Study on Novel Heterogeneous Packaging Material and Housing Design for Spaceborne T/R Module

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Abstract. A novel double-layer structure heterogeneous packaging material SiCp/Al+Si/Al was proposed. The packaging shell of X-band active phased array radar transmit/receive module for aerospace was developed. The deformation control, heat dissipation and anti-mechanical environment analysis of micro-assembly welding process were studied. The test and analysis results show that, compared with conventional materials, it has less deformation in the welding process with low temperature co-fired ceramics printed circuit boards. It has the advantages of laser capping, low expansion, high thermal conductivity and high reliability, and can meet the requirements of spaceborne power module packaging applications.

1. Introduction
As an active microwave imaging sensor, spaceborne synthetic aperture radar (SAR) using large-aperture active phased array has become an indispensable tool for earth observation by transmitting broadband signals and combining synthetic aperture technology. Especially, high-frequency SAR antennas such as X-band have more significant advantages in high-resolution images [1-3].

X-band large-aperture SAR antenna includes thousands of transmitting and receiving channels. Transmit/receive (T/R) module is the core unit of active phased array radar (APAR) for power amplification and signal reception. Its performance directly affects the performance and reliability of the spaceborne SAR [4]. X-band T/R module contains many power amplifier chips, control chips, resistors, capacitors and other components, mostly in the form of gas-sealed packaging structure [5-6]. The packaging structure mainly includes shell and cover plate, mostly using laser sealing technology.

Various spaceborne T/R modules based on low temperature co-fired ceramics (LTCC) and AlN multilayer co-fired ceramics require shell materials with matching thermal expansion coefficient, high thermal conductivity and low density. Conventional T/R module packaging materials mainly include Kovar alloy, titanium alloy, silicon-aluminum (Si/Al), SiCp/Al and other metals or composites. Among them, Al-based composites reinforced by Si particles, SiC particles and diamond have the advantages of low density, high thermal conductivity and low expansion, which have become the research hotspot of packaging materials [7-9].
2. Packaging materials and structural design

As shown in Fig. 1, the thermal conductivity (TC) and thermal expansion coefficient (TEC) of conventional packaging materials are presented. Si/Al has high TC and laser sealing performance, but its TEC is higher than that of the LTCC. SiCp/Al composites have the characteristics of high thermal conductivity and low expansion, and have been used in aerospace products earlier [7-8], but they cannot be directly used in laser sealing and it is difficult to manufacture with high hardness. Therefore, it is urgent to develop a kind of material with high thermal conductivity, low expansion, machinability, laser sealing and other excellent comprehensive properties to meet the growing application requirements of high-power multi-chip packaged T/R modules in aerospace.

![Figure 1. TC and TEC of conventional electronic packaging materials.](image)

2.1. Design of packaging structure

For the low heat consumption T/R modules, as shown in Fig. 2 (a), the materials used include Kovar alloy, titanium alloy, aluminum alloy, etc. As for the high-power (>10W) T/R modules, the packaging materials include Si/Al, SiCp/Al, etc. However, due to the difficult processing and non-laser sealing characteristics of SiCp/Al, the composite shell structure of Fig. 2(b) is adopted, which includes two parts: the bottom plate and the enclosure. As shown in Fig.2 (b), the bottom plate is SiCp/Al composite and the enclosure is made of Kovar or titanium alloy, and the two parts are welded together at high temperature to ensure air tightness.

![Figure 2. Schematic diagram of t conventional packaging shell structure.](image)
In order to reduce the weight, reduce the manufacturing difficulty and improve the air tightness of the composite shell, the shell material is designed by layers, with SiCp/Al at the bottom and Si50-Al (50%, mass fraction) at the top, and Si27-Al (27%, mass fraction) as the corresponding cover material. Figure 3 shows the packaging T/R shell using a novel double-layer structure heterogeneous packaging material SiCp/Al+Si/Al.

Figure 3. Schematic diagram of the double-layer structure heterogeneous packaging shell.

2.2. Manufacturing method
As shown in Fig. 4, spray deposition method was used to prepare double-layer ladder packaging materials. Spray deposition technology, as a new development direction in the field of rapid solidification technology, has a history of nearly 50 years. In 1968, Professor A. Singer of Swansea University, UK, first proposed spray atomization rolling technology that is, spraying molten metal onto a rotating deposition roll and directly rotating the deposited blank to the rolling mill to produce sheets.

Figure 4. Schematic diagram of spray deposition technology.

The spray deposition process for preparing Si/Al has been very successful. The molten Al liquid is atomized into a semi-solid/semi-liquid Lake by high-pressure emotional gas and deposited on a rotating disc tube to form a billet. Similarly, by alternating SiC and Si with Al solution, the required double-layer Si/Al ingots can be prepared, which can be further treated by hot isostatic pressing and densification of materials. After the program, the density of the material can reach 99.9%, and there are no holes and cracks. Then it can be used as blank for T/R package shell. The flow chart of the T/R shell manufacture is shown in Fig. 5.
Figure 5. Flow chart of T/R shell manufacturing.

After machining and surface coating, the SiCp/Al+Si/Al blank was made into T/R shell product. As shown in Fig. 6, the double-layer structure of the SiCp/Al+Si/Al shell is very clear and the interface between layers is very straight.

