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CORRELATION BETWEEN THE FRACTAL DIMENSION OF SURFACE TEXTURE AND ITS LASER SPECKLES AS THE BASIS FOR A NON-CONTACT METHOD FOR ANALYZING CERAMIC MATERIALS

A quantitative relationship between the fractal dimension of the ceramic surface texture obtained by optical microscopy and the fractal dimension of the corresponding laser speckle field was studied. A low sensitivity of speckle analysis for defocus has been identified, which simplifies the control procedure. Analysis of homogeneous samples revealed statistically significant differences in the fractal characteristics of the images of the two types of ceramics, confirming the possibility of using them to identify materials and detect defects. In the case of a layered ceramic sample, fractal analysis of speckle paintings clearly reflected its structure, indicating the potential of the method for non-destructive layering and homogeneity testing. The demonstrated robustness of the approach highlights its metrological reliability and opens up prospects for its integration into standardized schemes of quality control, ensuring consistent and reproducible assessment of structural integrity in ceramic manufacturing. Prospects for further research are associated with the development of simplified optical speckle analysis schemes for the creation of portable systems for express quality control of ceramic products.

K e y w o r d s : *optical microscopy, laser speckles, microrelief, fractal dimension, ceramic surface, layered ceramic system.*

AMS 2020 classification: 78A45, 78A55.

Introduction

With the development of modern technologies in such key industries as aviation, astronautics, medicine and energy, the need for materials with improved performance characteristics is constantly growing. In this context, ceramic materials, due to their exceptional hardness, high thermal resistance and chemical inertness, open up broad prospects for application in extreme conditions.

Among ceramic materials, layered ceramic composites are of particular interest, demonstrating significant potential in applications requiring high strength and durability (Minatto et al., 2015). Their unique architecture using specially designed weak interfacial layers is key to effective damage localization. Interfacial layers, such as those based on boron nitride (BN), promote crack deflection and delamination, preventing catastrophic failure (Ahmad et al., 2025; Chen et al., 2022) and enhancing the performance of the composite.

Bulk properties of ceramic materials, determined by the conditions of synthesis and processing, are reflected in the microstructure of the surface, the set of parameters of which determines its texture (Bowman, 1994; Behera et al., 2021). Although this relationship is often complex and nonlinear, and its analytical description poses a significant problem, it is this correlation that opens up promising opportunities for the development of non-destructive methods for studying the internal structure and properties of materials by analyzing their surface.

Traditional methods of analyzing the texture of microrough surfaces based on optical microscopy are well developed and provide high resolution. However, their application is often associated with the need for precise positioning of the sample relative to the optical system, which significantly limits the possibility of rapid screening analysis. In addition, the contact nature of some microscopic techniques and the complexity of integration into technological lines make it impossible to conduct studies in real time, for example, during the processes of forming or processing of the materials under study. Therefore, there is a need to develop new, non-contact and operational methods for determining surface characteristics. One of the possible effective solutions is the use of coherent optics methods, in particular, speckle surface microscopy.

In our previous work (Yakunov, & Sachko, 2024) it has been demonstrated that the analysis of laser speckles – characteristic spotty structures that arise from the interference of coherent light waves scattered by microscopic inhomogeneities of a rough surface – is an effective approach for studying key surface parameters. It has been shown that the statistical characteristics of the speckle field carry information about such important surface properties as its roughness, anisotropy and other spatial correlation parameters.

The aim of this study is to establish a quantitative relationship between the fractal dimension of the ceramic surface texture obtained using optical microscopy and the fractal dimension of the corresponding laser speckle field. Fractal dimension was chosen as the most physically justified texture parameter, since it is closely related to surface roughness and is able to effectively quantitatively describe complex microreliefs of ceramics, and on the other hand, it adequately describes images with large-scale self-similarity, to which laser speckles belong. Considered potential opportunities speckle microscopy for determining layer boundaries and assessing the homogeneity of the structure in layered systems.

1. Surface texture and bulk properties of materials

Surface texture, determined by a set of micro-irregularities of different scales and orientations, is in many cases a direct reflection of the bulk properties of the material, which are formed at the stages of its synthesis, processing, and operation. Micro- and nanorelief of the surface carries information about the crystalline structure, phase composition, presence of defects, mechanical stresses and other internal characteristics of the material. Thus, detailed analysis of textural parameters provides the possibility of non-destructive study of bulk properties, opening up prospects for quality control, prediction of material behavior and development of new technological processes with specified surface characteristics. (Bunge, 2013).

