International Journal of Engineering Trends and Technology
ISSN: 2231 – 5381 /doi:10.14445/22315381/IJETT-V68I11P204 Volume 68 Issue 11, 25-32, November 2020

The Influence of Laser Impact on Wettability of Brass Surface

A.V. Ryzhenkov*, M.R. Dasaev, S.V. Grigoriev, E.M. Tyabut, E.S. Trushin
National Research University "Moscow Power Engineering Institute", Moscow, Russia
*artyom.v.ryzhenkov@mail.ru

Abstract: *This work discusses the influence of modification of brass surfaces using laser equipment on wettability properties; wetting and roll-off angles on modified surfaces were determined and analyzed as a function of laser radiation parameters and atomic composition. The most energy efficient hydrophobic surfaces characterized by the wetting angle of 149° and the roll-off angle of 3°, as well as the wetting angle of 147° and the roll-off angle of 2°, were obtained upon modification of brass surface at laser power of 15 W and 20 W, respectively, and beam speed of 100 mm/s, forming relief in the form of equidistant by 100 µm lines.*

Keywords: *hydrophobicity, laser texturing, L63 brass, wetting angle, roll-off angle, relief.*

I. INTRODUCTION

High transportation expenses caused by significant hydraulic loss are an urgent and common problem in various industries. Nowadays, numerous studies are carried out aimed at reduction of hydraulic resistance by means of hydrophobization of functional surfaces, which also promotes increase in corrosion resistance of materials and, as a consequence, increase in operation lifetime of equipment, decrease in deposits on pipeline walls during transportation of liquid mediums, decrease in icing rate, etc. [1]

One of the properties of solid surfaces significantly influencing the variation of hydraulic resistance is wettability, which, in its turn, is characterized by wetting angle [2]. Wetting angle is determined by the angle between tangent to the surface at liquid–solid interface and solid surface with the top in the contact point of three phases (see Fig. 1) [3].

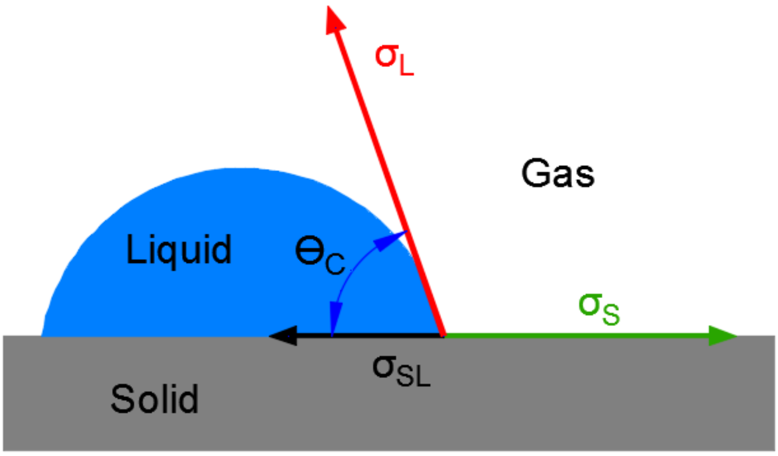


Fig. 1 Wetting angle and surface tension forces at interphase boundary: σ_S – specific free solid state energy; σ_L – liquid surface tension; σ_{SL} – interphase tension at solid–liquid boundary; Θ_C –wetting angle

Numerical value of wetting angle of solid surface is described by the Young–Laplace equation (1):

$$\sigma_L \cos\theta_C = \sigma_S - \sigma_{SL}, \qquad (1)$$

where σ_S is the free surface energy of solid state; σ_L is the liquid surface tension; σ_{SL} is the interphase tension at solid–liquid boundary; θ_C is the wetting angle.

