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DETERMINATION OF THE EFFICIENCY OF SHOT BLASTING OF METAL SURFACES

The object of this research is the process of transformation of kinetic energy of the attacking air-abrasive torch in the process of dynamic impact on metal surfaces of products during their shot blasting.

The importance of the research is due to the need to solve the problem of increasing the efficiency of the technological process of preparing metal surfaces of products by shot blasting for the subsequent application of protective, stable non-metallic coatings.

In the work, based on the energy balance of the "shot-obstacle" system, a method for determining the efficiency coefficient of the shot blasting surface preparation process was developed, which was associated with the torch energy recovery coefficient. The relationship of the coefficients with the potential energy of the surface layer accumulated in the process of elastic deformation was established. The depth of the hole formed by the shot on the surface of the attacked body was taken as a measure of this energy. When determining the depth of the hole, the deformation of an elementary cylindrical element clamped in the surface layer of the attacked body was considered, the dimensions of which are compatible with the dimensions of the elastic deformation hole.

The classical recovery coefficient is not a characteristic criterion for revealing the physical aspects of the complex multifactorial shot blasting process. The ease of application in practical calculations, especially when establishing the productivity of the process, prompts the search for improving the methods of its determination, since the existing models of an ideal impact in this case are not capable. This coefficient at average attack speeds of 100–120 m/s and angles of 40° < α < 70° turned out to be 15–20% less than the classical one.

The obtained research results can be used to increase the productivity of the shot blasting process of products of the defense, agricultural, machine-building, chemical, aviation and other industries.

***Keywords**: energy balance, shot blasting, efficiency, ricochet velocity.*

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1. Introduction

Increasing the efficiency and reliability of technological processes for surface treatment of metal products is one of the key tasks of modern mechanical engineering, especially in conditions of high requirements for quality, durability and wear resistance of parts. One of the common methods of surface preparation is shot blasting, which provides high-quality cleaning of metal surfaces, forming a given roughness, and also strengthens the surface layer. This process is widely used in the production of machinery, defense, medical, aviation, energy and construction equipment, as well as in vehicle maintenance.

The effectiveness of shot blasting largely depends on the dynamics of the interaction of attacking abrasive particles (shots) with the metal surface. In this context, the recovery coefficient, as a measure of energy absorption, is an important parameter that determines the degree of impact on the surface layer, and therefore the volume of removed metal, which is an indicator of process productivity. The classical models of Johnson et al. [1] of a single impact for determining the recovery coefficient are unable to take into account the complex phenomena that occur during a mass attack (≈5 million per minute) of pellets under shot blasting conditions. These phenomena relate to the destruction of the surface layer, changes in the shape and size of the shot, the probability of collision of the attacking pellets with ricocheting pellets, chipping (~1 fragment per mm^2) [2], adhesion and other effects.

An analysis of recent studies on shot blasting indicates insufficient attention to the energy balance of the process. Thus, in [3] the results of shot blasting of steel reinforcement and their effect on the dynamic characteristics after low-cycle fatigue tests are presented. It was found that shot blasting provides a slowdown in the onset of corrosion, since compressive stresses act on the outer surface of steel samples. The authors of [4] considered the effect of the size of abrasive particles from ~20 μm to ~50 μm used for processing on the microstructure of thermal barrier coatings at different process parameters. However, in both cases, as in a number of other works [1], energy losses were not analyzed, the energy distribution between deformation and microcracks formed during processing was not investigated. The lack of models that take into account the full energy balance during abrasive blasting is also emphasized in [5]. In [6], studying the quality of adhesion of Al and Cu coatings to a Q355B steel substrate, the effect of the size of the abrasive fraction of shot blasting was found, without describing the energy component. Although the researchers in [7] indicated the influence of different types of media on energy consumption during processing of low-carbon steel, they also did not analyze the mechanisms of energy distribution. This confirms the need to create complex models of energy interactions during shot blasting.

The collision of bodies is evaluated mainly by the coefficient of recovery, a parameter that measures the elasticity during collision. This parameter is used to predict the behavior of particle rebound after impact [8]. The problem of determining the coefficient of recovery during impact interaction of abrasive particles with a metal surface remains one of the main ones in research related to surface treatment technologies of various materials. The foundation for the analysis of this process is the understanding of the laws of energy exchange, in particular the relationship between dynamic hardness, elastic energy and ricochet kinetics. Scientific works of recent years focus on a comprehensive understanding of the coefficient of recovery of particle (grain) velocity, which significantly affects the quality of processing, the duration of the abrasive resource and the productivity of the process. Thus, the authors of [9] proposed an improved model for calculating the contact force taking into account the yield point, which improves the estimation of the coefficient of recovery, but does not take into account the influence of the roughness and shape of the abrasive particles. In the study [10], it was experimentally established that an increase in the diameter of the shot leads to greater plastic deformation and higher energy losses, and therefore, lower recovery coefficients.

