On the method of calculating the energy density of laser radiation in a metal surface modification

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Abstract. Today, modification of metal surfaces using laser radiation (laser ablation) is one of the most common processing methods in various scientific studies. At the same time, there is no unified approach to estimating the energy of laser radiation impact on the metal surface, which significantly complicates the comparison of the results of studies performed at different parameters of laser radiation. In the present work, a universal method of calculating the energy density of laser radiation impact on the surface is presented. The formation of relief with identical geometric characteristics at different parameters of laser radiation, but with the same energy density of radiation effect on the surface being modified, was experimentally confirmed.

1. Introduction

Surface wettability of any material is one of the main parameters characterizing interaction of liquid and solid body. The degree of wettability is determined by the value of the contact angle, which is formed between the tangent to the drop profile and the solid surface. According to the degree of the surface wettability they are divided into hydrophobic and hydrophilic, for which the value of the contact angle is more than 90° and less than 90°, respectively [1]. Separately, there are superhydrophobic (a contact angle of more than 150°) and superhydrophilic surfaces (a contact angle of more than 10°). Hydrophobic and superhydrophobic surfaces with the following properties have the greatest practical application in power engineering and industry: resistance to ice formation [2] and fouling of deposits [3], inhibition of corrosion processes [4], reduction of hydraulic resistance in liquid fluid transportation [5], intensification of heat exchange processes [6].

As a result of the scientific direction development associated with the study of the wettability properties of the surfaces of various materials, the basic conditions, the joint implementation of which can create hydrophobic surfaces with high values of the contact angle of more than 140 degrees, are highlighted [7-10]:

- ensuring the reduction of surface energy at the solid-gas interface;
- texturing on the material surface of a micro/nanoscale relief with such geometric parameters that the condition of forming a stable heterogeneous wetting regime is fulfilled.

Changing the geometric parameters of the metal surface is possible using the following modern methods: chemical etching [11], plasma surface treatment [12], photolithography [13]. The main disadvantages of the listed methods of surface modification are the complexity of the technological processes, high cost, and rather low mechanical properties of the modified surface structure [14]. The above disadvantages are deprived of mechanical methods, which provide the creation of the relief structure by the surface deformation (knurling and slicing) [15]. However, knurling and slicing do not
allow the geometric characteristics of the relief to be varied over a wide range due to the fact that such modification is performed using cutters, which must be manufactured individually for each geometry.

Currently, one of the most promising ways to create hydrophobic surfaces of various materials is a method based on the use of laser equipment [16-18]. The high interest in this method is caused by the fact that laser radiation of metal surfaces performs texturing of micro/nanoscale relief and due to flexible variation of laser radiation parameters it is possible to control specific geometric parameters of formed textures with sufficient accuracy, providing an increase in the contact angle.

Most research works on surface hydrophobization based on laser effect in the description of laser equipment usually specify the type of laser source and the basic parameters of laser radiation: pulse repetition rate, radiation power, and speed of surface treatment. Some works specify the spot diameter of the laser pulse at the focal distance from the lens (on the modifying surface). The complex of the parameters listed above determines the energy density of laser radiation, which in turn determines the geometric parameters of the relief.

2. Materials and methods

Modern laser complexes used in various research works for modification of metal surfaces are based on pulsed laser sources. In this case, spots of diameter $d$ (mm) are formed on the metal surface due to the effect of separate pulses of laser radiation with a given frequency ($f$, Hz), power ($P$, W) and speed of laser beam movement relative to the modified surface ($v$, mm/s). Thus, by varying the specified parameters of radiation, three variants of relief formation on the metal surface are possible:

1) In the form of a continuous groove $l$, consisting of $n$ spots - when the spots overlap each other and their partial overlap occurs, that is, the distance between the centers of the spots $L$ is less than the diameter of the spot $d$ (see Figure 1, a);

2) In the form of separate contacting spots, when the distance between their centers is equal to the diameter of the spot (see Fig. 1, b);

3) In the form of contiguous separate spots, when the distance between their centers is greater than the diameter of the spot (see Figure 1, c).

![Figure 1. Schematic representation of the distribution of laser radiation pulses (n=2) on the modifying surface: a) spots overlap each other; b) spots touch each other; c) spots do not cross each other.](image)

The most practical interest is the relief in the form of a continuous groove. Various textures are formed on the metal surface in the form of parallel lines, meshes, rhombuses, etc. on the basis of such a relief [19-20]. The distance between the centers of the spots at known given laser radiation parameters can be determined with equation (1):

$$L = \frac{(v \cdot t - d)(f \cdot t - 1)}{1}$$  \hspace{1cm} (1)

there $v$ – the velocity of the laser beam relative to the surface to be modified, mm/s; $t$ – laser exposure time, s; $d$ – spot diameter, mm; $f$ – frequency of laser radiation, Hz.

As mentioned above, the main energy parameter of laser radiation that determines the geometric characteristics of the generated relief is the energy density of laser radiation, which is determined by equation (2):

$$W = \frac{P \cdot t \cdot S}{1}$$  \hspace{1cm} (2)
where \( P \) – power of laser radiation, \( W \); \( S \) – the area of laser radiation exposure on the surface, \( m^2 \); \( t \) – laser exposure time, \( s \).