Usually the following wettability regimes are highlighted: when the wetting angle is in the range of 0-90°, the surface is referred to as hydrophilic, which means complete or partial wetting of surface by liquid; when the wetting angle is in the range of 90-150°, the surface is referred to as hydrophobic, which means nonwetting of surface by liquid. Modern methods of modification of solid surfaces are aimed at maximization of wetting angles in order to achieve superhydrophobic state of surface, at which liquid droplets formed on surface tend to spherical shape, herewith, wetting angle exceeds 150° and the surface is referred to as superhydrophobic [4].

It has been mentioned in [5] that high wetting angle does not guarantee good water repellent properties, that is, even at high wetting angle, liquid droplets are not evacuated from the surface. From practical point of view, the interest is attracted by hydrophobic surfaces with low roll-off angle: the angle determining the required surface inclination, at which a droplet spontaneously rolls off by gravity.

Actually, upon rolling off the surface, the droplet is deformed and inclined towards the direction of motion (see Fig. 2). Herewith, the contact angle at the front edge is determined as the inflow angle, which is always higher than the wetting angle, and the angle at the rear edge is the outflow angle, which is always lower than the wetting angle.

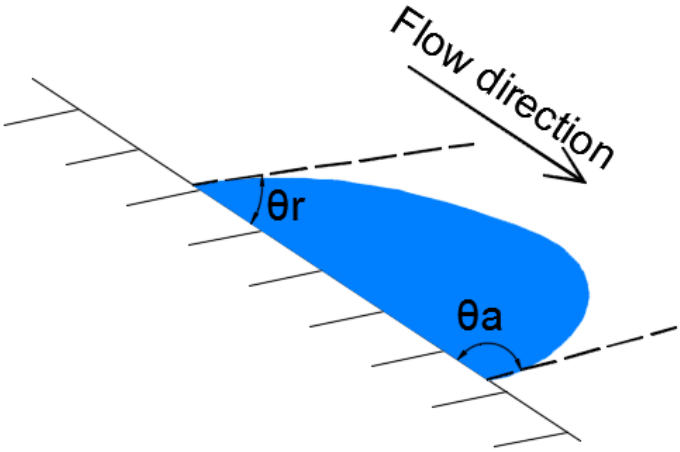


Fig. 2 Inflow and outflow angles of liquid droplet: θ_a – inflow angle, θ_r – outflow angle

The difference between the inflow angle and the outflow angle is determined as the wetting angle hysteresis H (2), herewith, low H evidences low roll-off angle [6].

$$H = \theta_a - \theta_r, \qquad (2)$$

where Θ_A is the inflow angle, Θ_R is the outflow angle.

II. LITERATURE REVIEW

Numerous solutions are available aimed at achievement of hydrophobic and superhydrophobic state of surfaces with low roll-off angle, including plasma treatment, coating polymerization, cold sputtering which is an efficient method to fabricate polymer coatings on various substrates, chemical and electric deposition, etching, etc. [7]-[11]

At present, the fabrication methods of superhydrophobic surfaces can be conventionally subdivided in terms of two main approaches: descending and ascending. The first approach is based on application of various treatments by physical impact on surface, that is, top–down approach resulting in formation of micro-/nanoscale relief. The descending approach can be exemplified by engraving, molding, laser treatment, and others. The second approach implies achievement of the required geometrical parameters of relief by growing of structures on initial surface. The ascending process, that is, down–top approach, is comprised of such methods as treatment by sol–gel solution, layer-by-layer deposition, chemical deposition, colloidal assemblies, and others. In addition, some methods are based on combination of the top–down and down–top approaches, for instance, electrospinning [3].

One of the challenging methods allowing to achieve hydrophobic properties is laser texturing of surfaces described in [12]–[14]. This is an efficient method suitable for various structural materials, which makes it possible to achieve relief with various geometrical parameters.

Nowadays significant attention is attracted by brass hydrophobic surfaces. Due to good heat and electric conductivity as well as certain mechanical properties, brass is widely applied as structural material in various industries. However, since brass is the alloy of copper and zinc, this metal is reactive to ambient conditions, resulting in corrosion. Therefore, provision of hydrophobicity allows to improve anticorrosive, anti-icing, self-cleaning, and other properties [15].