In [11], it was experimentally established that chipping, delamination, oxidative wear and plastic deformation are the main mechanisms of impact wear of TP316H steel. With increasing impact, the recovery coefficient increases, but the quantitative description of energy losses remains difficult. And in [12], the dependence of the recovery coefficient on the materials of the contacting bodies and the shape and size of the shots was experimentally established. Scientists describe the nature of energy dissipation during contact. Researchers numerically model the collision of spherical and non-spherical particles with plastic surfaces at different angles of attack from 0° to 90° [13], which brings the study closer to real conditions of shot blasting.

The influence of wave processes and plate thickness on the recovery coefficient in the collision of spheres with elastic-plastic surfaces was studied in [14], where a significant role of the plate material properties was noted. A very good correspondence was found between the results obtained experimentally and by the finite element method. Scientists in works [15–17], based on the developed elastic-plastic model, investigated the effective operation time of technical shot during the processing of metal products and assessed the quality criteria for cleaning metal surfaces. In the cited works, the distribution and energy consumption between different components of the resistance forces during the collision of the shot with an elastic-plastic half-space are also ignored. The analytical model [18] takes into account the impact velocity and the geometry of the obstacle, and shows that reducing the plate thickness significantly reduces the recovery coefficient due to wave effects and plastic deformations. In [19], the complex influence of various factors on the recovery coefficient is taken into account, which helps to increase the accuracy of predicting motion trajectories, but does not take into account the conditions of a multifactorial process. Thus, the sources considered indicate the difficulty of accurately estimating the recovery coefficient in shot blasting as a measure of energy absorption due to the multifactorial nature of the process and the lack of models that take into account the full energy balance.

The object of this research is the process of transformation of the kinetic energy of the attacking air-abrasive torch in the process of dynamic impact on the metal surfaces of products during their shot blasting.

The aim of research is to establish the coefficient of useful action of shot blasting of metal surfaces based on the energy balance of the contact interaction of the torch with the metal surface, with the release of a portion of energy directed to performing useful work.

To achieve the aim, it is necessary to perform the following tasks:

1. Conduct an experimental and analytical analysis of the distribution of the kinetic energy of the shot blasting torch depending on its individual effects on the attacked surface.
2. Determine the recovery coefficient during shot blasting on steel surfaces and, as a result, the coefficient of useful action of the process.
3. Establish the influence of the torch energy recovery coefficient on the productivity of the steel surface treatment technology.

The research is aimed at improving the understanding of impact-deformation processes and forming practical foundations for increasing the efficiency of shot blasting technology for metal surfaces and finding production reserves.

2. Materials and Methods

The determination of the recovery coefficient during shot blasting was based on a comprehensive approach that combines theoretical analysis, mathematical modeling and experimental research.

Conducting a theoretical analysis of the mechanism of interaction of pellets with a metal surface, which includes a description of the phases of elastic-plastic deformation, the transition of the kinetic energy of the pellet into the potential energy of deformation and destruction of the surface layer. As well as determining the energy consumption for internal and external friction, plastic deformation, microcutting and other physical phenomena of the complex shot blasting process. For this purpose, the classical laws of deformed body mechanics, models of impact theory, as well as the principles of energy balance were used.

The formulation of analytical dependencies describing the work performed by a single shot is endowed with a generalized mass impact function on the treated surface. Special attention was paid to taking into account energy losses due to various components of the surface resistance forces due to mass attack by a shot-jet torch. For this purpose, experimental proportionality coefficients were introduced, which reflect the share of work spent on various types of torch impacts on the treated surface and possible self-absorption of energy.

Standard steel balls according to GOST 3722-2014 were used to hit a single shot on a test sample made of steel 10. The attack and ricochet speeds of the shot were measured using a certified optoelectronic measuring complex IBKh-731 (LLC "Latek", Ukraine). Using a digital microscope Adoreco Inskam 315 (China) and a micrometer, the experimental dimensions of the attack and ricochet traces were determined.

