Study on Interlaminar Shear Properties of SiO$_2$f/SiO$_2$ Composites Based on Different Braided Structures

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Abstract. The interlaminar shear properties of SiO$_2$f/SiO$_2$ composites reinforced by needle-punched and 2.5D braided preforms are studied and analyzed. The effects of different temperatures and braiding structures on the interlaminar shear strength were investigated by analyzing the stress curves, macrostructure and microstructure of the composites. The increase of temperature, in a certain range, will change sintering condition of matrix and the bonding between matrix and interface, and thus increase the interlaminar shear strength. Because of the different shape of warp and weft yarn, there is a considerable discrepancy in the interlaminar shear strength of different direction. The interlaminar shear strength of needle-punched braided SiO$_2$f/SiO$_2$ composites is a little higher than the warp direction of 2.5D braided SiO$_2$f/SiO$_2$ composites. The interlaminar shear strength, time and economic cost should be considered comprehensively to select a more suitable braiding structure.

1. The first section in your paper Introduction

SiO$_2$f/SiO$_2$ composites have excellent mechanical, thermal shock resistance and dielectric properties. The surface melting temperature of SiO$_2$f/SiO$_2$ composites is close to quartz ceramic. It is an ideal choice for radome materials. SiO$_2$f/SiO$_2$ composites use quartz fibre preform as reinforcement and silica as matrix and retain the advantages of quartz ceramic material. Because of the reinforcing and toughening effect of fibres, SiO$_2$f/SiO$_2$ material has the characteristics of non-brittle fracture and has the ability to resist catastrophic damage. The composites were prepared by SIS(Silica-Sol Impregnated Sintering) method.

2.5D braided structure is widely used in braiding of near-net-shape manufacturing technology for radome. Because of long braiding cycle, high human cost and difficulties in the braiding of complex special-shaped structure,2.5D preforms are hardly to be widely used. In recent years, three-dimensional braided structures, such as needle-punched, stitched and orthogonal, have been more and more widely used because of their high level of mechanization and short braiding time. The interlaminar damage of traditional unidirectional composites and 2D fabrics reinforced SiO$_2$f/SiO$_2$ is prone to happen, besides, its shear strain distribution has periodic variability. The interlaminar shear strength of 3D four-directional braided composites is higher than 2.5D (shallow straight-joint) SiO$_2$f/SiO$_2$ composites, which is due to the fibre along with the orthogonal coordinate axes [1-4]. Because of the fluctuation shape of warp yarn of 2.5Dbraided SiO$_2$/SiO$_2$, the ratio of the flexural strength of warp strength and weft strength does not match with the ratio of the warp yarn density and weft yarn density. According to the fracture curve, the warp direction tends to ductile fracture, while
the weft direction tends to brittle fracture.

Compared with 3D n-directional (n = 4, 5, 6) braided SiO$_2$/SiO$_2$ composites, 3D 7-directional samples exhibited the maximum shear strengths. The stitching preform is to knit two or more layers of 2D fabrics into desired shapes with needle. The puncture process of needle-punched preform is to pre-lay the steel needle (carbon rod) according to the matrix, and then puncture the paved fabric. During the puncture process, the fibres between layers are replaced, so that the fibres between layers are perpendicular to the cross-section direction. The puncture process of needle-punching structure has initially realized robotic automation, which will greatly improve the homogeneity of preform and the speed of knitting in the future.

2. Experimental method

2.1. Composite preparation

The 2.5D braided preforms were provided by Jiangsu Bolong Aerospace New Materials Technology Co., Ltd. China. The needle-punched preforms were provided by Jiangsu Tianniao High-tech Co., Ltd. The fibre volume fraction of 2.5D braided and needle-punched preform was 44.3% and 31.8%, respectively. The SiO$_2$/SiO$_2$ composites were prepared by SIS (Silica-Sol Impregnated Sintering) method; the sintering temperature of the preparation process was relatively low. The Archimedes technique was used to determine the specimen density. The density of the 2.5D braided SiO$_2$/SiO$_2$ composites and 3D needle-punched braided SiO$_2$/SiO$_2$ composite were 1.72 g/cm$^3$ and 1.65 g/cm$^3$, respectively after 6 cycle of SIS.

![Figure 1. One cycle of SIS method.](image1)

![Figure 2. The dimension of the sample.](image2)

2.2. Test method

The test method of the interlaminar shear strength of SiO$_2$/SiO$_2$ composites we used is same as the fibre-reinforced plastic composites determination of interlaminar shear strength, the loading rate is 10mm/min. The shape of the sample as shown in the figure 2.

3. Results and discussion

3.1. The interlaminar shear properties of 2.5D braided SiO$_2$/SiO$_2$ composites

Figure 3 shows that the interlaminar shear strength of weft direction is more than twice as much as the interlaminar shear strength of warp direction. When the shear force is applied on the weft direction,
and the direction of shear force is perpendicular to warp yarn. Because of the structure is shallow curve-joint and the undulation of warp yarns. When the shear force load on the sample, the warp yarn needs to be pulled out and cut, which will consume a lot of energy. Figure 4 shows the fracture cross section of the specimen is parallel to the surface of the specimen.