III. METHODS

This work presents the results of modification of experimental samples made of brass, grade L63, using an FMark NS-FB-20 laser accessory with infrared ytterbium fiber laser with the following specifications: wavelength is 1,064 nm, pulse duration is 4–200 ns, nominal laser power is 20 W.

The wetting angle of initial nonmodified surface is 82º, the roll-off angle is 85º. Atomic composition of the surface is as follows: C – 12.18%, O – 4.33%, Cu – 52.61%, Zn – 30.88%. Fig. 3 illustrates electronic image of initial surface of a sample.

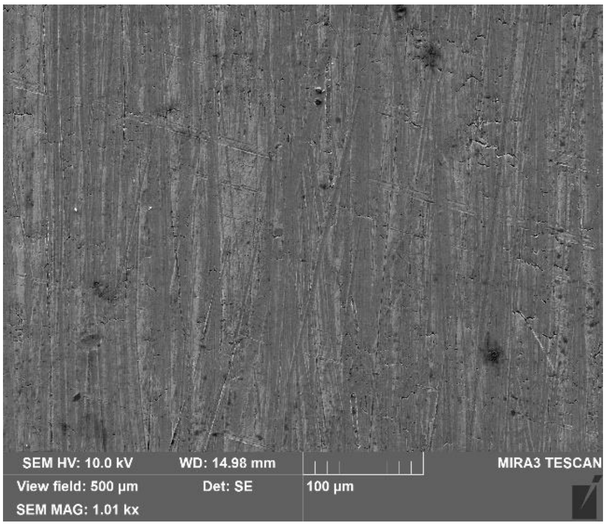


Fig. 3 Initial surface of brass sample

In this work the experimental studies of the influence of laser radiation parameters on wetting angle and roll-off angle were carried out with variation of laser power in the range from 50 to 100% of the nominal values with the increment of 25%, variation of beam scanning rate from 100 to 500 mm/s with the increment of 100 mm/s. The pulse frequency of laser radiation was constant equaling to 20 kHz. Herewith, laser beam travelling over surface was arranged along the route of equidistant parallel lines, the incensement between them was 100 or 300 µm.

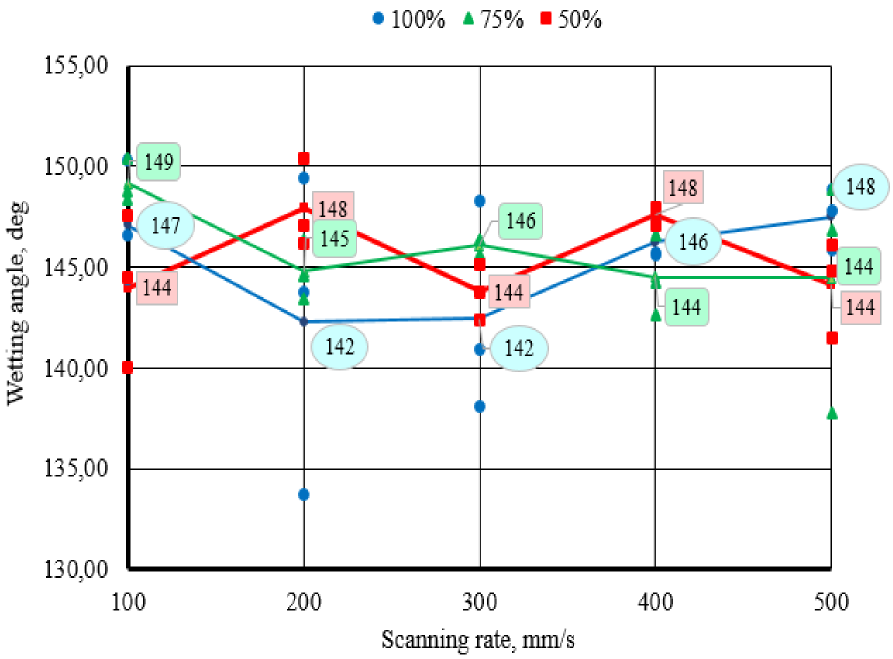
The samples were marked as follows: AA.BB.CC.DD, where AA was the laser power (% of nominal power), BB was the beam scanning rate (mm/s), CC was the pulse frequency (Hz) and DD was the distance between the lines (µm), along which the beam was travelling.