Fractal methods are an effective tool for modeling rough surfaces, as they are able to adequately reflect their hierarchical organization and statistical characteristics (Militký, & Bajzík, 2001; Nayak et al., 2019). Fractal dimension, as a measure of the complexity and self-similarity of an object at different scales, quantifies the degree of roughness and spatial filling of rough surfaces. It is calculated by various methods, such as the box-counting method, structural function method or radial basis function method, which analyze the change in surface characteristics with a change in the observation scale. Formally, higher fractal dimension correlates with greater surface roughness, as it indicates the presence of finer details and a more complex hierarchical structure of the microprofile.

Scattering of coherent laser radiation on a rough surface leads to interference of secondary waves and formation of a speckle pattern, which also demonstrates signs of large-scale self-similarity. Despite the complexity and non-obviousness of the direct connection between the fractal dimension of a rough surface and its speckle field, experimental studies confirm the existence of a statistically significant correlation between these characteristics. (Li et al., 2006; Shao et al., 2023; Souza et al., 2021). This opens the prospect of non-contact estimation of surface roughness by analyzing the statistical properties of the corresponding laser speckles.

2. Materials and methods

The work investigated homogeneous composite materials and multilayer structures based on them. Two types of composites were synthesized, differing in the excess content of boron carbide (hereinafter referred to as sample A) or titanium carbide (sample B). Multilayer samples (C) were formed from the two specified composite systems, separated by a graphite layer, which was formed during the reactive hot pressing process and functioned as a weak interface for crack deflection. Detailed way sintering samples covered in the previous the work of one of the authors (Ovcharenko, Dibrov, & Semenko, 2024).

The study was conducted on samples in the form of cylindrical tablets with a diameter of 10 mm. Each sample was fixed on the microscope stage and sequentially illuminated by two sources: a white light LED lamp (for visualization of the surface microstructure) and a helium-neon laser (for formation of a speckle pattern from the same place on the surface). Laser radiation was directed to the sample surface at an angle of incidence of about 40°. The area on the sample surface illuminated by the laser beam, which formed the speckle pattern, had the shape of an ellipse, which, when visualized through the microscope objective with a 10-fold magnification, occupied the central part of the field of view. Registration of the surface microrelief and the corresponding speckle pattern was carried out by a digital camera with a resolution of 1024 x 768 pixels. The central rectangular area of the image measuring 340 x 250 pixels was characterized by an almost uniform distribution of illumination intensity both for visualization of the microrelief and for registration of the speckle pattern (Fig. 1). Optimization of exposure parameters and other camera settings, as well as conversion of color images into 8-bit format with 256 gray levels, were performed using specialized software. These procedures were aimed at obtaining images with optimal qualitative and informative characteristics necessary for further analysis.

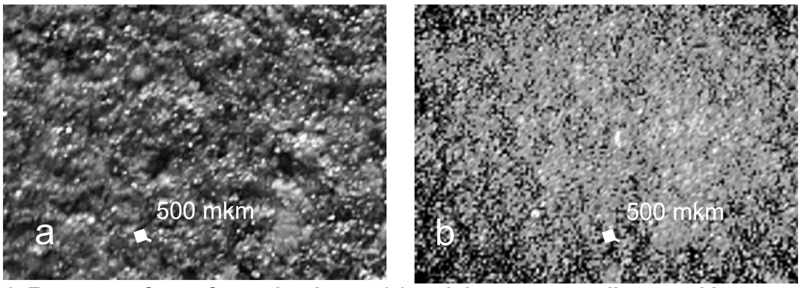

Fig. 1. Fragment of a surface microimage (a) and the corresponding speckle pattern (b)

The fractal dimension of the surface microrelief images and the corresponding speckle patterns was determined using the *ImageJ* program with specialized plugins. To verify the obtained results, the original software developed by the authors was used in parallel, which did not provide for any image preprocessing procedures. The comparative analysis showed the general consistency of the values of the fractal dimension of the microimages obtained by both methods. At the same time, certain discrepancies were observed in the values of the fractal dimension of the speckle patterns, which may be related to the specifics of their structure and the potential loss of information due to preprocessing. The numerical values given below were obtained using the original software.

□

3. Results and analysis

At the previous stage of research, the influence of the accuracy of microscope focusing on the values of fractal dimensions of microimages and corresponding speckle patterns was analyzed. Experiments were carried out using flat surface of one of samples. Figure 2 illustrates dependence fractal dimensions microscopic images and corresponding speckle structures from degree defocus optical systems that varied in steps of 40 μm.