In equation (2) the power of the laser source \( P \) is a known and specific value for the laser complex used in the study. The laser exposure time on the surface (time of formation of a groove of length \( l \)) is determined by a given speed of movement of the laser source relative to the surface to be modified. Thus, in order to determine the energy density of the radiation using equation (2), it is necessary to find the surface area \( S \) of the laser radiation on the surface.

The schematic representation of the used areas and equations for their determination at a given distribution of pulses on the modifying surface is presented in Table 1.

**Table 1.** Calculation of the impact area \( S \) of the laser radiation on the surface.

| \( S = S_1(n-1) + S_2 \) | \( S_1 = S_2 - S_3 \) | \( S_2 = \pi d^2/4 \) |
|--------------------------|------------------------|---------------------|
| \( S_3 = 2(S_4 - S_5) \) | \( S_4 = (d/4)^2(\alpha/4) \) | \( S_5 = (d^2/8)\sin(\alpha) \) |

\( \alpha = 2\arcsin(\sqrt{d^2 - L^2/d}) \)

To determine the area \( S \) of the laser beam effect on the surface for the case when there is no overlap of pulses (see Fig. 1, b, c), it is sufficient to know the number of pulses and the area \( S_2 \) of one spot. The area \( S \) for the discussed case is determined by equation (3):

\[ S = nS_2 = n\pi d^2(4)^{1/4} \]  

**3. Results and discussions**

As mentioned above, the geometric characteristics of the forming relief determine the degree of hydrophobicity of the surface and depend on the density of radiation energy. The main geometric characteristics of the forming relief in the form of a continuous groove, as a rule, are the height of the projection \( h_1 \) and groove \( h_2 \), the width of the projection \( a \), the groove \( b \) and the channel between the projections \( c \) (see figure 2). A groove on the metal surface is formed because of the melting and evaporation of material at the point of contact between the laser radiation and the surface of the sample. Part of the molten material moves from the center of the laser-surface contact to its edges, cools and crystallizes, which leads to the formation of lateral projections near the groove.

**Figure 2.** Schematic representation of the main geometric characteristics of the relief.

The verification of the method of determining the energy density of laser radiation was carried out using experimental samples of brass L63. Using a laser complex based on a nanosecond ytterbium fiber laser source, a relief in the form of equidistant lines was formed on the surface of the experi-
mental samples at the same energy density of 86 J/cm$^2$ and at different parameters of laser radiation presented in Table 2. Figure 3 shows images of the modified surface and thin sections of the experimental samples, indicating the main geometric characteristics of the relief, obtained using a scanning electron microscope.

**Table 2.** Laser radiation parameters and contact angle values for the initial and modified surfaces of the experimental samples.

| №  | Energy density, J/cm$^2$ | Laser radiation parameters | Contact angle, degree |
|----|-------------------------|----------------------------|----------------------|
|    |                         | Power, W                   | Frequency, kHz       | Processing speed, mm/s | Value of the contact angle |
| 1  | 86                      | 20                         | 20                   | 400                   | 90 ± 0.5 |
| 2  | 15                      | 20                         | 20                   | 300                   | 90 ± 0.5 |

**Figure 3.** Images of the modified surface (a, d) and thin sections (b, c, e, f) of experimental brass samples.

Table 3 shows the values of the main geometric parameters of the relief formed on the surface of experimental samples №1 and №2 using the laser complex. Table 2 also shows the values of the contact angle obtained using the optical device OCA 20 and 5 µl drops of distilled water for the original and modified surfaces of the experimental samples. In order to improve the accuracy of the obtained values, measurements were made on three different sections of the modified surface, and the average value of the contact angle was determined.
Table 3. Geometric parameters of the relief formed on the surface of the experimental samples.

| № | a, μm | b, μm | c, μm | h1, μm | h2, μm | Contact angle, degree |
|---|---|---|---|---|---|---|
| | | | | initial surface | modified surface |
| 1 | 8.4 | 56.9 | 33.6 | 2.0 | 10.0 | 79.94 | 146.26 |
| 2 | 9.7 | 45.4 | 30.7 | 2.6 | 9.6 | 77.53 | 146.10 |

Table 3 shows that the values of geometric characteristics of the textured relief on the surface of experimental samples №1 and №2 are almost identical. Insignificant differences in the values of parameters a, c, h1 and h2 are in the range of errors of the measurement technique. The difference in the values of the groove width b can be explained by the presence of defects on the initial surface of the experimental samples, as well as by the non-uniform movement of parts of the molten metal from the center of the place of contact of laser radiation with the surface to its periphery.

Thus, the experimental brass samples modified at different parameters of laser radiation, but with the same energy density, have identical values of the surface contact angle and the characteristics of the formed relief, which confirms the correctness of the developed method of calculating the energy density of laser radiation in the metal surface modification.

4. Summary
1. Today there is a lot of research on the creation of hydrophobic metal surfaces. One of the most promising ways to create such surfaces is micro/nanoscale texturing using laser ablation.
2. As a rule, most scientific studies provide only laser radiation parameters (source power, frequency, speed of laser beam movement over the modifying surface), which is insufficient for comparing the results of various studies.
3. The above method of determining the energy density of laser radiation exposure on the surface is universal and can be applied to most laser radiation sources.
4. Experimental testing of the presented technique confirmed that with the same exposure energy density, but different parameters of laser radiation, the relief with identical geometric characteristics is formed.

5. References
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