Study on molding technique for millimeter-wave radome with frequency selective surface

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Abstract. In the paper, the molding process of the millimeter-wave radome with frequency selective surface was studied, and the key factors were discussed such as the selection of the material, the design of the mould and the curing parameters. The millimeter-wave radome with FSS has the high requirement for thickness uniformity and surface precision. The layout design and the moulding parameters control were discussed to achieve the high performance of the radome. The testing results show that the manufactured radome has the smooth surface and thickness precision of ±0.1mm. The average transmission efficiency of the radome working at the operating frequency and in the sweep range is ≥90%. The performances of the radome entirely meet the design requirements.

1. Introduction
With the development of millimeter-wave technology, millimeter-wave antennas are used more and more widely. As the transmission window of antenna, the millimeter-wave radome is an indispensable component of antenna system. Its design parameters directly affect the antenna technical specifications [1-3]. In the millimeter wave band, the microwave loss in medium is very large, so the requirements of the radome are high dimensional accuracy and low dielectric loss [4-5].

In this paper, the molding process of a certain type of airborne millimeter wave frequency selective radome is discussed, and the key manufacturing techniques in the manufacturing process are discussed in detail, including material selection, mold design, reflecting surface manufacturing, etc.

2. Brief description of the radome structure
The airborne millimeter wave radome is cylindrical in shape, and a reflecting surface is designed on the inner side of the top of the radome, as shown in Figure 1. The frequency selective metal pattern is the outermost layer of the inner surface of the radome. The thickness of the reflecting surface is 0.7mm, and the metal pattern is linear. In order to meet the high electrical performance index of millimeter wave band, the radome requires high accuracy of thickness and uniformity of components, especially for the reflecting surface, which requires higher surface accuracy.

The thickness of the radome cylinder is 2.1±0.1mm, the thickness of the reflecting surface is 1.7±0.1mm, and the thickness of the flange reinforcing zone is 4.1±0.2mm.
3. Research of material properties

Material is very important for millimeter-wave radomes, which require material with low dielectric loss and good performance. Cyanate ester resin is a kind of high-performance thermosetting resin with excellent comprehensive performance [6-7]. Especially the extremely low dielectric loss can meet the requirements of millimeter wave radome for dielectric properties. Considering the performance, cost and equipment, a certain type of medium temperature curing cyanate ester / alkali-free glass fiber prepreg is used to manufacture the airborne millimeter wave radome.

3.1. Physical properties of the prepreg

The physical properties of the prepreg include resin mass content, volatile content, fiber mass per unit area, single-layer prepreg pressing thickness, etc. These items were studied according to the corresponding test method, and the results are shown in Table 1.

| Properties                   | Average value | Test method       |
|------------------------------|---------------|-------------------|
| Resin mass fraction          | 40%           | JC/T 780-1987     |
| Volatile content             | <1.0%         | JC/T 776-1985     |
| Fiber mass per unit area (g m$^{-2}$) | 170.0         | JC/T 780-1987     |
| Single-layer prepreg thickness (mm) | 0.10          |                   |

3.2. Analysis of curing characteristics

DSC analysis of the resin curing process was carried out to determine the optimum curing temperature range. DSC analysis was carried out for the resin system at a heating rate of 2 °C / min, 5 °C / min and 10 °C / min, respectively. The results showed that there were two exothermic peaks during the curing reaction of the resin. Table 2 shows the results of DSC analysis of the resin, and the initial, peak and final temperatures extrapolated to the rate of 0 are obtained.

According to the results of DSC analysis, the curing process of the composites was cured in two steps. The material is initially cured in autoclave and post-cured in oven. Combined with the actual test conditions, the preliminary curing temperature was determined to be 135°C/2hr, and the post-curing temperature was 180°C/3hr.
Table 2. The DSC analysis results of the resin.