After modification of the surfaces using laser accessory at the aforementioned parameters, the wetting and the roll-off angles were measured. In order to obtain the most accurate values, the angles were measured three times in different points of the modified surface, the measurements were averaged to obtain final result.

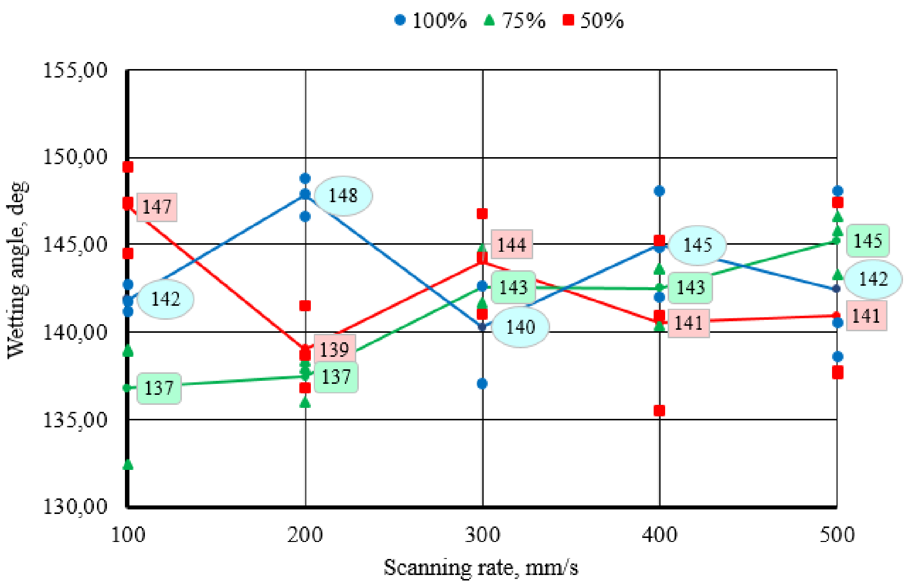
IV. RESULTS

1. Wetting angle and roll-off angle as a function of laser radiation parameters and relief geometry.

Fig. 4 illustrates wetting angle as a function of scanning rate (travelling speed of laser beam over the surface) and laser power equaling to 50%, 75%, and 100% of nominal value upon formation of relief in the form of equidistant by 100 µm (see Fig. 4, a) and by 300 µm lines (see Fig. 4, b). The lines in the figure are plotted on the basis of average values, their numerical values are also shown.



(a)



