Digital Technologies for Monitoring the Dielectric Properties of Carbon-Carbon Composites

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Abstract**:** The paper discusses the implementation of digital technologies in monitoring the dielectric properties of carbon-carbon composites. It is shown that real-time measurement of complex dielectric permittivity enables control of key parameters during graphitization, pyrolysis, and impregnation processes. The integration of dielectric spectroscopy methods with automated control and digital modeling systems is substantiated, ensuring adaptability and accuracy of modern manufacturing processes.

Keywords**:** digital technologies, monitoring, dielectric permittivity, CCCM, automation.

I. INTRODUCTION

Modern high-tech materials manufacturing requires monitoring methods capable of tracking dynamic changes in the structure and properties of materials in real time. Each material is characterized by a specific set of electrophysical properties, which are largely determined by its dielectric behavior. The electrical parameters of materials are generally described in terms of electrical conductivity and dielectric permittivity. Conductivity reflects the ability of a material to conduct electric current and is directly related to its specific electrical resistance. At the same time, dielectric permittivity quantitatively characterizes the degree of polarization induced in the material under the influence of an applied alternating electric field. This parameter is one of the key factors that determine the electromagnetic, thermophysical, and electrochemical behavior of a material.

For carbon-carbon composites (CCCM), monitoring dielectric properties is of particular importance, as they serve as indicators of microstructural changes, phase transitions, impregnation level, and the degree of graphitization. Dielectric properties, especially the complex dielectric permittivity, are highly sensitive to thermal, electromagnetic, and chemical factors.

Therefore, they form the basis for building automated control systems for technological processes, since they provide objective feedback directly during material processing. One of the key directions of development is the integration of dielectric spectroscopy methods into digital monitoring systems.

II. MODELING AND ANALYSIS OF THE OBTAINED RESULTS

Monitoring dielectric properties during the production of CCCM is an effective tool for controlling the key technological parameters of the process. This enables real-time regulation of temperature, pressure, heating rate, and impregnation parameters, ensuring increased stability, reproducibility, and, as a result, high final material quality. The use of dielectric observation methods provides a deeper understanding of the physicochemical changes occurring inside the composite structure, thereby contributing to the optimization of technological solutions.

The complex dielectric permittivity $\varepsilon^{*}(\omega)$ is a function of the frequency of the applied electric field and is calculated as follows:

$$\varepsilon^{*}(\omega) = \varepsilon^{'}(\omega) - j\varepsilon^{''}(\omega),$$

where $\varepsilon^{'}(\omega)$ – the real part, which characterizes the ability of the material to accumulate electrical energy;

$\varepsilon^{''}(\omega)$ – the imaginary part, associated with thermal energy losses in the material.

The use of high-frequency measurement systems makes it possible to register both the real and imaginary components of permittivity, which respectively reflect the energy storage capacity of the material and the level of losses. The obtained frequency and temperature dependencies allow real-time identification of relaxation processes, interfacial polarization, and structural transformations that critically affect the quality of the final product.

One of the critical technological parameters is the temperature gradient, which directly affects the direction and intensity of structural formation. A high gradient promotes the development of an ordered, anisotropic structure with improved thermal conductivity, but its excessive increase can induce internal thermal stresses and microcracks. Continuous monitoring of dielectric properties enables tracking the uniformity of material heating and timely adjustment of the temperature field, thus preventing local defects.

The maximum processing temperature is another key parameter regulating the degree of graphitization, final porosity, and electrical conductivity of the composite. To achieve the necessary structural transformation, the temperature is typically set in the range of 1600-2200°C. Insufficient heating results in the preservation of the amorphous phase, whereas exceeding the optimal level may cause excessive shrinkage or structural degradation. Changes in the imaginary component of the complex dielectric permittivity serve as a reliable indicator of structural transformation stages, providing accurate determination of the completion of graphitization.

Furthermore, heating and cooling rates require automated regulation, as rapid thermal changes may cause residual stresses and structural defects. Slow temperature elevation ensures uniform shrinkage and contributes to the stabilization of the internal structure, while real-time dielectric monitoring enables the prompt identification of phase transitions accompanied by changes in polarization mechanisms, thereby allowing adaptive correction of the temperature profile according to the current state of the sample.