Factory studies of the effect of an abrasive torch, the length of which was 100, 200 and 300 mm, on the surface destruction process were carried out using a pumping-type apparatus on flat round metal samples with a diameter of 80 mm made of steel 10 and 09G2S, subjected to normalizing annealing. Standard steel balls of different grain sizes of 0.6–1.2 mm were used, which were accelerated to a planned speed of 100–120 m/s using compressed air (0.6 MPa) through a cylindrical nozzle with a material hole diameter of 6, 8 and 10 mm at angles of attack from 20° to 90°. The shot feed through a nozzle with a diameter of 10 mm per unit of time was 20–25 kg/min, with a diameter of 8 mm – ~15 kg/min and with a diameter of 6 mm – ~10 kg/min. A total of 48 samples were studied. By weighing the samples before and after cleaning, the mass of metal removed per unit of time was determined and the useful work (destruction coefficient) of the mass attack of the pellets was determined.

3. Results and Discussion

In the zone of interaction of the air-abrasive torch with the attacked surface, various physical and mechanical processes occur [20]. These processes lead to the destruction of the surface layer and the transformation of energy of both the individual attacking shot and the torch as a whole, which determines the degree of useful action of shot blasting of metal surfaces of products. The coefficient of useful action of shot blasting based on the energy balance of the process is defined as the ratio of the useful work of the torch to the work performed during the contact attack

$$\eta=\left(\frac{A_{cor}}{A}\right)=\left(1-k_r^2\right). \tag{1}$$

This coefficient depends on k_r, the coefficient of recovery of the energy parameters of the reflected torch, i. e. the average velocity of the ricocheting shots.

To simplify the description of the issue, it is possible to give an individual shot the function of the mass impact on the attacked surface with the appropriate energy distribution. But first, let's establish the nature of the effect of the phenomenon of irreversible loss of initial energy of the torch, such as the probability of collision of attacking pellets with ricocheting ones, which leads to the effect of self-absorption of energy even before contact with the surface. To do this, it is possible to use our factory experimental studies of the destruction coefficient k_d of the surface layer in the shot blasting process (Fig. 1), linking it, as a measure of useful work, with the irreversible self-absorption of the initial energy of the torch.

These studies of the impact of the shot blasting torch indicate an almost proportional increase in the destruction coefficient with increasing angle of attack a. At $\alpha > 70°$, the growth intensity slows down and even decreases (Fig. 1, dashed line). The latter is explained precisely by the increasing decrease at large angles of the number of working attacking pellets in the torch due to their collision with ricocheting pellets. It is difficult to analytically assess such an effect, although it makes no sense to do so, since the rational angles of attack for shot blasting are angles $40° < \alpha < 70°$, when the effect of the collision of pellets can be neglected (Fig. 1) and the nature of the destruction of the surface layer at angles $\alpha < 40°$ is not corrected. When changing the process modes within the usual limits for shot blasting, the nature of the dependence "destruction coefficient – angle of attack" practically does not change.

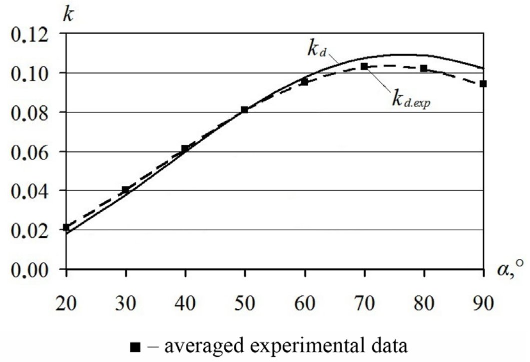

Fig. 1. Dependence: destruction coefficient k_d – angle of attack α

Therefore, let's consider the energy balance of the "shot-obstacle" system at angles of attack $40° < \alpha < 70°$, which fully satisfies the aim of research. The energy balance of the system is that at each moment of time the total energy of the system is a constant value. It is equal to the sum of the instantaneous values of the kinetic energy of the body T and the work of the inertial force A, spent on deformation and other effects that change the state and shape of the surface layer. That is, a separate attacking shot, to which the functions of mass influence were delegated in the process of interaction with the surface, performs a certain amount of work A_a, which is equal to the kinetic energy of the attacking shot

$$A_a = T_a = mv^2/2, \tag{2}$$

where m – the mass of the shot; v – the speed of attack by the shot on a stationary surface.

The energy of the shot is spent in the form of work performed on elastic and plastic deformation, microcutting, abrasion of the treated surface, on internal and external friction in the surface layer, possible rubbing, etc.

$$A_a = \sum_{i=1}^{n} A_i, \tag{3}$$

where $A_1 = A_{el}$ – work spent by the shot on elastic deformation; $A_2 = A_{pl}$ – work spent on plastic deformation; $A_3 = A_{s.fr}$ – work spent on overcoming external friction forces; $A_4 = A_{fr}$ – work spent on internal friction in the surface layer; $A_5 = A_{mc}$ – work spent on microcutting.