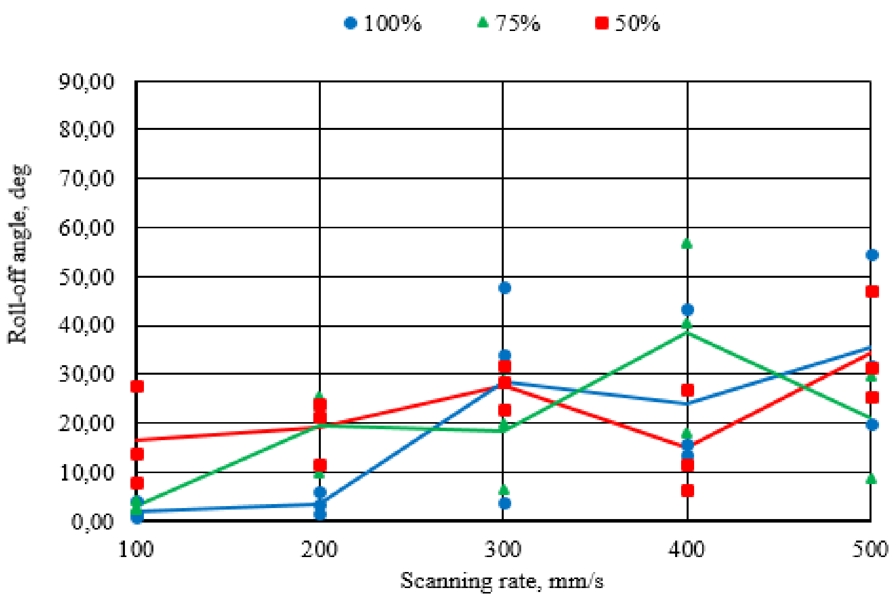
(b)

Fig. 4 Wetting angle as a function of scanning rate and laser power (50%, 75%, 100% of nominal value) during formation of relief in the form of equidistant by 100 μm (a) and 300 μm (b) lines

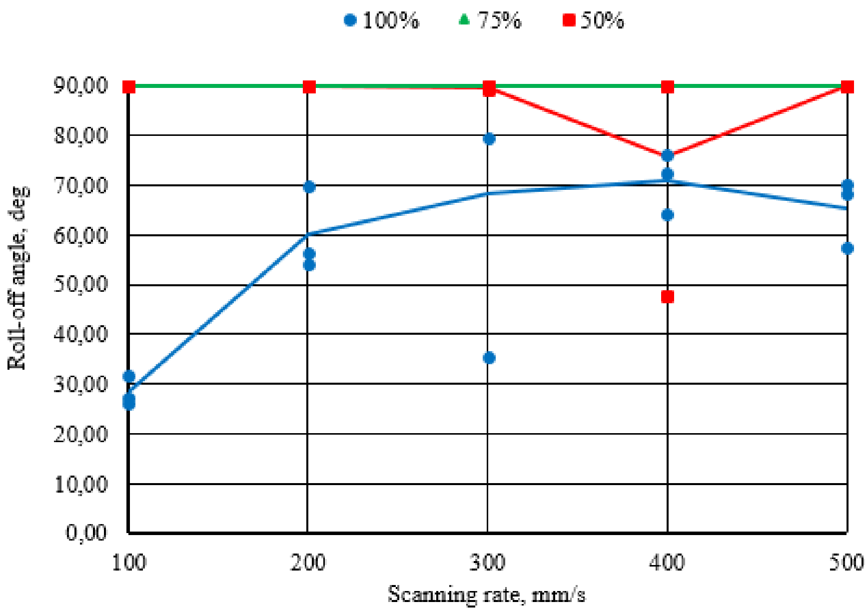
It was revealed that the surfaces of all brass samples modified by the laser accessory at the mentioned parameters became hydrophobic. The maximum wetting angle of 149° was achieved upon modification of brass surface at the laser power of 15 W (75% of nominal value) and the scanning rate of 100 mm/s with resultant relief in the form of equidistant by 100 μm lines.

As can be seen in Fig. 4, the wetting angle as a function of laser radiation parameters is not characterized by any explicit regularity. However, the wetting angles obtained upon modification of brass surfaces by laser texturing of relief in the form of equidistant by 100 μm lines exceed the values obtained under the same parameters of laser radiation upon formation of laser relief in the form of equidistant by 300 μm lines.

As mentioned above, water repellent property of the surface is determined not only by wetting angle but also by roll-off angle. Fig. 5 illustrates roll-off angle as a function of scanning rate and laser power upon formation of laser relief in the form of equidistant by 100 μm (see Fig. 5, a) and by 300 μm lines (see Fig. 5, b). In the case of complete adherence of a droplet to the modified surfaces, i.e. when the droplet did not roll off upon rotation of the surface by 90° to horizon, the roll-off angle was taken as 90°.



