrics is close to each other.

Fabrication of polyurethane composites

In this study, the spacer fabric is combined with polyurethane foam to produce the foam core materials firstly. The polyurethane foam is made of isocyanate and polyether polyol (BASF, Shanghai, China), and the foaming process was carried out at room temperature with a mass ratio of 43.9:100. Meanwhile, the weighted hollow glass microspheres were added to the polyurethane foam. The parameters of microspheres are shown in table 2. A mixer machine named FlackTek Speed Mixer (DAC 150.1

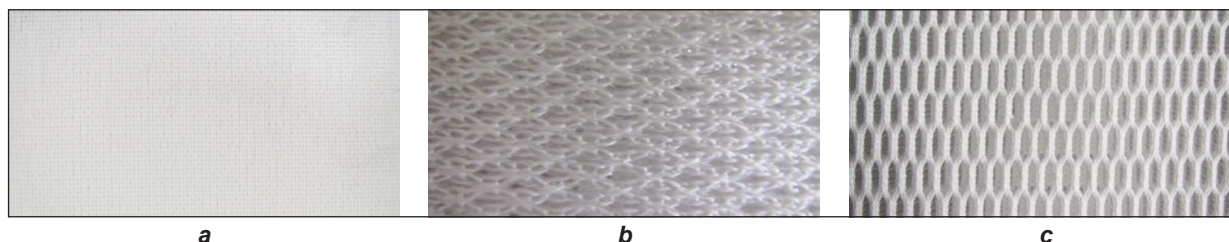


Fig. 1. The surface layer structures: a – chain; b – rhombic; c – hexagonal mesh

Table 1

STRUCTURE AND PARAMETERS OF WARP-KNITTED SPACER FABRIC								
Surface layer structures	Materials		Thickness (mm)	Course-wise density (w/5 cm)	Wale-wise density (c/5 cm)	Density of surface (g/m ²)	Yarn count (Tex)	Lapping movement
	surface layer	spacer yarns						
Chain	A	B	7.72	7.07	5.57	8817	33.3	GB3: 1-0, 3-2/3-2, 1-0// GB4: 3-2, 1-0/1-0, 3-2//
Rhombic Mesh	A	B	7.66	7.24	5.57	772.0	33.3	GB3: 1-0, 3-2/3-2, 1-0// GB4: 3-2, 1-0/1-0, 3-2//
Hexagonal Mesh	A	B	7.64	7.07	5.79	756.8	33.3	GB3: 1-0, 3-2/3-2, 1-0// GB4: 3-2, 1-0/1-0, 3-2//

Note: A represents 300D/96f PET multifilament yarn, B represents 0.2 mm diameter PET monofilament.

FVZ, American) was carried out for the mixing process to ensure a slow and uniform speed so that the microspheres can be distributed evenly in the solution. The preparation of the foam core materials was carried out in a mould. All specimens are placed for 24 hours to reach full maturation and moulding. The prepared foam core materials are placed in a polyurethane resin with a 1:1 mass ratio of isocyanate to polyether polyol in a mould (BASF, Shanghai, China). The polyurethane composites were placed at a temperature of 25°C for 8 h to complete curing. The produced polyurethane composites are shown in figure 2, while the details of polyurethane composites are shown in table 3. In this study, two representative microbeads with different inner and outer diameter ratios and thus different mechanical properties, namely S15 and im16K, were selected as microbead fillers for the warp-knitted spacer fabric reinforced composites.

Flexural properties test

The three-point flexural test was conducted by using Hua long WDW-20 universal material testing machine with test standard ISO 14125:1998 (fibre reinforced plastic composites-determination of flexural properties). The size of the specimen was set to 160 mm × 15 mm × 8 mm, and the clamping distance was set to 120 mm. The loading speed was set to 2 mm/min and the test was stopped when the deflection of the centre point of the fabric-reinforced composite specimen reached 17 mm, and the load-displacement curves were plotted using the load and displacement values obtained from the test, and the flexural strength (MPa) and flexural modulus (MPa) of the samples were calculated using equations 1 and 2, respectively:

$$\sigma = \frac{3PL}{2wt^2} \quad (1)$$

$$E_f = \frac{L^3k}{4wt^3} \quad (2)$$

where P is the maximum value of the load, k – the slope value of the initial phase of the load-displacement curve.

