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Research Article

Electrical Property of 3D Printed Continuous Fiber Reinforced Thermoplastic Composite Mesh Reflecting Surfaces

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Continuous fiber reinforced thermoplastic composites have been widely used in modern aerospace and other high-end manufacturing fields because of their light weight, high strength, fatigue resistance, and corrosion resistance properties. Due to the reinforcement of carbon fiber strands, continuous fiber reinforced thermoplastic composites have good conductivity which makes it a potential material for the preparation of space-borne antennas reflecting surfaces. The reflecting surfaces of common mesh antennas are usually prepared by gold-plated molybdenum wire which is expensive and hard to produce. In this study, the continuous fiber reinforced thermoplastic composites mesh reflecting surfaces are prepared by 3D printing technology. The effect of different mesh shape and mesh size on the electrical properties are investigated systematically. The electrical property of the reflecting surface were tested by waveguide method at the S band with the frequency of 1.9 ~ 2.3GHz. The results show that the reflection loss of the 3D printed continuous fiber reinforced thermoplastic composite mesh reflecting surfaces are lower than 0.25 dB, which can well meet the requirement of space-borne antennas in the S waveband. The reflection loss of the 3D printed continuous fiber reinforced thermoplastic composite mesh reflecting surfaces increases with the increase of mesh size accordingly for both the quadrangular and the triangular mesh reflecting surface. The reflecting property of the mesh reflecting surface tends to be better with a higher surface mass density. The results foresee that the continuous fiber reinforced thermoplastic composites can be used to develop the reflector of large mesh antenna in the future work.

1. Introduction

Space-borne antennas are one of the most important payloads on the satellite used for communication, deep space exploration, remote sensing, navigation radio astronomy, and earth observation. In order to meet the demand of increased resolution or sensitivity for multiple functions, the size of space-borne antennas tends to be larger and larger during the past decades [1–5]. Considering the constraints of the current launch vehicle, traditional space-borne antennas are designed as deployable structures which folded in the fairing during launch stage and unfolded independently in space. The size of deployable space-borne antenna is always restrained by the fairing size and weight requirements of the launch vehicle with a limit of one hundred meter level [6–8].

In order to construct super large space antennas in the kilometer scale, the deployable antenna cannot meet the requirements. The focus now on in-space construction technology is becoming very noticeable due to the capacity of constructing large space structure on the orbit, the moon, the mars, and another planet [9–11]. Nowadays, agencies like National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) have been conducting research in how to use additive manufacturing in a variety of space-related applications, from using it to print CubeSat propulsion systems, to printing ceramics, and to printing large spacecraft in space [12]. NASA released a national initiative in 2020 to accelerate “in-orbit space assembly and maintenance”. The Defense Advanced Research Projects Agency (DARPA) also listed “in-orbit manufacturing of large antennas” in its top 10 aerospace frontier technologies. The European Union released the “Space Factory” project in 2021, which aims at building a manufacturing platform for spacecraft such as satellites and large antennas in space orbit. In the 2020 China Space Conference, “on-orbit additive manufacturing technology for space ultra-large antenna structure” was listed as the “top ten scientific and technical problems” in the field of aerospace.

As the most vital part of space-borne antenna, the reflecting surface is the most likely component to be constructed in space by additive manufacturing technology. The performance of deployable space-borne antennas depends primarily on the properties of reflecting surfaces which is always made of knitted wire mesh with different kind waves to reduce weight and volume [13–15]. However, considering the complexity technology of wire mesh, it is hard to produce the wire mesh surface in space. An alternative is to consider continuous fiber reinforced thermoplastic composites as the raw material of reflecting surface to printing the reflecting surface in space by additive manufacturing technology.

