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APPLICATION OF TEXTURE ANALYSIS TO STUDY THE RELATIONSHIP BETWEEN SURFACE MICRORELIEF AND LASER SPECKLES

The aim of the study was to establish a quantitative relationship between the structural properties of metal surfaces and the properties of laser speckle patterns that arise from the reflection of laser radiation on such surfaces. A texture analysis of the surfaces of seven different metal samples with different microreliefs was carried out. Two types of images were obtained for each sample: a surface micrograph taken with a microscope and a laser speckle pattern. To quantify the textures, the following parameters were calculated: fractal dimension, anisotropy, contrast, correlation, entropy, second angular momentum and energy. To determine quantitative dependencies between the texture parameters of micrographs and speckle images, pairwise regression and correlation analysis was performed. The study found a significant correlation between structural parameters of photomicrographs and speckle patterns such as fractal dimension, anisotropy and entropy. These results open up new possibilities for non-destructive quality control of materials. In addition, analyzing speckle patterns can predict material properties such as strength, corrosion resistance and wear resistance. This opens up prospects for the development of new materials with specific properties and the optimization of technological processes.

Keywords: *laser speckles, microrelief, texture analysis, correlation analysis, fractal dimension, anisotropy, entropy, materials science.*

AMS 2020 classification: 78A45, 78A55.

Introduction

Surface microrelief is a series of small micron-sized irregularities that form on the surface of the material during manufacturing, processing and operation. The analysis of surface microreliefs is one of the fundamental directions of modern materials science (Chambers, Roach, & Shirtcliffe, 2022). The use of machine learning methods allows you to predict the mechanical, physical and chemical properties of a material, model its behavior under various operating conditions and develop new materials with specified properties based on microrelief data (Harde, 2024; Huang, Guo, Chen, & Nie, 2023; Shiga, & Watanabe, 2023).

A wide variety of methods are used to examine the microrelief of the surface (Whitehouse, 2004), among which optical methods occupy a special position (Leach, 2011), which are characterized by their non-invasiveness and high accuracy. These methods make it possible to obtain detailed information about the geometric properties of the surface without physically touching it. One of the promising optical methods is laser speckle interferometry, which analyzes random interference patterns created by the scattering of coherent light from a rough surface (Dainty, 2013). Thanks to portable laser systems, this method can be used not only in laboratory conditions, but also directly in production, in the operation of systems or even for remote examination of objects. This makes speckle analysis an essential tool for quality control, technical condition monitoring and other application tasks.

Formally, the parameters of a speckle image can be related to the surface properties using the Van Zittert-Zernike theorem (Kononchuk, Prokopets, & Stukalenko, 2010). However, the practical application of this knowledge requires detailed experimental studies that allow confirming theoretical predictions on real objects with known surface microstructure.

Using modern texture analysis methods, we conducted a study aimed at establishing a quantitative relationship between the characteristics of laser speckles and the microrelief parameters of real metal surfaces.

1. Surface and speckle textures

Surface texture – is a complex set of properties of the microrelief of the material, which is formed under the influence of external factors throughout the entire life cycle of the product, from production to operation (Chiffre et al., 2000). For metals, the surface quality depends heavily on processing processes such as milling, grinding and polishing. At the same time, the extent of irregularities on the metal surface can vary from tens of micrometers to nanometers. Milling creates a rough surface with macroerosions visible to the naked eye. Grinding provides a smoother surface with microfines that can be observed with an optical microscope. Polishing creates a reflective surface with small nanodefects that are only visible in an electron microscope.

The surfaces of metal parts change during operation: conjugate surfaces wear due to friction and non-conjugate surfaces change under the influence of corrosion and temperature fluctuations. Gradually, under the influence of various influences, the texture of metal surfaces becomes more complicated and turns into a complex system of ordered and chaotic elements.

When a laser beam falls on a rough surface, it is scattered at microinhomogeneities and forms a characteristic interference pattern ‑ laser speckle (Dainty, 2013). The speckle image has a grainy structure and is not an exact replica of the surface microstructure. However, it contains data about the statistical properties of the surface, encoded in the spatial distribution of light intensity. In other words, the speckle image is a kind of optical code of the surface, where information about its properties is encoded in texture parameters.

Basic parameters such as contrast, correlation, entropy, energy (other name "inverse difference moment") and the second angular moment correspond to local texture properties (Bunge, 2013; Chiffre et al., 2000). They are calculated using the universal tool – the so-called Gray-Level Co-Accurrence Matrix.