The three-point flexural test was conducted at a temperature of 25°C and relative humidity of 60%, and each three-point flexural test sample was tested at least five times, and the average value was taken and the standard deviation was calculated. The

Table 2

PARAMETERS OF GLASS MICROSPHERES		
Types of micro microspheres	Intensity (Mpa)	Average particle size (µm)
S15	2.07	55
im16K	113.7	20

Table 3

THE DETAILS OF POLYURETHANE COMPOSITES			
Sample	The surface layer structures	Types of micro microspheres	Content of microspheres (%)
S1	None	None	None
S2	Chain	None	None
S3	Rhombic	None	None
S4	Hexagonal Mesh	None	None
S3-1-S15	Rhombic	S15	1
S3-1-im16K	Rhombic	im16K	1
S3-3-S15	Rhombic	S15	3
S3-3-im16K	Rhombic	im16K	3

Note: S1 represents pure resin without spacer fabrics and microspheres in the thickness of 7.4 mm.

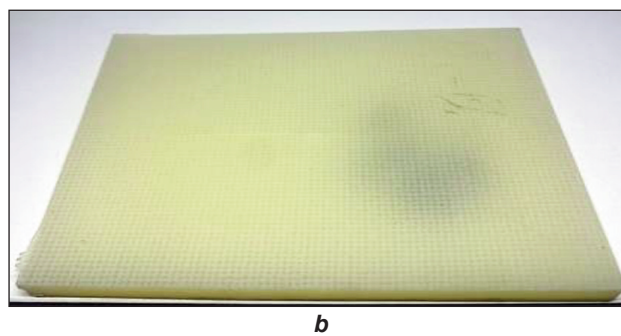
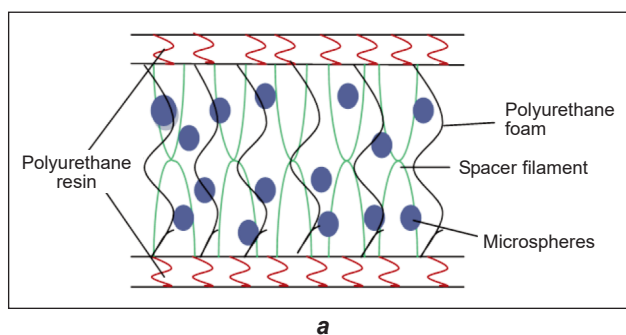


Fig. 2. Schematic and real diagram of polyurethane matrix composite: a – schematic of composites; b – real diagram of composites

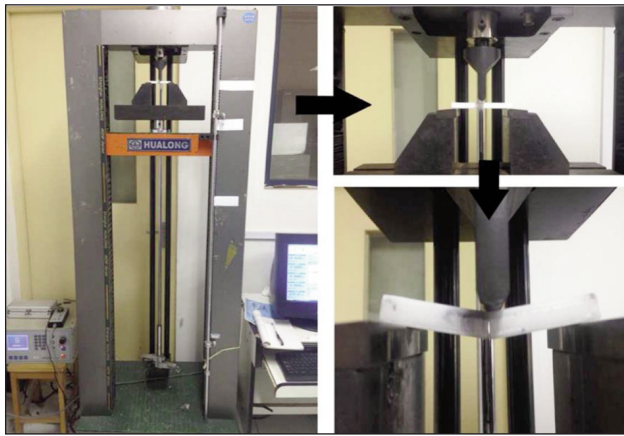


Fig. 3. Three-point flexural test machine and experimental process

experimental machine and test procedure are shown in figure 3.

RESULTS AND DISCUSSIONS

Effect of surface structure on flexural performance

Figure 4 shows the load-displacement curves of the flexural test for three composites (S2~S4) and the pure resin panel (S1). It can be seen from figure 4 that the load-displacement curves of all samples show a similar linear region in the initial stage. At the end of the linear region, i.e., the load reaches the peak, all curves show a slowly decreasing trend, among which the load value of S1 which is not reinforced by the warp spacer fabric is lower, which indicates that S1 has a poor flexural performance in the three-point flexural test. The flexural load of the other three composite samples with different fabric parameters did not drop to 0, which indicates that the composite still has a certain flexural resistance. At the same time, it can be found that the peak flexural load of the three samples with different fabric parameters is higher than that of the S1. The above mentions