(a)



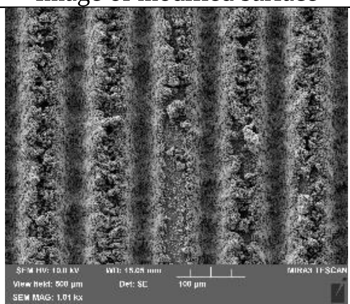
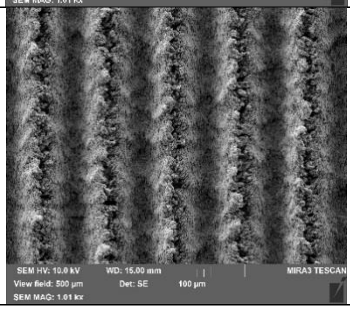
(b)

Fig. 5 Roll-off angle as a function of scanning rate and laser power (50%, 75%, 100% of nominal value) during formation of relief in the form of equidistant by 100 µm (a) and 300 µm (b) lines

The minimum roll-off angle in these studies was 2º for the sample marked as 100.100.20.100, the wetting angle of this sample was 147º.

For the sample marked as 75.100.20.100 with the maximum wetting angle (149º) the roll-off angle was 3º (see Table 1).

TABLE I. MODIFIED SURFACES WITH ACHIEVED WETTING AND ROLL-OFF ANGLES

Marking	Image of modified surface	Wetting angle, deg.	Roll-off angle, deg.
75.100.20.100		149	3
100.100.20.100		147	2

2. Atomic composition as a function of laser radiation parameters

The main elements of atomic composition of nonmodified brass surface are copper (52.61%), zinc (30.88%), carbon (12.18%), and oxygen (4.33%).

As a consequence of surface modification by laser texturing, it was detected that variation of laser radiation parameters led to variation of the contents of the mentioned constituents of atomic composition on the surface. Fig. 6 illustrates variations of element ratio of atomic composition on brass surface at 50%, 75%, and 100% of nominal laser power.

(a)

(b)

(c)

Fig. 6 Variation of atomic composition of brass upon surface modification at 50% (a), 75% (b) and 100% (c) laser power of nominal value

It can be seen in Fig. 6 that in comparison with the initial surface, the copper content on the surface significantly decreases and the oxygen content increases after the laser texturing. At the same time, the zinc content varies insignificantly.

It should be mentioned that the pattern of variation of carbon atomic content on the surface does not allow to reveal explicit dependence.

However, for the aforementioned samples similar trend can be observed for variation of carbon content after surface modification: for the sample with the maximum wetting angle of 149º, the carbon atomic content decreased from 12.18% to 9.20%, for the sample with the wetting angle of 147º, the carbon content decreased from 12.18% to 8.77%.

Fig. 7 illustrated wetting angle as a function of carbon content on surface after modification at 50%, 75%, and 100% laser power of nominal value.