In (3), it is possible to limit ourselves to $n = 5$, although there may be more types of work, for example, losses on wave processes and so on.

Let's consider the process of shot attack on the plane of the elastic-plastic half-space using the example of a direct impact. Let's divide the process into two phases.

The first phase of the process, associated with shot attack, begins with the moment of collision with a metal obstacle. Elastic deformation of the treated surface to a certain depth h_{el} occurs, the value of which depends on the physical and mechanical properties of the material of the attacked body.

During the elastic deformation time t_{el}, part of the kinetic energy of the attacking pellet is converted into the potential energy P of the deformed surface layer, which is equal to the work $A_{el} = P$ spent by the pellet on elastic deformation of the surface.

After elastic deformation, the hole is plastically extruded during the time t_{pl}. The pellet is then deepened into the surface layer by a certain amount h_{pl}. Having exhausted the entire reserve of kinetic energy T for performing work A_a (3), the pellet stops at a certain point at a depth h. The first phase is over.

The second phase begins, which is associated with the ricochet of the pellet. The duration of the phase is t_p, during which the reverse transition of the potential energy P accumulated by the obstacle into the kinetic energy of the pellet T_p occurs, which induces its ricochet. In this case, the depth h of the formed hole is reduced by the amount h_{el}.

The total duration of the impact t is the sum

$$t = t_{el} + t_{pl} + t_p.$$

The work done A_p is equal to the kinetic energy T_p of the ricocheting pellet

$$A_p = T_p = \frac{mu^2}{2} = \frac{m(k_r v)^2}{2}, \tag{4}$$

where u – the ricocheting velocity of the pellet (second phase); $k_r = u/v$ – the coefficient of recovery of the pellet's attack velocity.

Thus, the work done by the pellet is the difference

$$A = A_a - A_p = \frac{mv^2}{2} - \frac{mu^2}{2} = \frac{m}{2} v^2 \left(1 - k_r^2\right). \tag{5}$$

As is seen, the value of the work performed A is significantly affected by the recovery coefficient k_r. The lower it is, the greater the work performed. Accordingly, the work A_{el}, which is spent by the shot to overcome the elastic forces of the treated surface and is proportional to the work A_p (4), decreases with a decrease in the recovery coefficient.

In this regard, the task of experimentally and analytically determining the recovery coefficient k_r for specific conditions of shot blasting cleaning of metal products arises, which are noticeably different from the studied processes of ideal impact of solid spherical bodies on a stationary obstacle with elastic-plastic properties [14, 15].

The attacking shot acts on the surface with a certain impact force F_a, the magnitude of which decreases as the shot penetrates the metal obstacle (as the kinetic energy decreases). The treated surface resists the action of the active impact force F_a with a certain variable increasing force

$$F_R=\sum_{i=1}^{n}F_{Ri},$$

formed from individual components that perform the corresponding parts of the work A_i, given in (3).

Thus, to penetrate the metal surface to a depth h, the attacking shot must perform the work

$$A_a=\sum_{i=1}^{n}A_{Ri}, \tag{6}$$

where i = 1...5, the content of which corresponds to the explanation of (3).

The work performed due to the averaged main resistance forces in expanded form is written as

$$A_a=F_{R1}h_{el}+F_{R2}h_{pl}+\left(F_{R3}+F_{R4}+F_{R5}\right)h. \tag{7}$$

Creating an analytical method for determining the work performed by the torch in such a multifactorial technological process in terms of changing initial conditions over time is not promising. Therefore, a system of coefficients obtained by direct and indirect experimental studies related to the energy balance and productivity of the shot blasting process was applied.

As shown by the conducted studies, 10–15% of the total work is spent on plastic deformation of the holes (A_{R2}). The work to overcome the external friction forces and microcutting, i. e. A_{R3}, A_{R5}, are insignificant, as are the others were not taking take into account. The greatest work is performed by the pellets when overcoming the internal friction forces A_{R4}. The total share of the work of these forces through the proportionality coefficient k_i, which takes into account the measure of the work performed to overcome the corresponding forces $\left(\sum_{i=1}^{2...5}A_{Ri}=\sum_{i=1}^{2...5}k_iA_a\right)$, reaches 90–95% of the work performed. Thus

$$\sum_{i=1}^{2...5}A_{Ri}=\sum_{i=1}^{2...5}k_iA_a=k_gA_a, \tag{8}$$

where k_g = 0.90–0.95 is the generalized proportionality coefficient, which takes into account the share of the work performed, except for the work spent on the elastic deformation of the holes.