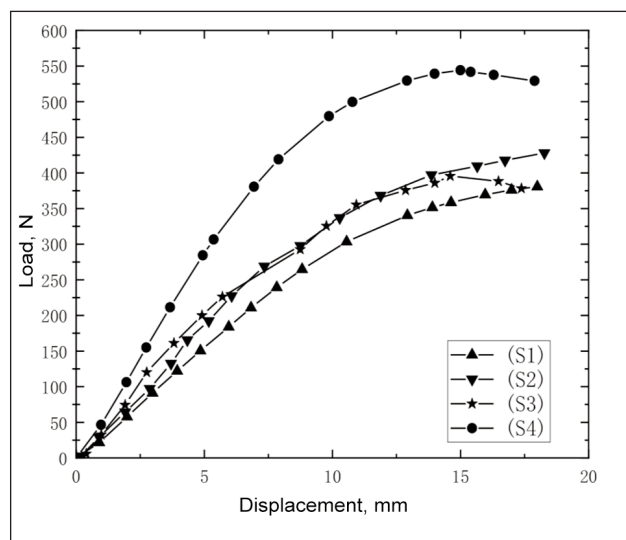


Fig. 4. Flexural load-displacement curves of spaced fabric composites

show that the flexural performance of the polyurethane composites with spacer fabric reinforcement is higher than that of the S1. Furthermore, the flexural performance of the polyurethane composites with hexagonal mesh surface structure was the best.

The flexural strength and flexural modulus for the specimens are shown in figures 5 and 6. From figures 5 and 6, it can be found that the flexural strength and flexural modulus increase as compared to S1. The flexural strength and flexural modulus of S4 increase the most, indicating that the flexural performance of the polyurethane composite with hexagonal mesh surface structure is the best. It can be also found that the shorter spacer yarn in S4 can withstand a larger critical force value and is less likely to be bent than the spacer yarn in S2 and S3, thus improving the flexural performance of the whole material. As the spacer fabric selected in this paper has the same spacer diameter, and the spacer and resin matrix in the warp-knitted spacer fabric reinforced

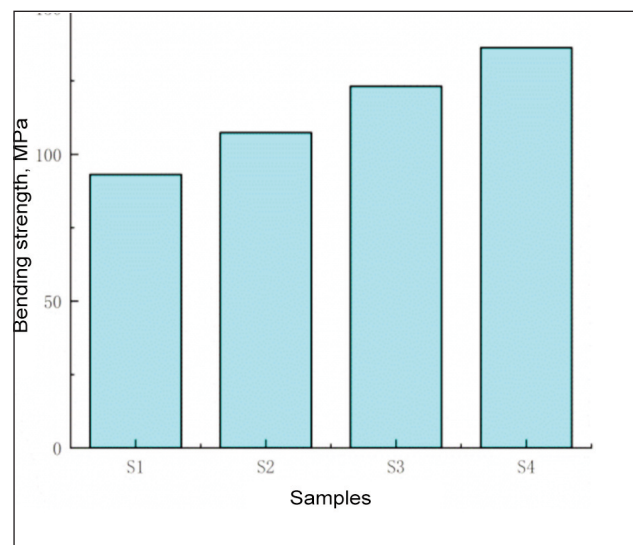


Fig. 5. Flexural strength of polyurethane composites

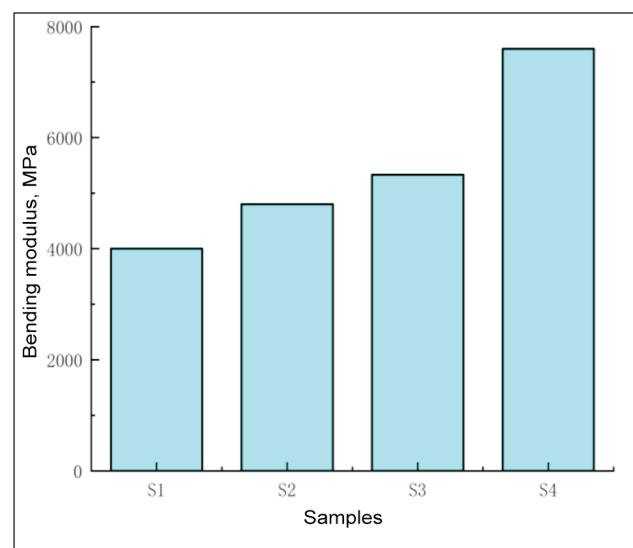


Fig. 6. Flexural modulus of polyurethane composites

composites are the main load bearers, and the spacer is subjected to bending load when its main form of damage is dislodged and deformed, and there is no case of pulling off damage. Therefore, the influence of the spacer filaments on the bending properties of the composite is excluded.

