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Метод динамической решетки для бесконтактной диагностики материалов: измерение теплопроводности

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Аннотация. С непрерывным развитием промышленности и технологий растет спрос на точное измерение тепловых свойств материалов. Традиционный стационарный метод не смог удовлетворить потребности современной промышленности и научных исследований из-за длительного времени измерения и сложной эксплуатации. Как новая бесконтактная измерительная технология, метод динамической сетки показал большой потенциал в области измерения теплопроводности материалов благодаря своей высокой эффективности и точности. В этой статье будут подробно представлены основные принципы, экспериментальные устройства и этапы, методы обработки и анализа данных метода динамической сетки, а также продемонстрирован эффект его применения при измерении теплопроводности материалов на реальных примерах. Наконец, обсуждаются преимущества и ограничения этого метода, а также прогнозируется будущее направление развития.

Ключевые слова: метод динамической сетки, теплопроводность, бесконтактное измерение, диагностика материалов.

Dynamic grating method for contactless material diagnosis: measurement of thermal conductivity

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Abstract. With the continuous development of industry and technology, the demand for accurate measurement of thermal properties of materials is increasing. The traditional steady-state method has been unable to meet the needs of modern industry and scientific research due to its long measurement time and complex operation. As an emerging non-contact measurement technology, the dynamic grid method has shown great potential in the field of material thermal conductivity measurement due to its high efficiency and accuracy. This paper will introduce the basic principles, experimental devices and steps, data processing and analysis methods of the dynamic grid method in detail, and demonstrate its application effect in material thermal conductivity measurement through actual cases. Finally, the advantages and limitations of this method are discussed, and the future development direction is prospected.

Keywords: dynamic grid method, thermal conductivity, non-contact measurement, material diagnosis.

1. Introduction

Thermal conductivity is an important physical parameter for measuring the thermal conductivity of materials, which is of great significance for optimizing material design and improving energy efficiency. Traditional thermal conductivity measurement methods, such as the steady-state plate method and the hot wire method, have high accuracy, but have disadvantages such as long measurement time and complex operation. In recent years, with the rapid development of optical technology and computer technology, non-contact measurement technology has gradually emerged. As one of them, the dynamic grid method has attracted widespread attention with its unique advantages.

2. Basic principles of the dynamic grid method

Heat conduction is the process of heat transfer by the thermal motion of microscopic particles inside a substance, which follows Fourier's law of heat conduction. According to this law, the amount of heat passing through a unit area per unit time is proportional to the temperature gradient, and the proportional coefficient is the thermal conductivity of the material. The dynamic grid method is based on this principle and measures the temperature change on the surface of the material to infer its thermal conductivity.

The dynamic grid method uses a periodically changing heat source (such as a laser or electron beam) to form a dynamic temperature field on the surface of the material, namely a "grid". The change of the surface temperature of the material over time is recorded by a high-precision infrared camera or thermal imager, and then the propagation characteristics of the temperature wave are analyzed to calculate the thermal conductivity of the material. This method has the advantages of non-contact, fast, and accurate, and is particularly suitable for objects that are difficult to measure by traditional methods such as high temperature, corrosive environment, or soft and fragile materials.

3. Experimental device

3.1 Experimental device

The figure 1 shows a laser optical complex developed by the Institute of Physics of the National Academy of Sciences of Belarus, which mainly includes:

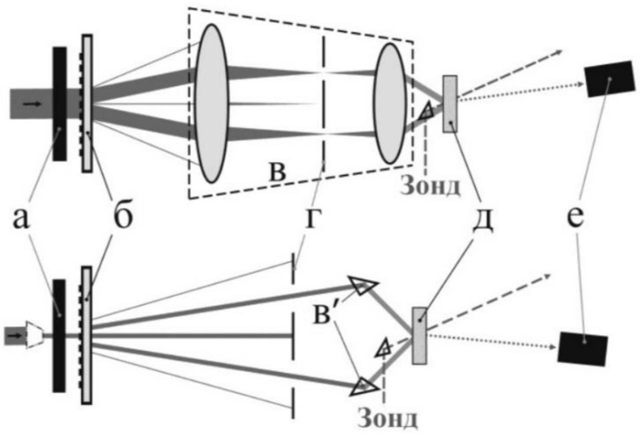

Figure 1. Optical diagram of the Optopicotest complex: а – attenuator; б – beam splitter;в – telescope; в' – rotating prisms; г – spatial filter; д – sample; е – photodetector.

3.1.1. Heat source system

The heat source system of the dynamic grid method usually uses high-energy lasers or electron beams to generate high-intensity, short-pulse heat fluxes to form a rapidly changing temperature field on the surface of the material. The laser source has the advantages of high energy density, adjustable beam quality, and short action time, and is suitable for thermal conductivity measurement of various materials.

3.1.2. Temperature measurement system

Temperature measurement is a key link in the dynamic grid method, and infrared thermal imagers or high-speed thermocouple arrays are usually used as temperature sensors. Infrared thermal imagers can capture the temperature distribution on the surface of the material in real time, and have the advantages of non-contact, fast response speed, and high spatial resolution. High-speed thermocouple arrays can provide higher time resolution and measurement accuracy, and are suitable for measuring rapidly changing temperature fields.