Figure 6. Sample chart of T/R shell.

3. Analysis and discussion
In order to ensure the reliability of spaceborne T/R modules, it is necessary to complete the thermal and mechanical tests on the ground, so mechanical and thermal analysis must be carried out.

3.1. Heat and structure calculation
As shown in Fig. 7, a finite element model was established for mechanical and thermal calculation.

Figure 7. Finite element model.

3.1.1. Heat transfer calculation. The spaceborne T/R module is installed on the instrument board, and it is affected by various space working environments [5, 14]. Temperature is an important factor affecting the operation of T/R module. There is no air in the space. Consequently, T/R heat dissipation
design mainly depends on heat conduction and radiation. The purpose of thermal control design is to ensure that the power chips and high heat flux components of T/R modules have good thermal environment and that they work normally and reliably under the prescribed thermal environment.

The main heating device of T/R module is power amplifier chip. The heat flow path from chip channel to instrument mounting board is: chip channel, solder layer, heat sink layer, solder layer, shell, and instrument board [15], and the temperature rises between each layer are \( \Delta T_1 \), \( \Delta T_2 \), \( \Delta T_3 \), \( \Delta T_4 \) and \( \Delta T_5 \), respectively. Consequently, the maximum temperature rise of the T/R chips can be expressed as,

\[
\Delta T = \Delta T_1 + \Delta T_2 + \Delta T_3 + \Delta T_4 + \Delta T_5
\]

(1)

The thermal analysis results of T/R module are shown in Fig. 8.

As shown in Fig. 8, when the heat consumption of T/R module is 8W, 10W and 20W, the maximum temperature rise of the T/R chip is 59.9, 63.6 and 82.2°C, while the corresponding maximum temperature of Si/Al alloy material is 62°C, 66.3°C and 87.6°C, respectively. The new packaging material can reduce the maximum temperature of T/R module chips. The greater the heat consumption density, the more obvious the effect. When the heat consumption is 20W, the maximum temperature can be reduced by 5.4°C, which meets the first-order reduction requirements of aerospace electronic equipment.

3.1.2. Mechanical analysis. According to the typical spaceborne mechanical appraisal level conditions, simulation analysis is carried out, including stiffness analysis, thermal deformation simulation analysis and so on. The results of modal analysis are presented in Fig. 9. The first six orders are 2573 Hz, 3872.6 Hz, 4245.4 Hz, 5548 Hz, 5878.8 Hz and 7495.8 Hz, respectively. The first-order fundamental frequency is 2573 Hz, which is much higher than 100 Hz, and meets the requirements of spaceborne applications.
In the process of micro-assembly of T/R module, because of the difference of thermal expansion coefficient between LTCC and shell, the welding thermal deformation of T/R module will occur. The bigger the difference of thermal expansion coefficient is, the bigger the thermal deformation is. General design specifications require that the flatness of the installation surface of T/R module is less than 0.1mm. Thermal deformation causes problems such as contact thermal resistance, poor grounding and excessive thermal stress of T/R module. Therefore, according to the finite element model in Fig. 7, the thermal deformation simulation of welding process is carried out, and Fig. 10 shows the evaluation results of two T/R shell schemes. The thermal deformation of Si/Al T/R shell reaches 0.14mm, while that of SiCp/Al+Si/Al T/R shell is only 0.084mm. Compared with Si/Al T/R shell, the flatness of SiCp/Al+Si/Al T/R shell assembly is less than 0.1mm, which has good thermal matching and heat dissipation performance, and can meet the requirements of spaceborne applications.

3.2. Sample test
In order to ensure the reliability of T/R module, it is necessary to test the gas tightness of T/R module, to ensure that the leakage rate of shell meets the requirements. Laser sealing welding of Si50-Al part of assembly shell and Si27-AL cover plate was carried out with LW600 equipment. Fig. 11 shows the microstructure of the welding material and the photograph of the weld seam, and the weld is compact and free of defects such as holes and cracks. The leak detector ULVAC-HELIOT700 of helium mass spectrometry was used to detect the air tightness of T/R module, which is $5\times10^{-8}\text{Pa.m}^3/\text{s}$, and meets the requirements of aerospace applications.
4. Conclusion

The rapid development of spaceborne APAR SAR technology requires high performance packaging materials and structures. The material and structure scheme of double-layer gradient packaging were proposed, and the heat dissipation analysis, mechanical stiffness analysis, welding thermal deformation analysis and calculation were carried out. The results of correlation analysis and test show that:

(a) Double-layer gradient SiCp/Al+Si/Al packaging material was manufactured by spray deposition method. It has good compactness and laser sealing performance and the gas tightness of the T/R module can reach up to $5\times10^{-8}\text{Pa.m}^3/\text{s}$.

(b) Compared with the conventional Si/Al shell, the SiCp/Al+Si/Al T/R module has better heat dissipation performance, higher structural stiffness and smaller thermal deformation in micro-assembly welding process, which can meet the requirements of spaceborne flatness.

(c) SiCp/Al+Si/Al packaging shell has high thermal conductivity, low expansion, machinability and laser sealing. It can meet the increasing application requirements of high-power multi-chip packaging T/R module in aerospace field.

Acknowledgments

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