Effect of microspheres parameters on flexural performance

As an important reinforcement in the composites, the effect of volume fraction and type (inner and outer diameter ratio) of glass microspheres on the flexural properties of the composites is significant. It should be noted that the change in volume fraction and type of microspheres significantly affect the density of the composites.

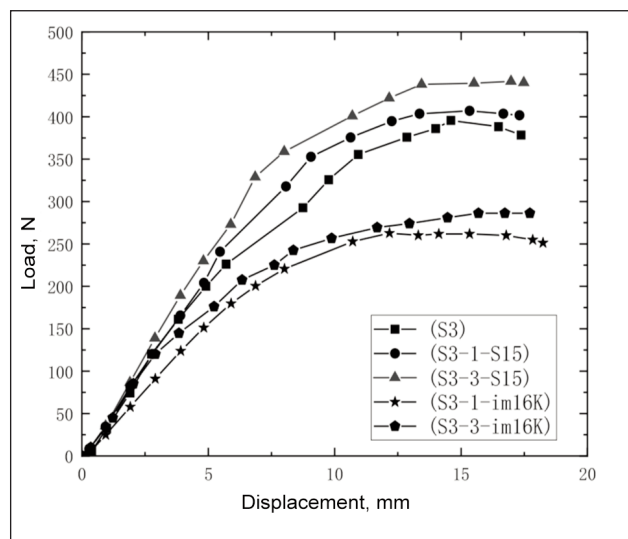


Fig. 7. Flexural load-displacement curves of composites

Figure 7 shows the load-displacement curves of flexural tests for S3-1-S15, S3-1-im16K, S3-3-S15, S3-3-im16K and S3. It can be seen from figure 7, the load-displacement curves of all samples show similar linear regions in the initial stage, and all curves show a slow decline when the load reaches its peak which is similar to S1 ~ S4. The load values of S3-3-S15 are higher than those of S3-3-im16K, which indicates the flexural performance of polyurethane composites reinforced by warp-knitted spacer fabric with S15 microspheres is higher than that of S3-3-im16K.

This means that the flexural properties of the polyurethane composites reinforced with warp-knitted spacer fabric and S15 microspheres are higher than those with im16K microspheres. Therefore, it can be basically concluded that the flexural performance of the warp-knitted spacer fabric reinforced composites increases with the increase of the inner and outer diameter ratio of the embedded microspheres.

S3-1-S15 and S3-3-S15 were embedded with the same type of diamond warp-knitted spacer fabric and S15 microspheres, but the volume fraction of the embedded microspheres was 1% and 3%, respectively.

It reveals from the figure that the load value of the sample with a 1% microspheres volume fraction (S3-1-S15) is lower, which means that the S3-1-S15 sample exhibits poor flexural performance in the three-point flexural test. This phenomenon is due to reason that the addition of more low-density microspheres and the creation of more pores during the sample preparation process. The findings show that the flexural performance of the polyurethane composites reinforced can be improved by increasing the microspheres volume fraction.

The flexural strength and flexural modulus of these composites' samples are shown in figures 8 and 9, respectively. The flexural strength and flexural modulus of S3-1-S15 and S3-3-S15 are similar and higher than those of S3. Therefore, the addition of S15 microspheres improves the flexural performance of the composites. In addition, the specific flexural strength and specific flexural modulus of sample S3-3-S15 with the highest volume fraction of microspheres were higher than those of S3-1-S15 due to the addition of more low-density microspheres and