Parameters that describe integral properties are calculated using special algorithms. In particular, the fractal dimension, which characterizes the degree of complexity and irregularity of the texture, is calculated using the box-counting method (Shanmugavadivu, & Sivakumar, 2012). Anisotropy reflects the degree of directionality of the texture and is calculated by algorithms for analyzing local structural elements (Hielscher et al., 2010).

2. Materials and methods

In this work, a comparative analysis of the texture properties of surface micrographs and corresponding speckles for seven different metal samples was carried out.

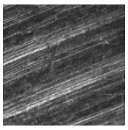
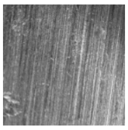
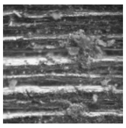
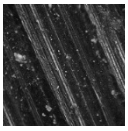
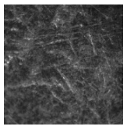
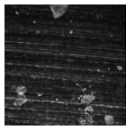
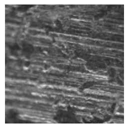
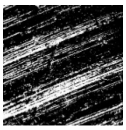
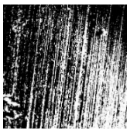
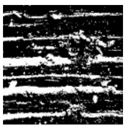
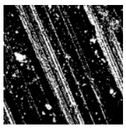
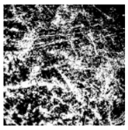
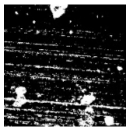
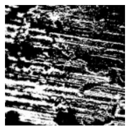
The microscopic images were taken using an LM-2A microscope with a SIGETA digital camera (resolution 1280 × 800 pixels). In order to obtain images with contrasting properties that make it easier to recognize the smallest relief details, the dark field microscopy method was used. To calculate specific texture parameters, additional binarization was performed using the Otsu method (Tab. 1).

To obtain speckle images of surfaces, an optical scheme was used that included a helium-neon laser with a power of 2 mW and a wavelength of 632.8 nm, a telescope beam expander F_1 = 10 mm, F_2 = 50 mm) and a KEYTON USB-camera with a resolution of 640x480 pixels. An expanded laser beam with a diameter of 5 mm was directed at the surface to be examined at an angle of 20° to the normal to reduce the influence of the direction of the microrelief. Light scattered perpendicular to the sample surface entered the chamber matrix. Each surface was represented by three images and three speckles.

For quantitative texture analysis, an *ImageJ* software with special *BoneJ* (Doube et al., 2010) and *GLCM Texture* (Hall-Beyer, 2000) plugins was used.

Table 1

Dark field and binarized images of metal sample surfaces. The size of each area is 40 x 40 µm.

№ Sample	1	2	3	4	5	6	7
Dark field image							
Binary image							

3. Results and analysis

We performed a comparative analysis of the micrographs and the corresponding speckles of seven samples and calculated the following texture parameters for each of them: fractal dimension (FD), anisotropy (A), contrast (CON), correlation (COR), entropy (H), the second angular momentum (ASM) and the energy (IDM). To determine the relationship between the microstructure of the sample surface and the speckle image properties obtained from that surface, we performed pairwise regression and correlation analysis of the texture parameters of both image types.

The results of measurements and calculations show that three out of seven parameters are reliably correlated, as indicated by the proximity to 1 of the Pearson correlation coefficient (Fig. 1). Let's consider these parameters in more detail.

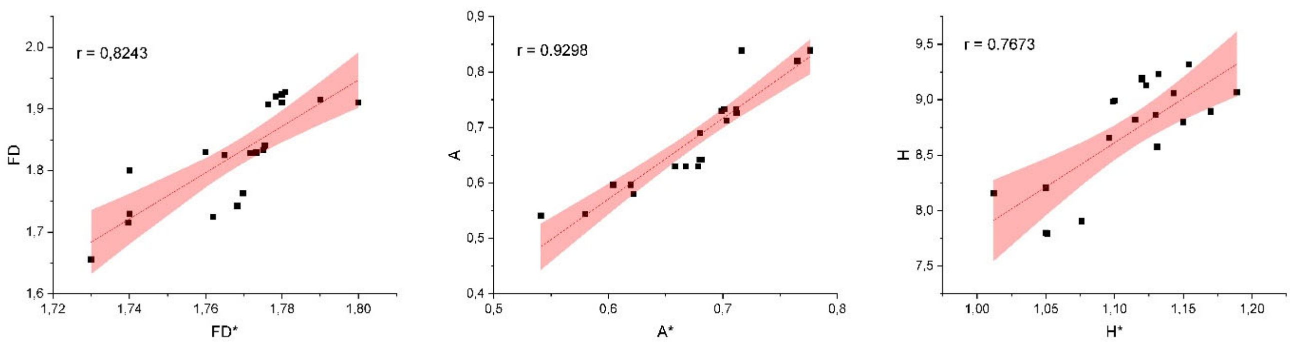


Fig. 1. Scatterplots for texture parameters with high correlation (micrograph parameters are plotted on the abscissa axis, speckle parameters – on the ordinate axis). Regression lines and a 95 percent confidence band are displayed

