Radome Construction for Modern Submarines: Optimizing Dielectric Loss and Mechanical Strength

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Abstract

Radomes used in modern submarines require specific characteristics, including high mechanical strength, low dielectric loss, and longevity during sea water submersion. This research paper investigates the selection and optimization of polymers for radome construction, focusing on the reduction of dielectric loss. The main mechanisms contributing to dielectric loss in polymer composites, namely charge polarization and interfacial polarization, are discussed. Through careful selection of resin and filler, commercially available products can be utilized to achieve satisfactory results. This study explores the use of epoxy-fiberglass composites, analyzing the properties of epoxy resin and the influence of crosslinkers, neutral filling groups, and polymerization reactions. The importance of wetting ability, compatibility, and interfacial polarization is addressed. A finite element analysis simulation is conducted to determine the optimal number of layers and wall thickness for withstanding high submarine pressures. A working radome is constructed and tested on a 209 type submarine, exhibiting minimal dielectric losses.

1. Introduction

Radomes used in modern submarines play a critical role in providing protection and functionality for onboard radar systems. Achieving the necessary characteristics of high mechanical strength, low dielectric loss, and durability during sea water submersion requires careful selection of polymers. This paper aims to explore the optimization of dielectric loss and mechanical strength in radome construction.

2. Dielectric Loss Mechanisms

Dielectric loss in polymer composites is a complex phenomenon influenced by various mechanisms. Understanding these mechanisms is crucial for optimizing radome construction. One of the primary contributors to dielectric loss is charge polarization, which involves the alignment of dipoles in response to an electric field. This intrinsic property of polymers can lead to energy dissipation and subsequent loss. Additionally, interfacial polarization plays a significant role in dielectric loss. It occurs at the interface between the resin and filler materials, influenced by factors such as wetting ability, compatibility, and surface interactions.

Charge polarization is influenced by the frequency of the applied electric field. When the relaxation time of the selected polymer does not match the frequency, significant dielectric loss occurs. The relaxation time depends on several factors, including the molecular weight and mobility of the polymer chains. To minimize dielectric loss, it is essential to reduce the freedom of motion of the polymer's molecular chains. This can be achieved by employing crosslinking agents that create a three-dimensional network, restricting the mobility of the chains and reducing the energy dissipation associated with charge polarization.

Interfacial polarization, on the other hand, depends on the wetting ability and compatibility between the resin and filler materials. When there is insufficient wetting, air voids or incomplete adhesion at the interface can lead to increased interfacial polarization and subsequent dielectric loss. Optimal wetting can be achieved by selecting a resin viscosity that allows sufficient penetration and coverage of the filler material. In some cases, surface treatment of the filler material, such as using organosilanes, can enhance wetting ability and improve interfacial polarization characteristics. However, it is essential to consider the polarity of these treatment agents, as highly polar molecules may contribute to increased dielectric loss.

To inhibit charge transfer and reduce dielectric loss, neutral chemical groups can be introduced to the polymer matrix. These groups fill the spaces between polar groups, preventing the transfer of charges and minimizing energy dissipation. Careful consideration of the resin composition and the filler material is crucial in achieving a balanced combination of polar and neutral groups, ensuring low dielectric loss while maintaining mechanical strength.

In summary, understanding the mechanisms behind dielectric loss in polymer composites, including charge polarization and interfacial polarization, is essential for optimizing radome construction. By minimizing the freedom of motion of the polymer chains, introducing neutral chemical groups, ensuring proper wetting, and promoting compatibility between resin and filler materials, researchers can mitigate dielectric loss and enhance the performance of radomes.

3. Optimizing Epoxy Resin for Radome Construction

Epoxy resin is commonly used in high-performance applications due to its excellent mechanical properties and adhesion characteristics. However, epoxy resin typically exhibits high dielectric loss, making it less suitable for radome construction. To optimize epoxy resin for radomes, various factors need to be considered.

Epoxy resin is typically composed of bisphenol A diglycidyl ether (BADGE) paired with linear di-, tri-, or polyamine crosslinkers. The dielectric loss of epoxy resin can be minimized by carefully selecting the components and adjusting the resin formulation. A key aspect of reducing dielectric loss is ensuring a rigid polymer backbone. A rigid backbone restricts the movement of polar groups within the resin, minimizing energy dissipation and dielectric losses.