| Heating rate | 1st peak | 2nd peak |
|--------------|----------|----------|
|              | Initial (°C) | Peak (°C) | Final (°C) | Peak (°C) | Final (°C) |
| 2 °C min⁻¹   | 101.1     | 121.9    | 136.4      | 155.7     | 196.6      |
| 5 °C min⁻¹   | 115.3     | 135.4    | 150.1      | 178.3     | 222        |
| 10 °C min⁻¹  | 120.3     | 142.1    | 157.1      | 195.9     | 242.2      |
| Extrapolate to rate 0 | 99.4 | 119.5 | 133.9 | 148.9 | 189 |

3.3. Study on gel properties
Reasonable pressurizing timing is one of the key factors for manufacturing composite parts with excellent properties [8]. Usually, the pressurization timing is a little earlier than the resin gel point. The gel properties of the resin were studied by picking method. The gel time of the resin at different temperatures is shown in Table 3. According to the data measured in the table, the suitable pressurizing time is about 30 minutes after the temperature reaches 110 °C.

Table 3. Gel time of the resin at different temperatures.

| Temperature (°C) | Gel time (min) |
|------------------|---------------|
| 100              | 75            |
| 110              | 40            |
| 115              | 25            |
| 120              | 15            |

3.4. Analysis of TMA characteristics
Glass transition temperature (Tg) is an important characteristic parameter of the material. The Tg of the resin directly affects the maximum service temperature of the resin matrix composites. So, in this experiment Tg of the material was analyzed by thermomechanical analysis method (TMA). When the post-curing temperature is 180°C/3hr, the Tg of the composite material is 195°C. The maximum working temperature of the radome is 80°C, so the cured composite material can fully meet the requirements of the working temperature of the product.

3.5. Properties of the composites
The dielectric properties and mechanical properties of the composites are given in Table 4 and Table 5, respectively. The state of the processed sample has a great influence on the test data of mechanical properties. Due to the limitation of processing equipment, the edges of the standard sample made from the composite material plate have delamination and fluffing phenomenon, so the measured performance data is slightly lower, especially the reduction of tensile strength is more obvious.

Table 4. Dielectric properties of the composites.

| Properties     | Average value | Test method                      |
|----------------|---------------|----------------------------------|
| Dielectric constant | 4.30          | Resonant cavity method (X band)  |
| Dielectric loss  | 0.010         |                                  |
Table 5. Mechanical properties of the composites.

| Properties               | Average value | Test method       |
|--------------------------|---------------|-------------------|
| Warp tensile strength (MPa) | 361           |                   |
| Warp tensile modulus (GPa)  | 22.8          | GB/T 1447-2005    |
| Weft tensile strength (MPa) | 305           |                   |
| Weft tensile modulus (GPa)  | 21.8          |                   |
| Flexural strength (MPa)    | 553           | GB/T 1449-2005    |
| Flexural modulus (GPa)     | 23.9          |                   |
| ILSS (MPa)                | 51            | JC/T 773-1982     |

4. Manufacturing Technology of Radome

4.1. Technological process
The radome body is solid wall structure, which is fabricated by the autoclave molding. The specific technological process is shown in Figure 2.

4.2. Key manufacturing technology

4.2.1. Mold design. Mold design is a key part of the composite molding process, which directly affects the quality of composite molding [9]. Mold design should consider factors such as composite molding methods, layup, and easy demoulding and so on. The composite mold suitable for the autoclave forming process includes the male mold and the female mold. Considering the structural characteristics of the radome, the male mold is used. When designing the radome forming tooling, the manufacturing of reflecting surface should be taken into account at the same time. The positioning pin is designed for the positioning of reflecting surface. According to the radome structure drawing, a number of holes are designed in the cylinder and the bottom thickening area of the radome. When the mold is designed, the hole punching problem is considered together. The holes are reserved on the mold. Elbow drills are used to punch without demoulding, and the radome is demoulded after drilling is completed. The demoulding of the workpiece is achieved by means of the ejection of the demoulding nail, so that the corresponding hole position should be left on the bottom plate of the mold to facilitate the release of the nail. The structure of the mold is shown in Figure 3.
4.2.2. Reflecting surface manufacturing. The fabrication of the reflecting surface includes two processes: the forming of the reflecting surface and the fabrication of metal graphics. After the forming of the reflecting surface, metallization is carried out on it, and then the fabrication of metal graphics is carried out by chemical etching method.