3.1.3. Data acquisition and control system

The data acquisition and control system is responsible for synchronously controlling the work of the heat source, temperature measurement system, and data acquisition equipment to ensure the accuracy and repeatability of the experimental process. The system usually includes high-speed data acquisition cards, multi-channel temperature collectors, and professional control software, which can realize real-time acquisition, storage, and processing of experimental data.

3.2. Experimental parameter setting

According to the characteristics of the sample and the experimental requirements, set the parameters such as the power, pulse width, and repetition frequency of the heat source, as well as the sampling frequency and exposure time of the temperature measurement system. Ensure the rationality and feasibility of the experimental parameters to avoid damage to the sample or affect the accuracy of the measurement results.

4. Data processing and analysis methods

By performing waveform analysis on the temperature data recorded by the temperature measurement system, the amplitude, period, phase and other information of the temperature wave can be extracted. This information is crucial for calculating the thermal conductivity of the material. For example, the thermal diffusion coefficient of the material can be inferred by analyzing the attenuation rate of the temperature wave, and then the thermal conductivity can be calculated. In order to more accurately analyze the propagation characteristics of the temperature wave, the temperature data can be Fourier transformed from the time domain to the frequency domain. In the frequency domain, the frequency components and amplitude distribution of the temperature wave can be more intuitively observed, so that the thermal conductivity of the material can be calculated more accurately. In addition, Fourier transform can also be used to filter out noise signals and improve the signal-to-noise ratio of the measurement results.

In the simplest case, the material can be assumed to be a one-dimensional semi-infinite object, ignoring the influence of boundary conditions. According to the Fourier heat conduction law and the principle of the dynamic grid method, the relationship between the thermal conductivity of the material and the propagation velocity of the temperature wave can be derived. By measuring the propagation velocity of the temperature wave, the thermal conductivity of the material can be calculated.

For actual materials, two-dimensional or three-dimensional heat conduction effects are often required. At this time, numerical simulation methods such as the finite element method or the boundary element method can be used to solve the heat conduction equation. By simulating the temperature field distribution and temperature wave propagation process under different boundary conditions, the thermal conductivity of the material can be calculated more accurately. However, these methods require higher computing resources and complex algorithm design.

5. Advantages and limitations of the dynamic grid method

The dynamic grid method adopts a non-contact measurement method, which avoids the thermal contact resistance problem that may occur in the traditional contact measurement method and improves the accuracy and reliability of the measurement. At the same time, non-contact measurement also reduces the risk of damage to the sample, and is particularly suitable for objects that are difficult to directly contact and measure, such as high temperature, corrosive environment or soft, fragile materials.

The dynamic grid method calculates the thermal conductivity of the material by measuring the propagation speed of the temperature wave, without waiting for the system to reach a steady state for a long time. Therefore, this method has the advantages of short measurement time and high efficiency, and is particularly suitable for occasions where a large number of samples need to be quickly tested.

The dynamic grid method is not only suitable for the thermal conductivity measurement of solid materials (such as metals, ceramics, plastics, etc.), but also for the study of the thermal properties of fluid materials such as liquids and gases. In addition, this method can also be extended to the evaluation of the thermal conductivity of complex structures such as multilayer composite materials and coating materials.

The dynamic grid method requires precise control of the heat source parameters and the performance indicators of the temperature measurement system to ensure the accuracy and reliability of the experimental results. In addition, this method also has high requirements for the experimental environment (such as temperature, humidity, airflow, etc.), and corresponding measures need to be taken for stable control.

The amount of data generated by the dynamic grid method is large and complex, and requires fine processing and analysis to obtain accurate measurement results. This increases the difficulty and calculation cost of data processing, and places high demands on the professional quality and skill level of the experimenters.

Although the dynamic grid method has wide applicability, there are still certain limitations on its scope of application. For example, for some special materials (such as strong magnetic materials, highly conductive materials, etc.) or materials under extreme conditions (such as ultra-high temperature and ultra-low temperature environments), this method may not be directly applied or require special improvements.

6. Conclusion and Prospect

As an emerging non-contact measurement technology, the dynamic grid method has shown great potential and application prospects in the field of material thermal conductivity measurement. This paper introduces in detail the basic principles, experimental devices and steps, data processing and analysis methods, and application case analysis of the dynamic grid method, and points out the advantages and disadvantages of this method compared with traditional methods through comparative analysis. Studies have shown that the dynamic grid method has the advantages of non-contact measurement, fast and efficient, and wide applicability, but it also has limitations such as high requirements for experimental conditions, complex data processing, and limited scope of application. Therefore, in practical applications, it is necessary to select a suitable measurement method according to specific measurement needs and conditions.

In the future, with the rapid development of optical technology, computer technology, and materials science, the dynamic grid method is expected to make further breakthroughs and improvements in the following aspects: first, improve the performance and stability of the experimental device; second, optimize the data processing algorithm and model; third, expand the application field and scope; fourth, strengthen the integration and innovation with other measurement technologies. It is believed that with the continuous progress and development of science and technology, the dynamic grid method will play a more important role in the field of material thermal conductivity measurement and provide strong support for research and industrial applications in related fields.

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