A) *Fractal dimension* (Pearson correlation coefficient r = 0.82) – is a numerical characteristic that describes the degree of complexity and self-similarity. Fractal properties are inherent to non-smooth surfaces, while the fractal dimension correlates with the quantitative parameter of their roughness (Nayak, Mishra, & Palai, 2019). The spectra resulting from the scattering of coherent radiation from rough surfaces also exhibit fractal properties (Li, Z., Li, H., & Qiu, 2006). Although there is no direct connection between the fractal dimension of the rough surface and the corresponding speckle image, the existence of such a connection can be explained, at least at the qualitative level, for the following reasons. A rough surface can be thought of as an opening that modulates an incident wave. According to the Van Zittert-Zernike theorem, a speckle image is a Fourier image of the transmission function of that aperture. The larger the fractal dimension of the surface, the larger the high spatial frequencies in its spectrum. This means that a speckle image from a surface with a larger fractal dimension will have smaller and more chaotic speckles. Accordingly, its fractal dimension will be larger.

B) In the context of rough surfaces, *anisotropy* (r = 0.93) means a different degree of roughness in different directions. If a surface is anisotropic, its Fourier spectrum is also anisotropic. This means that the distribution of spatial frequencies will be different in different directions. Since the speckle image is a Fourier transform of the transmission function of a rough surface, the anisotropy of the Fourier spectrum leads to the anisotropy of the speckle image. If high spatial frequencies predominate in one direction in the spectrum, smaller and chaotic spots can be observed in the speckle image in the corresponding direction. Conversely, the species become larger and less chaotic in the direction in which low spatial frequencies predominate.

C) *Entropy* (r = 0.77) – This is a measure of the unpredictability or randomness of the brightness distribution of the pixels of the texture image of both the surface and the speckle image. Another interpretation of entropy – is a measure of the ratio of regular (predicted) and irregular (unpredicted) components. The greater the entropy, the more complex and less predictable the texture. Textured stain images directly reflect the texture of the surface that created them. The more complex and chaotic the structure of the surface is, the more complex and chaotic the structure of the speckle image will be. Since the speckle image is a Fourier transform of the aperture transfer function, which is a rough surface, the Fourier transform stores information about the entropy of the signal. That is, the high entropy in the spatial domain (surface texture) corresponds to the high entropy in the frequency domain (speckle image spectrum).

There are no other parameters of a reliable correlation (Fig. 2). This can be explained by the fact that they do not describe the real surface, but its graphic image – an image that depends on the registration conditions: lighting, focusing, observation angle, etc. and little reflects the physical properties of the surface itself. In addition, these parameters characterize the local features of the textures and in the case of a real microrelief can be subject to significant fluctuations, which significantly reduces their informative value.