The study of dielectric properties of carbon–carbon composites is highly relevant in the context of monitoring structural changes during their production, particularly under thermogradient processing and multistage impregnation. At low frequencies (50 Hz - 1 MHz), the most suitable methods are those that account for the complex heterogeneous nature of composites, particularly interfacial effects. One of the most effective approaches to modelling the dielectric permittivity of such materials is the generalized Maxwell-Wagner model, which represents a development of the interfacial polarization theory applied to porous, layered, and multiphase systems. In this framework, the complex dielectric permittivity is described as a function of the frequency of the applied electric field:

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\Delta\varepsilon}{1 + j\omega\tau},$$

where ε_∞ – high-frequency dielectric permittivity, which reflects instantaneous polarization (electronic and atomic);

$\Delta\varepsilon$ – dielectric relaxation strength, or the dispersion amplitude, equal to the difference between the static and high-frequency dielectric permittivities;

τ – relaxation time, which characterizes the period required for polarization equilibrium to be established after a change in the electric field.

A characteristic temperature dependence of the real and imaginary parts of the complex dielectric permittivity for CCCM, modeled using the Maxwell-Wagner model in the temperature range of 600-1600°C at a frequency of 1 GHz, is shown in Fig. 1.

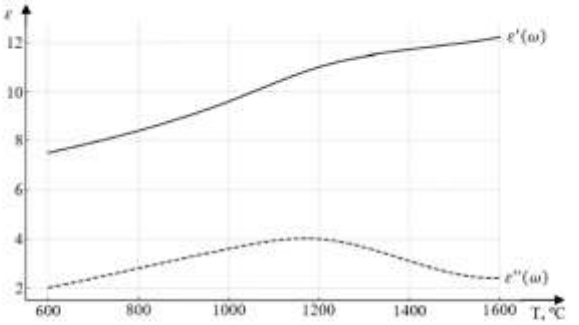

Fig. 1 – Temperature dependence of the real and imaginary parts of the complex dielectric permittivity of CCCM

Analysis of the experimental data shows that, with increasing temperature, the real part of the complex dielectric permittivity increases monotonically. This trend directly correlates with an increased degree of graphitization of the material, reduced porosity, and improved structural ordering. At the same time, the imaginary part of the dielectric permittivity demonstrates a pronounced relaxation maximum in the temperature range around 1200°C. This peak indicates intense relaxation processes associated with phase transitions or deep structural rearrangements, including the removal of residual volatile components, local deformations, or changes in the topology of the porous network. Such behavior is typical of heterogeneous composite systems, where interfacial polarization and heterogeneity of conductive properties cause significant dielectric losses at specific critical temperatures.

The information obtained from *ε'(T)* and *ε''(T)* can be used as an informative indicator for monitoring internal changes in the material during heat treatment. In particular, stabilization of ε′ at high temperatures signals the achievement of a saturated state of graphitization, while local peaks of ε″ allow the identification of temperature ranges in which relaxation or diffusion processes occur.

These functional dependencies can be integrated as a feedback element into automated control systems for the heat treatment of highly loaded composite materials. Such an approach ensures improved final material quality by accurately regulating the temperature profile, optimizing impregnation modes, and minimizing the likelihood of structural defects.

An important component of digital monitoring is the use of mathematical models. Among them, the Maxwell-Wagner model, which describes interfacial polarization in heterogeneous systems, and the Maxwell-Garnett model, which allows evaluation of porosity effects on effective dielectric permittivity, hold special importance. Using these models in combination with experimental data provides a high level of predictive reliability and enables optimization of processing parameters.

Digital technologies make it possible to integrate diagnostic results into automated control systems. The combination of microwave probes, induction heating, and software-based regulation creates conditions for adaptive control of graphitization and pyrolysis processes. This allows timely adjustment of temperature, heating rate, pressure level, and other parameters that affect CCCM microstructure formation.

III. CONCLUSION

The application of digital monitoring technologies has several advantages. First, it ensures continuous control and enables prompt response to any deviations. Second, such integration improves the accuracy and reproducibility of material characteristics. Third, it creates prerequisites for the use of intelligent control algorithms, including artificial intelligence, capable of analyzing large datasets and making optimal decisions without operator involvement.

The results confirm that digital monitoring of dielectric properties is an effective tool for ensuring high-quality CCCM. These technologies can be used both for real-time control and for verification of numerical models applied in the design of technological regimes. This makes them highly promising for widespread implementation in the manufacturing processes of instrumentation, aerospace, and energy industries.

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