Benefit from the superior conductivity of carbon fiber, continuous fiber reinforced thermoplastic composites tends to be a good electrical conductor which makes it a potential candidate material for the reflecting surface of space-borne antenna [16, 17]. Fused deposition modeling (FDM) is one of the most commonly used additive manufacturing technologies (also known as 3D printing) [18, 19]. Tian et al. proposed a novel FDM process to print continuous fiber reinforced thermoplastic composites using fiber and plastic filament as the raw materials [20]. The FDM process is used to print the reflecting surface in this study. In a typical process, a filament of material is fed into a machine via a pinch roller mechanism. The feedstock is melted in a heated liquefier with the solid portion of the filament acting as a piston to push the melt through a print nozzle. A gantry moves the print nozzle in the horizontal x–y plane as the material is deposited on a build surface that can be moved in the vertical z direction. The extruded material rapidly solidifies and adheres with the surrounding material to accumulate the required complex plastic parts. The 3D printed continuous fiber reinforced thermoplastic composites with a fiber content of 27% achieve the maximum flexural strength of 335 MPa and flexural modulus of 30GPa. The technology has been tested in space by Chinese Changzheng-5B rocket, which has shown high application value in in-space manufacturing field. Markforged Company also developed a 3D printer for continuous fiber reinforced thermoplastic composites process using pre-preg filament with continuous fiber and thermal plastic matrix.

For the continuous fiber reinforced thermoplastic composites, most of the researches focus on the material preparation process and properties [21]. There are few researches have been done for the continuous fiber reinforced thermoplastic composites as a reflecting mesh surface of antenna. The performance of space-borne antenna mainly depends on the electrical property of the reflecting surface at designated frequency. Li and Su developed a method to predict the electrical performances of the mesh reflector structures with complex weave patterns [22]. However, the electrical property of continuous fiber reinforced thermoplastic composites reflecting surface has not been studied yet, which will restrict the application of continuous fiber reinforced thermoplastic composites in the field of space-borne antenna.

In this research, the continuous fiber reinforced thermoplastic composites reflecting surfaces with different shape and mesh were prepared by the FDM process. The electrical property of 3D printed continuous fiber reinforced thermoplastic composites reflecting surfaces were systematically studied. Electrical property of the reflecting surface was tested by waveguide method. The effect of mesh shape, mesh size, and surface mass density on the electrical property was discussed in this paper. The structure of this paper is organized as below. In Section 2, the experimental platform, specimens and electrical property test method are presented. In Section 3, the effect of different parameters on the electrical property of the continuous fiber reinforced thermoplastic composites reflecting surfaces are discussed. Finally, the conclusions are given in Section 4.

2. Experimental Procedures

2.1. Experimental Platform. In this work, the FDM based 3D printing method was utilized to print the continuous fiber reinforced thermoplastic composites reflecting surfaces. The 3D printer was developed by Xi’an Jiaotong University, which was consisted of extrusion head, control system, building platform, X-Y motion mechanism etc., as shown in Figure 1. Detailed parameters and components of the 3D printer were introduced in the reference [20]. The printing process is called continuous fiber reinforced thermoplastic composite 3D printing technology. The scheme of printing head and process parameters are shown in Figure 2. During the 3D printing process, thermoplastic polymers filaments and continuous fibers were fed into the heated printer head simultaneously. As the action of high temperature, polymers filaments melted and formed a melting pool. Continuous carbon fibers were impregnated with molten polymers while passed through the printer head. Under the pressure in the printer head, impregnated continuous fibers were extruded. The carbon fibers and polymers solidified and bonded on the workbench with the preplanned print routes. The continuous fiber reinforced thermoplastic composite components were fabricated with layer by layers upon the deposited components.

2.2. Material and Specimens. The thermoplastic matrix material was polyamides wire produced by Flashforge Corp in China. 1 K carbon fiber tows from TENAX-J Corp in Japan was used as the reinforcement. In order to investigate the effect of mesh shape and mesh size on the electric property of the continuous fiber reinforced thermoplastic composite mesh reflecting surface, two kinds of mesh shape with four kinds of fiber interval were prepared in this experiment as shown in Table 1. The mesh shape included

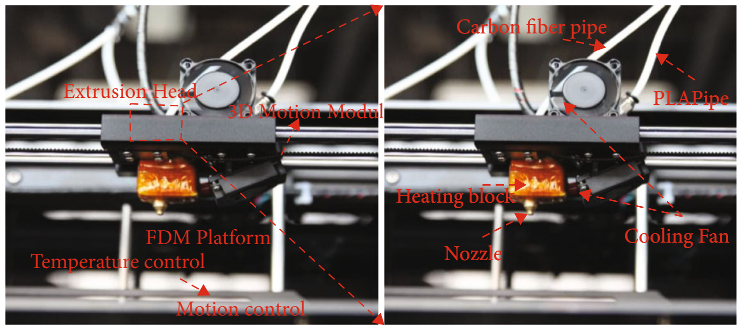


Figure 1: 3D printer used to prepare the continuous fiber reinforced thermoplastic composites.