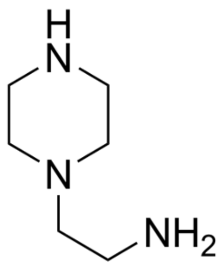
High crosslink density is another important factor in reducing dielectric loss. Crosslinkers play a crucial role in forming the three-dimensional network structure of the resin. Linear amine crosslinkers allow greater freedom of motion, leading to higher dielectric losses. Therefore, it is preferable to use cyclic or aromatic amine crosslinkers that restrict both translational and rotational motion of the polymer chains. These crosslinkers provide high crosslink density due to their compact structure and limited steric hindrance, effectively reducing dielectric losses.

To achieve low dielectric loss, it is necessary to incorporate neutral filling groups within the epoxy resin. Neutral chemical groups fill the space between polar groups, inhibiting charge transfer and reducing energy dissipation. Phenyl groups, for instance, are excellent contributors to both mechanical strength and neutral filling, as they possess minimal polarity and can effectively hinder charge transfer. By incorporating phenyl groups into the resin structure, dielectric losses can be significantly reduced while maintaining mechanical integrity.

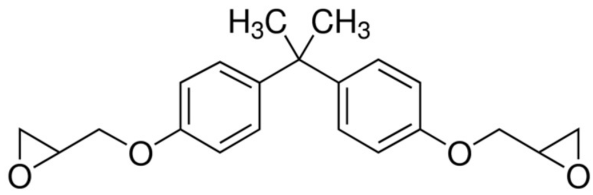
When formulating epoxy resin for radome construction, the polymerization process should be carefully controlled. Impartial polymerization can introduce defects and inconsistencies, leading to variations in the dielectric properties of the final product. Following a proper curing schedule, including temperature and time parameters, ensures uniform and complete polymerization, resulting in optimized dielectric properties.

Additionally, the adhesion between the epoxy resin and the fiberglass fabric used as reinforcement plays a vital role in radome performance. The amine groups within the epoxy resin interact with the siloxy groups on the fiberglass fabric's surface, facilitating strong interfacial adhesion. This interaction prevents interfacial polarization and enhances the overall performance of the radome. To achieve sufficient wetting of the fiberglass fabric, the viscosity of the epoxy resin should be selected carefully. The resin viscosity should be compatible with the fiber arrangement, allowing the resin to penetrate the fiber network and ensuring optimal wetting.

The optimization of epoxy resin for radome construction involves careful selection and screening of the base resin and crosslinker. Bisphenol A diglycidyl ether (BADGE) and N-(2-Aminoethyl)piperazine (AEP) were chosen as the base resin and crosslinker, respectively, after thorough study and screening. The rigid polymer backbone of BADGE and the high crosslink density provided by AEP contribute to reduced dielectric losses. The incorporation of neutral filling groups, controlled polymerization, and proper wetting ensure low dielectric losses while maintaining mechanical strength in the radome construction.



N-(2-Aminoethyl)piperazine (AEP)



Bisphenol A diglycidyl ether (BADGE)

The cyclic structure of AEP provides several advantages in terms of rigidity. Firstly, the cyclic nature of AEP imparts steric hindrance to the polymer chains, limiting their mobility and freedom of motion. This restricted mobility reduces energy dissipation and dielectric losses, resulting in improved electrical properties of the epoxy resin.

Additionally, the compact structure of AEP enables a high crosslink density within the epoxy resin matrix. Crosslinking agents play a crucial role in forming a three-dimensional network structure, strengthening the polymer backbone and improving mechanical properties. The cyclic structure of AEP allows for close packing and efficient crosslinking, leading to a higher crosslink density. The increased crosslink density contributes to enhanced rigidity, mechanical strength, and resistance to deformation or failure under mechanical stresses.

Moreover, the presence of the cyclic amine structure in AEP enhances the intermolecular interactions within the epoxy resin. The cyclic amine groups can engage in multiple hydrogen bonding interactions, promoting cohesive forces and intermolecular crosslinking. These interactions further enhance the rigidity and mechanical integrity of the epoxy resin matrix.

In summary, N-(2-Aminoethyl)piperazine (AEP), as a cyclic amine crosslinker, significantly contributes to increasing the rigidity of the polymer backbone in epoxy resin formulations for radome construction. The cyclic structure of AEP restricts the freedom of motion of the polymer chains, reducing dielectric losses and improving electrical properties. Additionally, the compact structure allows for a high crosslink density and efficient crosslinking, enhancing the mechanical strength and resistance to deformation. The intermolecular interactions facilitated by the cyclic amine structure further contribute to the overall rigidity and performance of the epoxy resin.