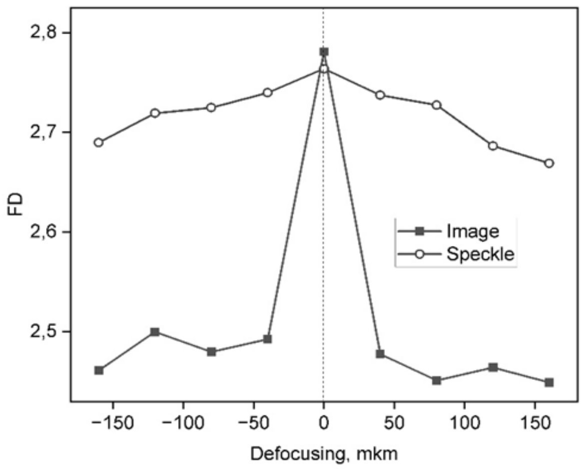

Fig. 2. Dependence of the fractal dimension of the microimage and the corresponding speckle pattern on the defocus value

Received results showed that for microimages indicated dependence characterized by sharp maximum, which corresponds to the optimal focusing condition. Even insignificant deviation leads to significant reduction value fractal dimensions. Further increase in defocus does not cause significant changes to this parameter, which probably reflects integral characteristics of the blurred surface, irregularities lighting and noise recording device.

In contrast this, similar dependence for speckle images demonstrates weak sensitivity fractal dimensions to defocusing.

With precise focusing observed minor local maximum, which can be associated with the modulation of the speckle picture by the surface relief With increase defocus this modulation disappears, and the fractal dimension speckle paintings slightly decreases. Such behavior consistent with the physical principles of formation speckle pattern where the maxima interference form elongated three-dimensional areas. Their cross-section by any plane forms the same two-dimensional distributions of illumination, the differences between which are mainly in scale coefficients.

At the main stage experimental research was two homogeneous samples (A, B) and one five-layer (C) were analyzed. For each of the homogeneous samples 20 measurements were taken fractal dimensions by two opposite flat surfaces (conditionally labeled as top and bottom). Five-layer sample was scanned along its lateral cylindrical surface with a step of 0.5 mm.

Figure 3 shows the results in the form of a scatter plot. Each point corresponds to a specific area of the surface of one of the samples and represents a pair of fractal dimensions of the microscopic image and the corresponding speckle picture. Statistical analysis shows that all the points that respond sample A, form single cluster with high density. Data for the sample B, obtained from different its surfaces, form two close clusters that may be due to different quality processing these surfaces. However, at the same time, a slight difference does not significantly affect the overall picture.

Clearly traced statistically significant excess average value fractal dimensions of both microimages and speckle patterns of the sample B comparatively from sample A.

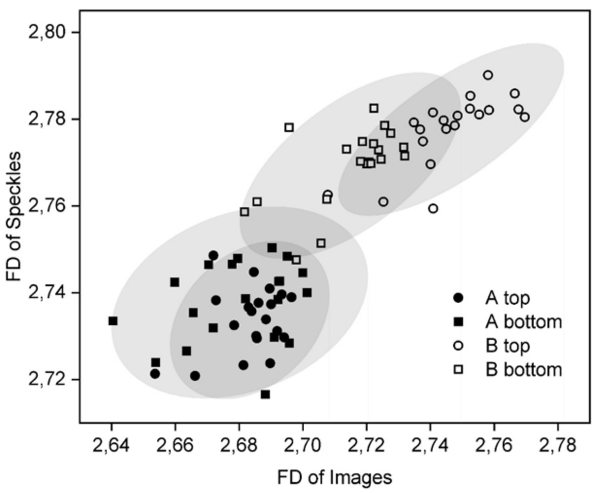

Fig. 3. Scatter plot of fractal dimension of microimage (abscissa axis) and speckle (ordinate axis) for two ceramic samples. The ellipses show a 95 % confidence region

Thus, the fractal analysis of the speckle pattern in terms of information capacity is at least not inferior to the analysis of microscopic images. However, it should be noted that the ellipses that delineate the 95 percent confidence regions show a tendency to be oriented along the horizontal axis (for this, it is necessary to take into account the ranges of values of the corresponding scales). This indicates lower scattering values of the fractal dimensions of speckle patterns compared to microimages. Thus, the set of surface parameters that are determined through speckle patterns is characterized by a higher value of the signal-to-noise ratio.

Figure 4 shows the results of scanning the lateral surface of sample C. The dependence of fractal dimensions on the coordinate of images and speckle patterns clearly demonstrates the five-layer structure of the sample. At the same time, the fractal dimension of the speckle pattern exhibits more regular behavior, which makes it a more reliable identification marker.