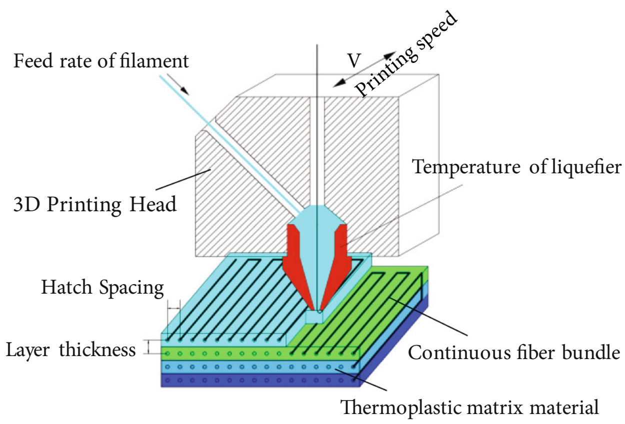


Figure 2: Scheme of 3D printing for the continuous fiber reinforced thermoplastic composites.

triangle and quadrangle mesh. The dimension of specimens was all 200 mm × 200 mm. The fiber interval of different mesh size was set as 2 mm, 3 mm 4 mm, and 5 mm, respectively. All of the specimens were prepared by the aforementioned FDM 3D printer with the same printing parameters. The specimens are shown in Figure 3.

2.3. Electrical Property Test. Waveguide method was utilized to test the electrical property of the continuous fiber reinforced thermoplastic composites mesh reflecting surface. The electrical property test schematic is shown in Figure 4. The electromagnetic wave energy was measured by the vector network analyzer which was produced by Agilent Technologies Inc. The recycling mesh was placed at one end of the waveguide and fixed by four bolts as shown in Figure 5. Before each test, a 5 mm aluminum plate was utilized for zero setting.

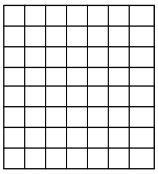
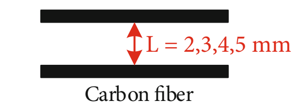
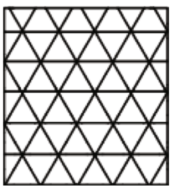
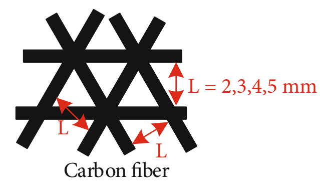
3. Results and Discussion

It is well known that the performance of mesh reflector antennas depended on how well the reflecting surface performs at the designed frequencies. The reflection loss is one of the main factors of reflecting surfaces due to the microwave leakage loss through the mesh gap. The mesh material, mesh structure, mesh shape and mesh size, and wire diameter are related to the reflection loss. In order to test the reflecting properties of 3D printed continuous fiber reinforced thermoplastic composite reflecting surfaces, the reflection losses of the reflecting surfaces with different mesh size and shape are get by the vector network analyzer at the S waveband with the frequency of 1.9 ~ 2.3GHz.

3.1. Effect of Mesh Shape on the Electrical Property. Triangle and quadrangle mesh surface are the most widely used reflecting surface of space-borne antennas, which can be well produced by the 3D printing technology layer by layers. In this experiment, the reflecting properties of different mesh shape surfaces are tested. Figure 6 shows the effect of triangle and quadrangle mesh surfaces on the reflection loss. In general, the reflection loss of the 3D printed continuous fiber reinforced thermoplastic composite reflecting surface is lower than 0.25 dB. It seems that the continuous fiber reinforced thermoplastic composite reflecting surface can well meet the requirement of space-borne antennas in the S waveband. When the mesh size is 3 ~ 5 mm, the reflection loss of triangle mesh reflecting surface is lower than the quadrangle mesh surface. It seems that the reflecting property of triangle mesh reflecting surface performs better than the quadrangle mesh reflecting surface at a larger mesh size. When the mesh size is 2 mm, the reflection loss of triangle mesh reflecting surface is larger than the quadrangle mesh reflecting surface with the reflecting loss of 0.06 dB and 0.10 dB, respectively. This is due to the reason that the surface mass density increases with the decrease of mesh size. For the smaller size mesh, the surface mass density is higher. The higher mass density means higher resin matrix content, which may have a significant effect on the reflection loss due to the poor reflection properties of resin matrix.