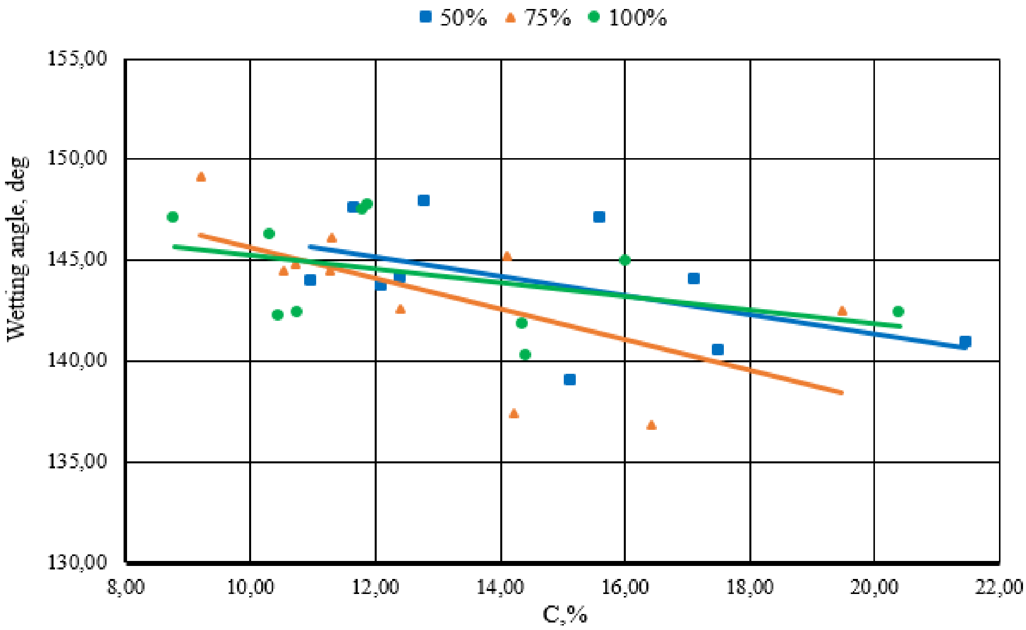


Fig. 7 Wetting angle as a function of carbon content on surface after modification at 50%, 75%, and 100% laser power of nominal value

V. DISCUSSION

Therefore, it can be concluded that the minimum roll-off angles were achieved at the laser scanning rate of 100 mm/s. With the increase in the scanning rate, the roll-off angles significantly increase and do not attract practical interest. The experimental results revealed optimum parameters (laser radiation of geometry of texturized relief) for production of energy efficient brass surfaces: the scanning rate: 100 mm/s, the laser power: 15 (20) W, the pulse frequency: 20 Hz, the interline distance: 100 µm.

It should be mentioned that application of laser equipment upon modification of brass surfaces makes it possible to obtain linear micro-/nanoscale reliefs with equidistant protrusions.

Approximating lines, which average wetting angles at 50%, 75%, and 100% of laser power, make it possible to observe linear trend of decrease in wetting angles with increase in carbon atomic content on brass surface after modification. Moreover, Fig. 7 illustrates that for the three considered cases, the approximating lines have different slope angles, the highest slope angle is observed at 75% of laser power.

VI. CONCLUSION

It has been demonstrated that, using laser texturing of brass surface, it is possible to form micro-/nanoscale relief with the required geometrical parameters, for instance, in the form of equidistant by 100 µm lines.

It has been detected that the wetting angle decreases with the increase in atomic content of carbon on the surface after modification.

The optimum parameters of laser radiation have been determined for production of the most energy efficient hydrophobic brass surfaces: at the beam scanning rate of 100 mm/s and the laser power of 15 W, the surface was obtained with the wetting angle of 149º and the roll-off angle of 3º, and at the laser power of 20 W, the wetting angle was 147º and the roll-off angle was 2º; in both cases the relief was in the form of equidistant by 100 µm lines.

ACKNOWLEDGMENTS

This work was supported by the Ministry of Science and Higher Education of the Russian Federation, the grant of the President of the Russian Federation for governmental support of young Russian scientists No. MD-2946.2019.8 (Agreement No. 075-15-2019-330 dated June 13, 2019).

REFERENCES

[1] A.H. Alamri., Localized corrosion and mitigation approach of steel materials used in oil and gas pipelines – An overview, Engineering Failure Analysis. 116 (2020) 104735.

[2] A.V. Pridatko, A.V. Mironyuk, and V.A. Sviderskii., Analiz podkhodov k matematicheskomu opisaniyu kharakteristik materialov s povyshennoi gidrofobnost'yu [Analysis of approaches to mathematical description of materials with higher hydrophobicity], Vostochno-Evropeiskii zhurnal peredovykh tekhnologii. 25(77) (2015) 30-41.