**Figure 3.** Comparison different direction of the shear load-displacement curves for 2.5D braided SiO$_2$/SiO$_2$ composites at RT: (a) warp direction; (b) weft direction.

**Figure 4.** The macrostructure of different direction of 2.5D sample (a) warp direction; (b) weft direction.

**Figure 5.** Schematic of 2.5D structure.
When the shear force is applied on the warp direction, the warp yarn afford the major force. The warp yarn needs more energy to be cut off than be pulled out. Compared with the shear force on the weft direction, the shear force on the warp direction require about half amount of the fibres to be broken when the specimen is destroyed. The fracture section of the sample is formed with an certain angle to the surface of the sample, which is almost parallel with the diagonal line of the two weft yarn of adjacent layers.

Figure 6 shows that at the same displacement point the interlaminar shear strength of weft direction test at 900°C is more than twice as much as the interlaminar shear strength test at RT.

![Figure 6. Comparison of the shear load-displacement curves for warp direction of 2.5D braided SiO2f/SiO2 composites at different temperature: (a) RT; (b) 900°C.](image)

The quartz fibres weaken seriously as the temperature increase, while due to the shorter testing time at 900°C the strength of quartz fibres does not decrease significantly. The SiO2 as the matrix, meanwhile, has better sintering condition and stronger bonding strength with the matrix because of the increase of temperature. As shown in the figure 7, the matrix shrinks due to the increase of temperature. Because of the microcracks produced by matrix shrinkage the displacement is more sensitive to load. While the final shear strength is better because the energy consumed by fibre pulling out is bigger.

![Figure 7. The microstructure of 2.5D braided SiO2f/SiO2 composites at different temperature: (a) RT; (b) 900°C.](image)
Compared with the shear force acting on the warp direction, the test results at room temperature and high temperature are quite different. As shown in the figure 8, at the same displacement point the interlaminar shear strength of warp direction test at 900°C is almost much the same as the interlaminar shear strength test at RT.

![Figure 8](image1.png)

**Figure 8.** Comparison of the shear load-displacement curves for the weft direction of 2.5D braided SiO$_2$/SiO$_2$ composites at different temperature: (a) RT; (b) 900°C.

When shear force acts on weft direction, the difference of test results between room temperature and high temperature is relatively small. As the test temperature rises, the interlaminar shear strength of the weft direction has some improvements. With the increase of temperature, the sintering effect is better and the bonding strength between fibres and matrix is stronger. The test result shows that the effect of fibre breaking strength is greater than that of separation of fibre and matrix in improving the weft direction shear strength.

![Figure 9](image2.png)

**Figure 9.** Comparison of the shear load-displacement curves for needle-punched braided SiO$_2$/SiO$_2$ composites at different temperature: (a) RT; (b) 900°C.
3.2. The interlaminar shear properties of needle-punched SiO$_2$/SiO$_2$ composites

As shown in the figure 9, when the test temperature rises, the interlaminar shear strength of needle-punched braided SiO$_2$/SiO$_2$ composites test at 900°C is nearly twice as much as the interlaminar shear strength test at RT and 900°C. At the same load point the interlaminar displacement test at 900°C is much higher than the interlaminar shear strength test at RT. The interlaminar shear strength of needle-punched braided SiO$_2$/SiO$_2$ composites slightly higher than the warp direction of 2.5D braided SiO$_2$/SiO$_2$ composites, and lower than the weft direction of 2.5D braided SiO$_2$/SiO$_2$ composites.

The needle-punched preforms have better interlaminar shear property because of the interlaminar normal fibres. Because of the appearance of the micro crack, at the same load point the interlaminar displacement is bigger test at high temperature. While the final shear strength is better because the energy consumed by fibre pulling out is bigger. The needle-punched preforms has excellent braiding speed and forming effect. In the case of low strength requirements needle-punched braided SiO$_2$/SiO$_2$ composites will be more widely used.

4. Conclusions

The interlaminar shear strength of weft direction of 2.5D braided SiO$_2$/SiO$_2$ composites is more than twice as much as the interlaminar shear strength of warp direction. When shearing force is applied to weft direction of sample, warp yarn needs to be pulled out and cut off, which consumes more energy. Because of the microcracks produced by matrix shrinkage at high temperature the displacement is more sensitive to load. While the final shear strength is better because the energy consumed by fibre pulling out is bigger. The interlaminar shear strength of needle-punched braided SiO$_2$/SiO$_2$ composites is a little higher than the weft direction of 2.5D braided SiO$_2$/SiO$_2$ composites. The different laminar of needle-punched braided SiO$_2$/SiO$_2$ composites have good connection because of the normal fibres which cross the interlaminar. The interlaminar shear strength, time and economic cost should be considered comprehensively to select a more suitable braiding structure.

References

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