3.2. Effect of Mesh Size on the Electrical Property. The effect of mesh size on the electrical property of the continuous fiber reinforced thermoplastic composites reflecting surfaces with different shape is shown in Figure 7. It can be seen that the reflection loss increases with the increase of mesh size accordingly no matter for the quadrangular or triangular mesh reflecting surface. For the quadrangular mesh reflecting surface in Figure 7(a), the reflection loss almost linear increases with the mesh size smaller than 4 mm. When the quadrangular mesh is larger than 4 mm, the effect of mesh size on the electrical property tend to decrease. For the triangular mesh reflecting surface in Figure 7(b), when the

Table 1: The continuous fiber reinforced thermoplastic composites reflecting surface with different mesh shape and mesh size.

Mesh shape of reflecting surface	Dimension of specimen (mm)	Mesh size L (mm)	Scheme
 Quadrangle	200×200	2, 3, 4, 5	
 Triangle	200×200	2, 3, 4, 5	

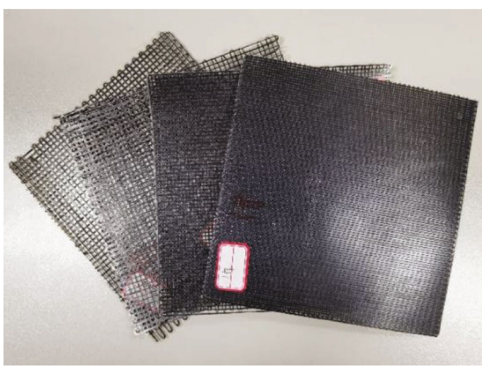


Figure 3: Continuous fiber reinforced thermoplastic composite mesh reflector specimen based on additive manufacturing technology.

triangular mesh size is smaller than 4 mm, the effect of mesh size on the reflection loss in not significant when the triangular mesh size is larger than 4 mm, a larger mesh size results in a higher reflection loss.

In order to express the electrical properties of reflecting surface clearly, the mean reflection coefficient Γ is calculated by the Equation (1), where L is reflection loss.

$$\Gamma = 10^{-L/20} \times 100\%. \tag{1}$$

The reflection wave, transmission wave, and loss are formed while the incident electromagnetic wave is reflected through the continuous fiber reinforced thermoplastic composites reflecting surfaces. Higher reflection coefficient corresponds to more reflection wave which means better reflection properties of the reflection mesh surface. The reflection coefficient of continuous fiber reinforced thermoplastic composites is generally greater than 97% which shows a perfect reflecting performance. Compared with the knitted wire mesh reflecting surface, the nonuniform mesh size and the imperfect electrical contact between the wires will cause unwanted clutter and power loss due to passive intermodulation. Passive intermodulation, also known as intermodulation distortion, represents the intermodulation products generated when two or more signals are transmitted through a passive device with nonlinear characteristics. Passive intermodulation may affect the transceiver characteristics of antennas and must be minimized for the antenna during the development stage. The continuous fiber reinforced thermoplastic composites reflecting surfaces produced by 3D printing technology layer by layer continuously results in a better interlayer bonding performance which may reduce the passive intermodulation properties. The excellent reflecting performance of the continuous fiber reinforced thermoplastic composites also makes it potential candidate materials for the in-orbit constructed larger antenna reflecting surface.

3.3. Effect of Surface Mass Density on the Electrical Property. For the mesh reflector antenna, the surface mass density is always related with the reflection performance of the mesh reflecting surface. In order to investigate the relationship between the surfaces mass density and reflecting properties of the continuous fiber reinforced thermoplastic composites. The mass and area of every specimen are measured by the electronic balance and ruler. The surface mass density D is calculated as follows:

$$D = \frac{m}{S}, \tag{2}$$

where m and S are the mass and area of the continuous fiber reinforced thermoplastic composites reflecting surface specimen, respectively.