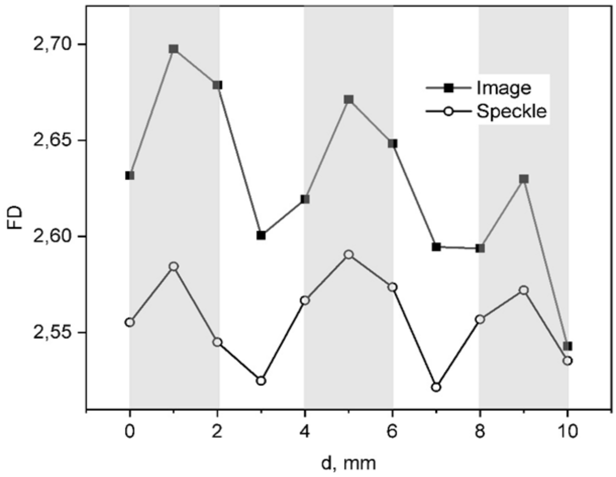

Fig. 4. Dependence of the fractal dimension on the coordinate for the microimage and the corresponding speckle pattern when scanning on the side surface of a five-layer sample

Considering low sensitivity speckle patterns to accuracy focusing optical systems, they are significantly more convenient object for express analysis surfaces ceramic materials compared to their microscopic images. Given the physical nature of the formation speckle-picture, exists possibility substantial simplification optical schemes microscopy speckle images or even full refusals from her.

An alternative approach may be to analyze the local characteristics of the surface (for example, roughness) using a speckle structure, which is formed over a small area of a given size using a focused laser beam and recorded by a video camera matrix located in a convenient place in the optical circuit.

In comparison with established techniques of non-destructive evaluation, such as ultrasonic inspection, X-ray microtomography, or Raman spectroscopy, speckle-based analysis combines operational simplicity with sufficient sensitivity to surface and near-surface features, while avoiding the need for complex and expensive instrumentation. At the same time, its limited depth of penetration and sensitivity to external perturbations remain challenges for practical application.

Discussion and conclusions

The conducted research confirms the effectiveness of fractal analysis of speckle patterns for the characterization of ceramic surfaces. The method demonstrates informativeness comparable to microscopic imaging while offering the important advantage of low sensitivity to optical focusing, which significantly simplifies measurement procedures and enables rapid control of technological parameters.

Statistically significant differences in fractal characteristics of ceramics of various compositions, revealed in both microimages and speckle patterns, indicate the suitability of the approach for material differentiation and process monitoring. Higher stability of fractal dimensions in speckle analysis highlights its greater reliability for unambiguous surface evaluation. In multilayer ceramics, the method clearly reflects stratified structures, underscoring its potential for non-destructive testing of composite systems.

Future research should aim at improving robustness of the optical setup, expanding depth-sensitive capabilities, and integrating speckle analysis with complementary methods to establish comprehensive and reliable diagnostics of ceramic materials.

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КОРЕЛЯЦІЯ МІЖ ФРАКТАЛЬНОЮ РОЗМІРНІСТЮ ТЕКСТУРИ ПОВЕРХНІ ТА ЇЇ ЛАЗЕРНИМИ СПЕКЛАМИ ЯК ОСНОВА БЕЗКОНТАКТНОГО МЕТОДУ АНАЛІЗУ КЕРАМІЧНИХ МАТЕРІАЛІВ

Досліджено кількісний зв'язок між фрактальною розмірністю текстури керамічної поверхні, отриманої за допомогою оптичної мікроскопії, та фрактальною розмірністю відповідного лазерного спекл-поля. Виявлено низьку чутливість спекл-аналізу до дефокусування, що спрощує процедуру контролю. Аналіз однорідних зразків виявив статистично значущі відмінності фрактальних характеристик зображень двох видів кераміки, підтвердивши можливість їхнього використання для ідентифікації матеріалів і виявлення дефектів. У випадку шаруватого керамічного зразка фрактальний аналіз спекл-картин чітко відображав його структуру, вказуючи на потенціал методу для неруйнівного контролю шаруватості й однорідності. Продемонстрований підхід підкреслює його метрологічну надійність і відкриває перспективи для його інтеграції у стандартизовані схеми контролю якості, забезпечуючи послідовну та відтворювану оцінку структурної цілісності у виробництві кераміки. Перспективи подальших досліджень пов'язані з розробленням спрощених оптичних схем спекл-аналізу для створення портативних систем експрес-контролю якості керамічних виробів.

Ключові слова: ***оптична мікроскопія, лазерні спекли, мікрорельєф, фрактальна розмірність, керамічна поверхня, шарувата керамічна система.***

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