Manufacturing of the reflecting surface is a crucial step in the manufacture of the radome. The surface quality of the reflecting surface directly affects the production of metal graphics on it. In order to fabricate a reflecting surface with high surface precision, it is necessary to control pressurizing timing in molding [10]. Usually, the pressurization timing is a little earlier than the resin gel point. At this time, the resin still has considerable fluidity, allowing bubbles to be extruded, but not too much resin, thereby ensuring the quality of the parts. According to the data measured in the Table 3, the suitable pressurizing time is about 30 minutes after the temperature reaches 110 °C. In the actual production process, the pressurization timing should be appropriately adjusted according to the ambient temperature, the temperature distribution inside the autoclave, the size of the radome, and the position of the radome in the autoclave. The reflecting surface is manufactured to fully meet the surface accuracy requirements of metal pattern etching.

According to the existing production conditions, the metallization of the reflecting surface is carried out by chemical copper deposition and electroplating thickening process. The graphic production draws on the traditional PCB manufacturing process, and the chemical etching method is adopted. Because the reflecting surface is a curved surface, the exposure mode is laser exposure which is not restricted by the shape of the parts. After measurements, the thickness of the metal film on the reflecting surface is 16-26 \( \mu m \), the width of the grid is 0.50-0.52mm, and the axial deviation is less than 0.03mm, which meets the design requirements.

4.2.3. Laying of the radome. The millimeter wave radome has a small wall thickness tolerance and a high thickness uniformity. Radome layup should satisfy the strength requirement and ensure the thickness accuracy requirement as far as possible. In the process of radome laying, measures such as zonal laying, ironing and pre-compacting are adopted to ensure the quality and thickness uniformity of the radome. The radome is divided into two areas for laying: reflecting surface area and cylinder area. The joint position of the two areas should be staggered, and the joint position should be in the form of docking, and the lap joint is forbidden. Secondly, in the course of laying, each layer should be ironed, and the layers should be vacuum pre-compacted several times. After pre-compacting, the wrinkles should be properly trimmed.

4.2.4. Curing of the radome. Reasonable curing process parameters are very important for the forming of composites, including reasonable pressurizing timing, curing temperature and curing time.
Reasonable pressurizing timing not only affects the molding quality of the composites, but also affects the thickness uniformity of the composites. Pressurizing too early, resin fluidity is large, will cause excessive resin loss, resin distribution is not uniform, resulting in uneven thickness of the radome; Pressurizing too late, some of the resin may have been cured, not easy to press down, resulting in high porosity, not compact, thus affecting product performance, uneven thickness of the radome. Therefore, selecting the appropriate pressurizing timing can not only ensure the quality of the radome, but also ensure the consistency of the composition and thickness of the radome, which provides a guarantee for the high dielectric properties of the radome. The pressurizing timing of the material can be determined by testing the gel point of the resin. The gel time of the resin at different temperatures is shown in Table 3. The results of the experiments showed that the optimum time for molding the radome is 10-20 minutes at 110 ℃.

In summary, the forming process parameters of the radome are: curing temperature 135 ℃/2hr, post curing temperature 180 ℃/3hr, the optimum pressurizing timing 110 ℃/10-20minutes. Usually the forming pressure of the composites is 0.4-0.6MPa.

Table 6 is the test data of the developed radome. The performance of the radome fully meets the design requirements.

| Test items                                | Average value |
|-------------------------------------------|---------------|
| The thickness of the radome cylinder (mm)  | 2.05-2.11     |
| The thickness of the reflecting surface (mm) | 1.67-1.73     |
| The thickness of the metal film on the reflecting surface (μm) | 16-26         |
| The width of the metal grid (mm)           | 0.50-0.52     |
| The average transmittance of the radome    | 93.0%         |

5. Conclusions
Through the breakthrough of key process technologies such as scientific and reasonable mold design, refined laying design and strict control of molding process parameters, the millimeter wave radome has been developed. Its surface is smooth, the thickness accuracy is no more than ±0.1mm, and the average transmittance of the radome in working frequency and scanning range is ≥90%. The performance of the radome fully meets the design requirements.

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