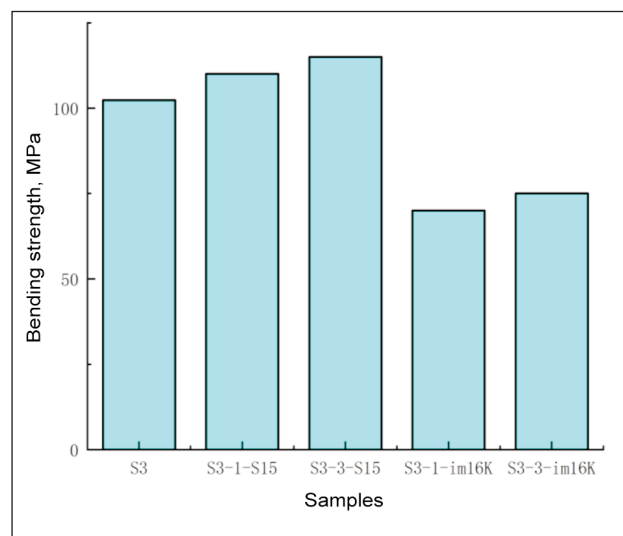


Fig. 8. Flexural strength of polyurethane composites

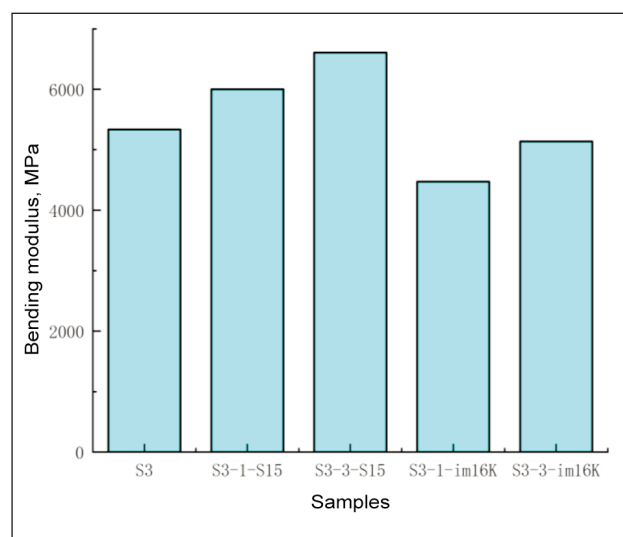


Fig. 9. Flexural modulus of polyurethane composites

more pores produced in the sample making process. In summary, when the volume fraction of S15 hollow microspheres was low, increasing the volume fraction of microspheres could improve the flexural properties of the composite more obviously.

Samples S3-3-S15 and S3-3-im16K were embedded with two different microspheres, S15 and im16K, respectively, while the volume fraction of warp-knitted spacer fabric and microspheres (3%) embedded in the three materials were identical. It can be seen that in the comparison of the above two indexes, S3-3-S15 with S15 microspheres embedded with the maximum inner and outer diameter ratio has the highest value, while S3-3-im16K with im16K microspheres embedded with the minimum inner and outer diameter ratio is lower than S3-3-S15 and S3. It may be due to the incorporation of microspheres and the creation of more pores during the sample-making process, which reduces the overall force of the composites. Therefore, it is obvious that the flexural properties of the composites decreased with the decrease of the inner and outer diameter ratio of the embedded microspheres.

Macroscopic appearance of the experimental process of three-point flexural

Figure 10 shows the three-point flexural test procedure of the representative warp-knitted spacer fabric-reinforced composite S3-3-S15. It can be seen from the figure that S3-3-S15 did not show cracks throughout the experiment, indicating that the warp-knitted spacer fabric-reinforced polyurethane composite exhibited excellent flexural performance and toughness. According to the flexural theory of materials, in the three-point flexural test, the test sample is firstly

subjected to compression load at the compression end, and then the load is propagated along with the thickness of the sample, and the sample is subjected to tensile load at the extension end, and the damage is firstly produced at the extension end. In summary, the three-point flexural test sample will be subject to vertical (compression and tension) and horizontal (shear) two directions of the load, therefore, based on the location of the material by the flexural load and the direction of crack propagation, you can determine the material in the three-point flexural test by which the main force of the load so that the macroscopic damage to the sample shape of the flexural performance analysis.

The morphology of the three-point flexural samples is presented by SEM images, and the SEM images of the three-point flexural test for samples S3-3-S15 are shown in figure 11. As can be seen in figure 11, the morphology of the glass microspheres in S3-3-S15 is well maintained, and no bead detachment occurs. It reveals that the microspheres of S15 were broken by the impact. In addition, the spacer filaments did not come out in S3-3-S15. In summary, the S15-type microspheres and the matrix resin were the main load carriers of S3-3-S15 in the three-point flexural test.