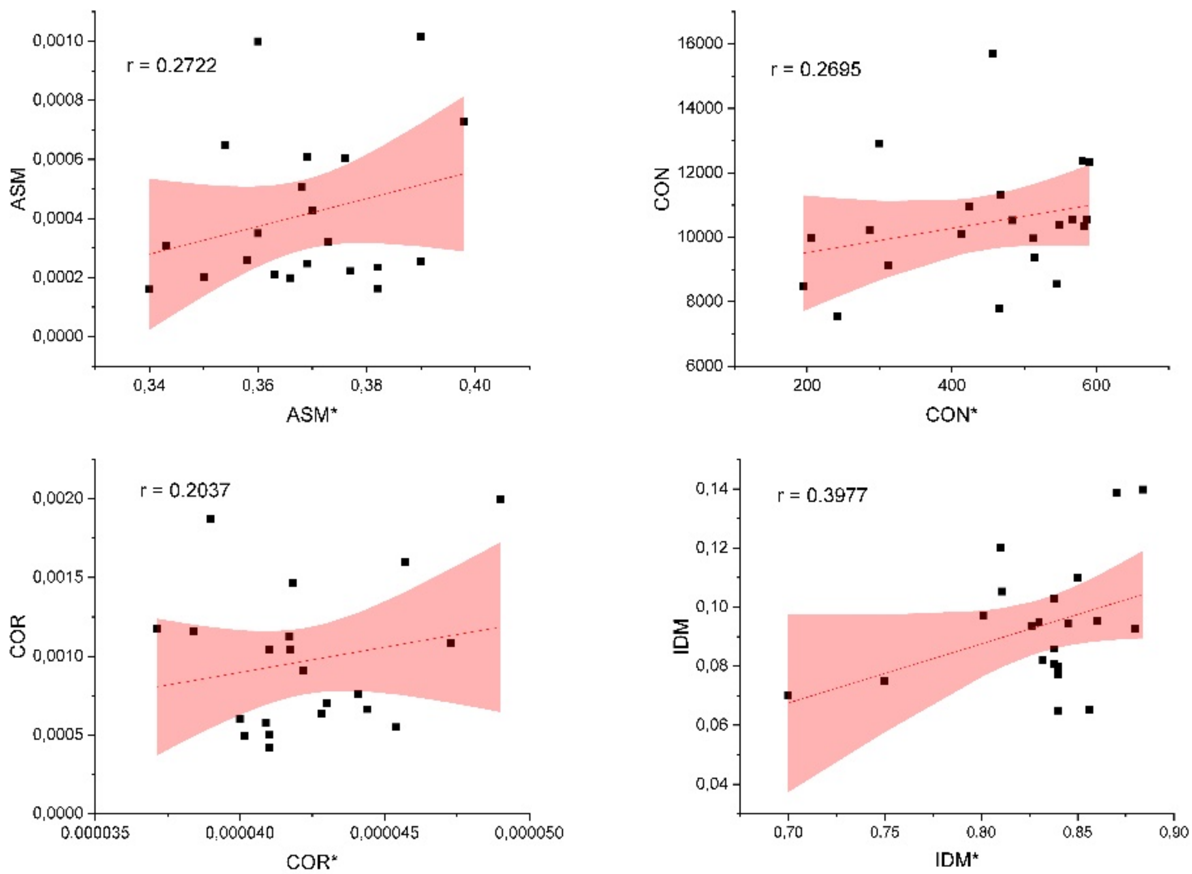


Fig. 2. Scatterplots for texture parameters with low correlation

Discussion and conclusions

Our studies quantified the degree of relationship between some structural parameters of real metal surfaces and the corresponding speckle images. A reliable correlation has been established between fractal dimension, anisotropy and entropy of microscopic images of surfaces and their speckles. The results show that the properties of the speckle image can be used to predict the properties of the microrelief and, on this basis, predict the mechanical, physical and chemical properties of the material, model its behavior under different operating conditions and develop new materials based on these characteristics.

Authors' contribution: Andriy Yakunov – conceptualisation, source analysis, methodology, empirical research; Artem Sachko – software, empirical research, computer calculations.

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ЗАСТОСУВАННЯ ТЕКСТУРНОГО АНАЛІЗУ ДЛЯ ДОСЛІДЖЕННЯ ВЗАЄМОЗВ'ЯЗКУ МІЖ МІКРОРЕЛЬЄФОМ ПОВЕРХОНЬ І ЛАЗЕРНИМИ СПЕКЛАМИ

Встановлено кількісний зв'язок між структурними особливостями поверхні металів і характеристиками лазерних спекл-картин, що утворюються під час відбивання лазерного випромінювання від таких поверхонь. Проведено текстурний аналіз поверхонь семи різних металевих зразків з різноманітними мікрорельєфами. Для кожного зразка отримано два типи зображень: мікрозображення поверхні та лазерна спекл-картина. Для кількісної оцінки текстур розраховано такі параметри: фрактальна розмірність, анізотропія, контраст, кореляція, ентропія, другий кутовий момент й енергія. Для встановлення кількісних залежностей між текстурними параметрами мікрозображень і спекл-картин проведено попарний регресійний і кореляційний аналіз. Унаслідок дослідження встановлено достовірну кореляцію між такими текстурними параметрами мікрозображень і спекл-картин, як фрактальна розмірність, анізотропія й ентропія. Отримані результати відкривають нові можливості для неруйнівного контролю якості матеріалів. Крім того, на основі аналізу спекл-картин можна прогнозувати такі властивості матеріалу, як міцність, корозійна стійкість і зносостійкість. Це має перспективи для розроблення нових матеріалів із заданими властивостями й оптимізації технологічних процесів.

Ключові слова: ***лазерні спекли, мікрорельєф, текстурний аналіз, кореляційний аналіз, фрактальна розмірність, анізотропія, ентропія, матеріалознавство.***

Автори заявляють про відсутність конфлікту інтересів. Спонсори не брали участі в розробленні дослідження; у зборі, аналізі чи інтерпретації даних; у написанні рукопису; у рішенні про публікацію результатів.

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