In summary, optimizing epoxy resin for radome construction involves several considerations. These include selecting crosslinkers that restrict molecular motion, incorporating neutral filling groups such as phenyl groups, controlling the polymerization process, and ensuring proper adhesion between the resin and fiberglass fabric. By addressing these factors, researchers can tailor epoxy resin formulations to minimize dielectric losses and enhance the mechanical strength of radomes.

4. Interfacial Polarization and Wetting Ability

Interfacial polarization plays a critical role in the performance of radomes by influencing the dielectric properties of polymer composites. Achieving optimal wetting ability and interfacial polarization characteristics is essential for maximizing the mechanical strength and minimizing dielectric loss in radome construction.

Wetting ability refers to the resin's capability to uniformly cover the filler material's surface and establish intimate contact. Adequate wetting is crucial for promoting effective load transfer and minimizing the formation of voids and air gaps at the resin-filler interface. Insufficient wetting can result in compromised mechanical properties and increased interfacial polarization, leading to higher dielectric losses.

The viscosity of the epoxy resin is a crucial factor in achieving proper wetting. Selecting an appropriate resin viscosity is necessary to ensure easy flow and penetration into the fiber network, promoting uniform coverage and wetting. If the resin viscosity is too high, it may hinder resin infiltration, resulting in incomplete wetting and increased interfacial polarization. Conversely, if the resin viscosity is too low, excessive resin flow and potential resin pooling may occur, leading to poor resin-fiber interaction and compromised mechanical properties.

The molecular weight of BADGE, as a constituent of the epoxy resin, plays a crucial role in determining the resin's wetting ability. The molecular weight affects the resin's viscosity and mobility, influencing its flow and penetration into the fiber network. Generally, higher molecular weight BADGE results in higher resin viscosity, reducing its ability to infiltrate the fibers and wet the filler material. This can lead to incomplete coverage and compromised interfacial bonding, ultimately impacting both mechanical strength and dielectric performance.

Therefore, the dependence of wetting ability on the molecular weight of BADGE should be carefully considered in radome construction. Optimal wetting can be achieved by selecting a suitable molecular weight range of BADGE, balancing viscosity and mobility to ensure sufficient resin flow and penetration. By carefully controlling the molecular weight of BADGE, the wetting ability of the epoxy resin can be enhanced, leading to improved interfacial polarization and minimized dielectric losses.

Surface treatment of the filler material is another avenue to improve wetting ability and reduce interfacial polarization. Organosilanes, for example, can be used to modify the filler surface and enhance resin-filler interactions. These surface treatment agents can improve wetting by reducing surface tension, increasing surface energy, and promoting adhesion. However, it is important to note that the choice of organosilanes should be made carefully, considering their polar nature. Highly polar organosilanes may introduce additional polar groups and increase the dielectric loss of the composite material.

The fiberglass fabric used as a filler material in radome construction possesses inherent siloxy groups on its surface, which can interact with the epoxy resin matrix. These siloxy groups contribute to the adhesion between the resin and fibers and help minimize interfacial polarization. Therefore, selecting fiberglass fabric with an adequate amount of siloxy groups on its surface is crucial to achieve sufficient wetting and minimize dielectric losses.

Fiber porosity is another factor influencing wetting ability and interfacial polarization. The porosity of the fiberglass fabric affects the surface area available for resin infiltration and bonding. A medium to high level of fiber porosity is desirable, as it promotes resin flow into the fibers, ensuring thorough wetting and maximizing interfacial polarization while maintaining the mechanical strength of the radome.