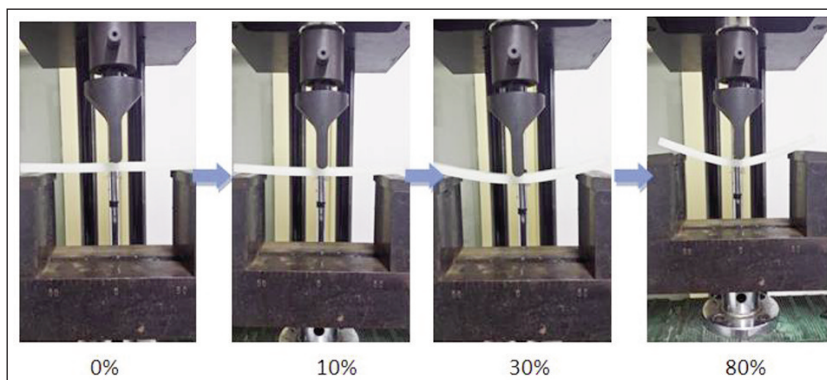


Fig. 10. The three-point flexural process of polyurethane composites

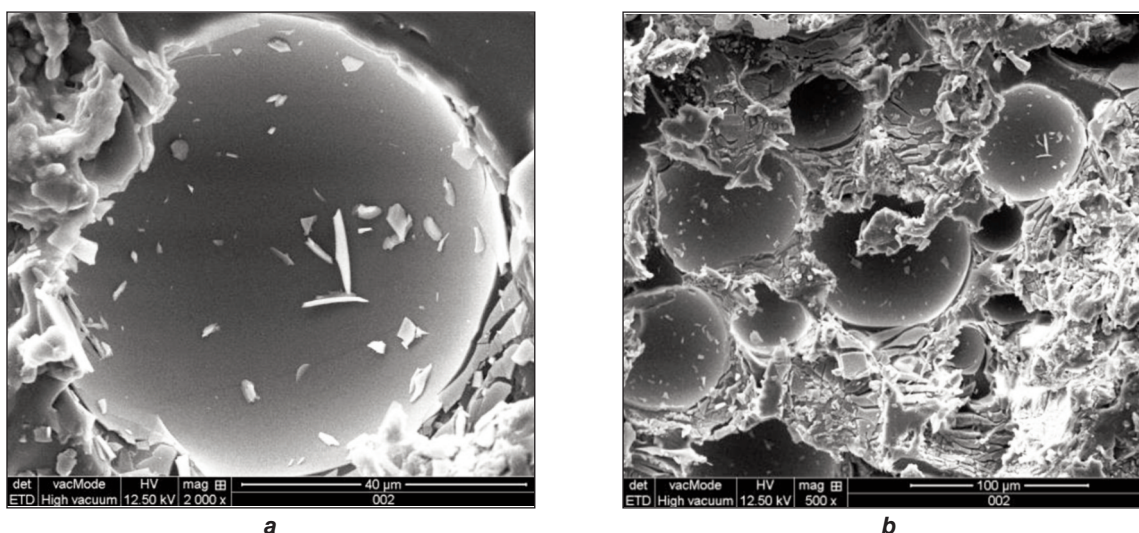


Fig. 11. SEM images of polyurethane composites: a – the SEM image for S3-3-S15 (500x); b – the SEM image for S3-3-S15 (2000x)

This is because the strength of S15-type microspheres is low, and when the matrix resin is subjected to flexural load to produce force, the microspheres will share the force and absorb part of the force thus increasing the overall flexural performance. In warp-knitted spacer fabric reinforced composites, in addition to the matrix resin and foam, the spacer filaments are also one of the main load carriers, so the presence of spacer filaments can improve the flexural resistance of the material. While glass microspheres are still not the main bearer of the flexural load, their presence will share the force and absorb part of the force thus achieving the purpose of improving the flexural performance of the material. In summary, it is the different reinforcement methods of spacer fabric and glass microspheres that make the flexural performance of warp-knitted spacer fabric reinforced composites significantly better than that of traditional composites.

CONCLUSIONS

In this chapter, the flexural properties of warp-knitted spacer fabric reinforced polyurethane composites are investigated. With the help of three-point flexural test results, the effects of microspheres parameters and

spacer fabric parameters on the flexural strength and flexural modulus of the composites are studied. The warp-knitted spacer fabric has significantly better load, flexural strength and flexural modulus, and thus better flexural properties and toughness. The structural parameters of the warp-knitted spacer fabric had a strong influence on the flexural properties of the material, with samples reinforced by spacer fabrics with a smaller number of spacer card back traverse stitches and a denser face structure showing better bending properties. Different volume fractions of microspheres and types of microspheres have a great influence on the flexural performance of the composites, and the flexural performance of the composites can be improved by appropriately increasing the volume fraction of microspheres and using higher strength microspheres. Additionally, this paper gives a theoretical explanation of damage conditions during the flexural process.

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