In Figure 8, the reflection coefficient of the continuous fiber reinforced thermoplastic composites reflecting surfaces is plotted versus the increase of surface mass density. The short dash lines in the figure, which is the linear fitting curves for the experimental results, have no exact physical meaning and just show the approximate changing trends of the data. The surface mass density seems to play an important role in the reflecting properties. For the quadrangular mesh reflecting surface, the reflection coefficient increases with the increase of surface mass density. On the other hand, the relationship between reflection coefficients

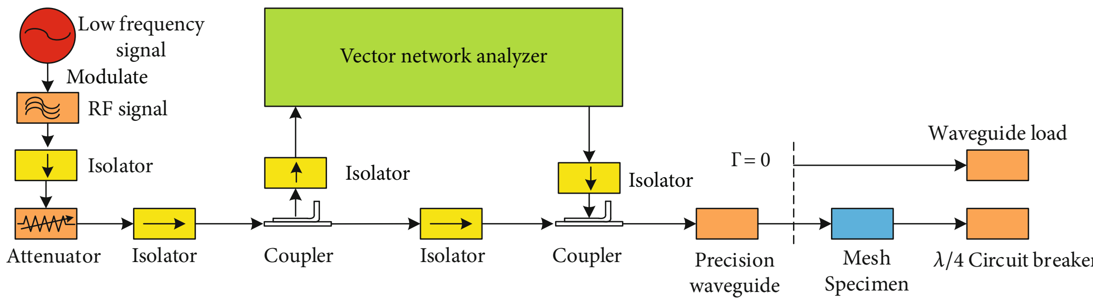


FIGURE 4: Electrical property test scheme by waveguide method.

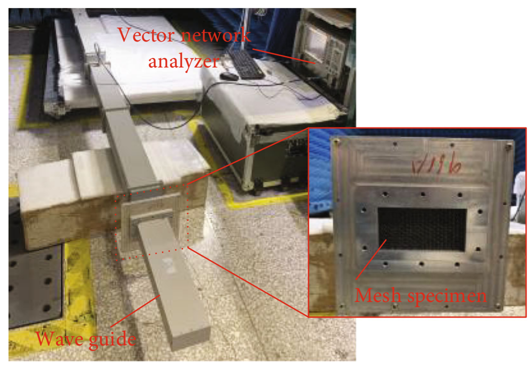


FIGURE 5: Electrical property test experiment.

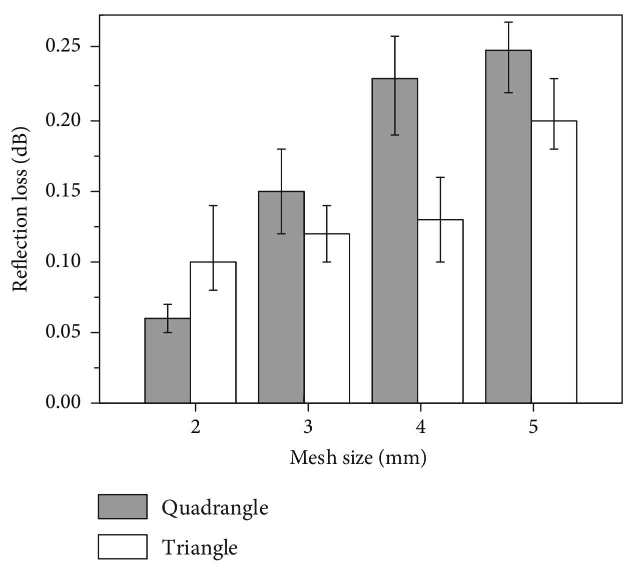


FIGURE 6: Effect of mesh shape on the reflection loss of the continuous fiber reinforced thermoplastic composites reflecting surfaces.

and surface mass density is not monotonic for the triangular mesh reflecting surface. The reflection coefficient tends to increase with a larger surface mass density of the triangular mesh reflecting surface while the surface mass density is lower than 0.03 g/cm^2. However, the reflection coefficient of the triangular mesh reflecting surface is not significant while the surface mass density is larger than 0.03 g/cm^2.