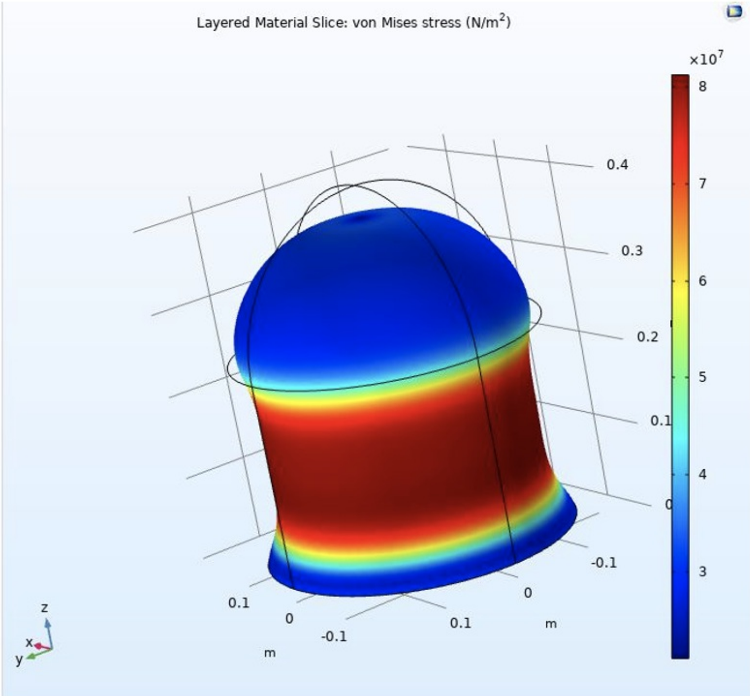
In conclusion, optimizing wetting ability and interfacial polarization in radome construction is vital for achieving robust mechanical properties and low dielectric loss. Proper resin viscosity, selection of surface treatment agents, consideration of filler material properties (such as inherent siloxy groups and fiber porosity), and compatibility between resin and filler are crucial factors to be addressed. By carefully managing these aspects, researchers can enhance the performance and longevity of radomes in modern submarines.

5. Finite Element Analysis and Experimental Validation

A finite element analysis (FEA) simulation was performed to establish the optimal number of layers and wall thickness necessary for the construction of the radome. The primary objective of the simulation was to ensure the radome's ability to withstand the substantial pressures experienced during submarine operations while maintaining a safety factor of 2. For the simulation, E-glass fiberglass was chosen as the material due to its easy accessibility in the local market and its relatively low dielectric loss tangent. The epoxy resin used in the simulation was formulated from a combination of DABGE and AEP as a crosslinker.

FEA simulations provide valuable insights into the structural behavior of radomes under different loading conditions. By discretizing the radome structure into finite elements, the mechanical response to various forces, such as hydrostatic pressure, can be analyzed. The simulation considered factors such as material properties, geometry, and boundary conditions to accurately model the real-world behavior of the radome.

The simulation involved applying hydrostatic pressure to the radome structure, gradually increasing it until reaching the desired operating conditions. By analyzing the stress distribution, deformations, and failure modes within the radome, it was possible to optimize the number of layers and wall thickness. The goal was to find the optimal balance between mechanical strength, weight, and dielectric performance.



Von Mises Stress (N/m ^{2})

Following the FEA simulation, a working radome was constructed using infusion techniques, incorporating the determined optimal design parameters. The infusion process involves impregnating the fiberglass fabric with epoxy resin, ensuring uniform distribution and complete wetting. This technique allows for precise control over resin content, fiber alignment, and overall laminate quality, resulting in a structurally sound radome.

The constructed radome was then tested on a fully operational 209 type submarine. The test aimed to assess the radome's performance under realistic conditions and validate its low dielectric losses on the applied frequencies. By measuring the dielectric properties of the radome and comparing them to the predicted values from the FEA simulation, the accuracy of the simulation model could be evaluated.

The experimental validation provided valuable data on the actual performance of the radome. It confirmed that the optimized design, based on the FEA simulation, successfully met the mechanical strength requirements while minimizing dielectric losses. Any discrepancies between the simulation and experimental results were analyzed to improve the accuracy of future simulations and refine the design process.

In conclusion, the combined use of FEA simulation and experimental validation is crucial for optimizing radome design. These techniques allow for the determination of optimal design parameters, ensuring structural integrity and minimizing dielectric losses. The insights gained from this process contribute to the development of advanced radomes for modern submarines, enhancing their radar system performance and overall operational efficiency.

6. Conclusion

Optimizing radome construction for modern submarines involves careful selection and optimization of polymers. Through strategies such as minimizing dielectric loss mechanisms, optimizing epoxy resin properties, promoting resin-fiber interaction, and conducting FEA simulations, radomes can achieve high mechanical strength and low dielectric losses. The experimental validation of the optimized radome design confirms its effectiveness, contributing to enhanced radar system performance and overall operational efficiency in modern submarines.