[3] M. Liravi, H. Pakzad, A. Moosavi, and A. Nouri-Borujerdi, A comprehensive review on recent advances in superhydrophobic surfaces and their applications for drag reduction, Progress in Organic Coatings. 140 (2020) 105537.

[4] A.V. Ryzhenkov, M.R. Dasaev, and S.V. Grigor'ev., Ispol'zovanie lazernogo oborudovaniya s tsel'yu povysheniya effektivnosti i nadezhnosti truboprovodov [Using laser equipment for improvement of efficiency and reliability of pipelines], in Advanced innovative developments. Challenges and experience, issues of commercial implementation. Proceedings: 9th International Conference, October 31, Part 1. (2019) 176-180.

[5] M. Langer, and D. Otto., Metody issledovaniya poverkhnostnykh kharakteristik polimerov posle plazmennoi obrabotki [Studying surface properties of polymers after plasm treatment], Analitika. 8(2) (2018) 68-74.

[6] X. Zhang, and Y. Qin., Contact angle hysteresis of a water droplet on a hydrophobic fuel cell surface, Journal of Colloid and Interface Science. 545 (2019) 231-241.

[7] L.B. Boinovich, and A.M. Emel'yanenko., Gidrofobnye materialy i pokrytiya: printsipy sozdaniya, svoistva i primenenie [Hydrophobic materials and coatings: principles of development, properties and application], Uspekhi khimii, 77(7) (2008) 619-638.

[8] M.-J. Chuang, and A.-K. Chu., Formation of a high hydrophilic/hydrophobic contrast surface on PET substrates by ECR generated sulfur hexafluoride plasma, Applied Surface Science. 257(9) (2011) 3943-3947.

[9] Ch. Ma, L. Wang, A. Nikiforov, Yu. Onyshchenko, P. Cools, K. Ostrikov, N.D. Geyter, and R. Morent., Atmospheric-pressure plasma assisted engineering of polymer surfaces: From high hydrophobicity to superhydrophilicity, Applied Surface Science. 535 (2020) 147032.

[10] K. Ravi, W. Lock Sulen, Ch. Bernard, Y. Ichikawa, and K. Ogawa., Fabrication of micro-/nano-structured super-hydrophobic fluorinated polymer coatings by cold-spray, Surface and Coatings Technology. 373 (2019) 17-24.

[11] Sh. Wang, Y. Xue, Ch. Ban, Y. Xue, A. Taleb, and Y. Jin., Fabrication of robust tungsten carbide particles reinforced Co-Ni super-hydrophobic composite coating by electrochemical deposition, Surface and Coatings Technology. 385 (2020) 125390.

[12] Zh. Yang, X. Liu, and Y. Tian., Novel metal-organic super-hydrophobic surface fabricated by nanosecond laser irradiation in solution, Colloids and Surfaces A: Physicochemical and Engineering Aspects. 587 (2019) 124343.

[13] G.B. Shirsath, K. Muralidhar, R.G.S. Pala, and J. Ramkumar., Condensation of water vapor underneath an inclined hydrophobic textured surface machined by laser and electric discharge, Applied Surface Science. 484 (2019) 999-1009.

[14] D. Huerta-Murillo, A.I. Aguilar-Morales, S. Alamri, J.T. Cardoso, R. Jagdheesh, A.F. Lasagni, and J.L. Ocaña., Fabrication of multi-scale periodic surface structures on Ti-6Al-4V by direct laser writing and direct laser interference patterning for modified wettability applications, Optics and Lasers in Engineering. 98 (2017) 134-142.

[15] H. Yan, M.R.B. Abdul Rashid, S.Y. Khew, F. Li, and M. Hong., Wettability transition of laser textured brass surfaces inside different mediums, Applied Surface Science, Part B. 427 (2018) 369-375.