The shape of mesh surface has an important effect on the surface reflecting properties. For the mesh reflecting surface with the same mesh size and different mesh shape, the surface mass density is different. The surface mass density of triangular mesh reflecting surface is higher than the quadrangular mesh reflecting surface with the same mesh size. For this reason, the triangular mesh reflecting surface seems to have better electrical properties with smaller mesh size. As the surface mass density increases further, the quadrangular mesh reflecting surface shows a greater reflecting performance than the triangular mesh reflecting surface. The larger surface mass density means more raw material and higher cost. The quadrangular mesh reflecting surface with

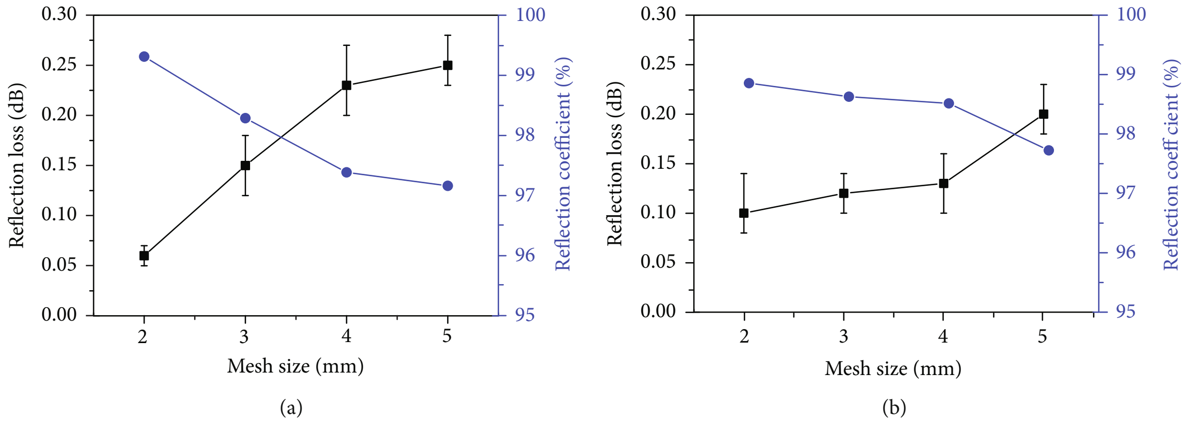


Figure 7: Effect of mesh size on the electrical property of the continuous fiber reinforced thermoplastic composites reflecting surfaces: (a) quadrangular mesh reflecting surface; (b) triangular mesh reflecting surface.

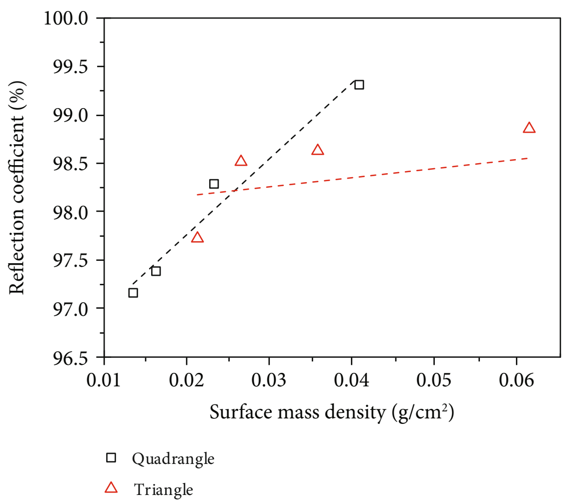


Figure 8: Effect of surface mass density on the reflection coefficient of the continuous fiber reinforced thermoplastic composites reflecting surfaces.

smaller mesh size is preferred for the antenna desired greater reflecting performance.

4. Conclusions

The electrical properties of 3D printed continuous fiber reinforced thermoplastic composite mesh reflecting surfaces with different mesh shape and mesh size have been investigated experimentally in this study. The reflecting properties of the mesh surface were obtained using waveguide method at the S waveband with the frequency of 1.9 ~ 2.3GHz. The main conclusions can be drawn as follows:

(1) The reflection loss of the 3D printed continuous fiber reinforced thermoplastic composite mesh reflecting surfaces are lower than 0.25 dB, which can well meet the requirement of space-borne antennas in the S waveband

(2) The electrical property of the 3D printed continuous fiber reinforced thermoplastic composite mesh reflecting surfaces is related with the surface mesh shape. The triangular mesh reflecting surface performs a better electrical property when the mesh size is larger than 3 mm

(3) The reflection loss of the 3D printed continuous fiber reinforced thermoplastic composite mesh reflecting surfaces increases with the increase of mesh size accordingly for both the quadrangular and the triangular mesh reflecting surface

(4) The surface mass density of the 3D printed continuous fiber reinforced thermoplastic composite mesh reflecting surfaces with 2 ~ 5 mm mesh size is found around 0.01~0.06 g/cm^2. The reflecting property of the mesh reflecting surface tends to be better with a higher surface mass density

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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