A similar energy distribution is confirmed by the experimental results obtained in the study of single impacts of the pellet [17]. The satisfactory coincidence of the depth limit of the attacking pellet with the viscoelastic resistance of the material with its experimental values indicates an insignificant (up to 5%) influence of elastic deformations, i. e. elastic resistance of the material.

It is possible to assume that the elastic and plastic resistance forces act sequentially, while the action of other resistance forces is simultaneous. Therefore, it is possible to assume that the work of the elastic resistance force F_{R1} of the attacked surface is a certain fraction of the work done by the attacking pellet

$$A_{R1}=A_a\left(1-k_g\right). \tag{9}$$

Work A_{R1} of the elastic resistance force F_{R1} on the path h_{el}, which is completely accumulated in the potential energy P of the surface layer of the processed product. This work accumulates in the process of elastic deformation and is converted into the kinetic energy of the pellet, which induces ricocheting. Therefore, when the elastically deformed well is straightened by the value h_{el}, work A_{R1} is performed, which is spent on ricocheting the pellet. It is equal to

$$A_{R1}=\frac{\left(F_{R1}h_{el}\right)}{2}=\frac{\pi dHD_{el}h_{el}^2}{2}. \tag{10}$$

Since $A_{R1}=A_p=mu^2/2$, then the velocity u of the pellet ricochet is found as

$$u=h_{el}\sqrt{\pi d\frac{HD_{el}}{m}}, \tag{11}$$

where HD_{el} – the dynamic hardness of the processed surface during elastic deformation.

As is seen, the ricocheting velocity of the pellet is proportional to the depth of the well h_{el}, formed in the process of elastic deformation of the surface, the value of which remains unknown. In this regard, let's imagine the local surface layer of the product attacked by the shot in the form of an elastic element of cylindrical shape, which is clamped in a metal base. The geometric dimensions of this element are related to the dimensions of the hole formed by the shot, depth h_{el}: diameter and height of the element $d_e=h_e=2\sqrt{dh_{el}}$, cross-sectional area $f_e=\pi dh_{el}$.

Then, based on Hooke's law, taking into account $\left(A_{R1}=\frac{\left(F_{R1}h_{el}\right)}{2}\right)$, the maximum possible value of the elastic deformation of the element can be determined by the formula

$$h_{el}=\sqrt[5]{\frac{1}{d}\left(\frac{2A_{R1}}{\pi E}\right)^2}, \tag{12}$$

where $A_{R1}=A_p$ – work of accumulated potential energy upon impact (A_p – work performed by the shot during ricochet); E – modulus of elasticity of the attacked metal; d – diameter of the shot.

Given that

$$A_p=\left(1-k_g\right)mv^2/2,$$

where k_g – a generalized proportionality coefficient that takes into account the fraction of work performed, except for the work spent on elastic deformation of the holes

$$h_{el}=\sqrt[5]{\frac{1}{d}\left(\frac{\left(1-k_g\right)mv^2}{\pi E}\right)^2}. \tag{13}$$

The maximum elastic resistance force $F_{R1}^{\max}$ is calculated by the formula

$$F_{R1}^{\max}=f_eHD_{el}. \tag{14}$$

Considering the high pressure developed by the shot during interaction with the metal surface, it can be assumed that the dynamic hardness of the metal HD_{el} during elastic collision with an obstacle exceeds the generalized literature data, as evidenced by indirect data of many researchers.

It is possible to calculate the elastic deformation measure by the depth of the hole h_{el} by (13), and the speed u of the shot ricochet by (11). Next, it is possible to determine the recovery coefficient of the averaged velocity $k_r=u/v$ of the ricochet of the working shots during a direct attack of the treated surface during the shot blasting process.

Thus, the efficiency of shot blasting based on the energy balance of the process will be determined by (1) as

$$\eta=\left(1-k_r^2\right)=\left(1-\left(\frac{u}{v}\right)^2\right). \tag{15}$$

As for the oblique impact, which corresponds to the shot blasting technology, when it mainly occurs at jet inclination angles α > 40–45°, in practical calculations, the recovery coefficient for direct impact is mostly used. If necessary, it is possible to consider the contact interaction of the shot with the attacked surface in two planes – normal and tangential.

Experiments confirm the applied approaches to the distribution and energy consumption between different components of the resistance forces in the process of the shot's collision with the elastic-plastic half-space, and the possibility of analytically determining the efficiency coefficient for shot blasting according to (15). At the same time, the use of the classical coefficient k_r of the recovery of velocity upon impact in calculations of the productivity of shot blasting of steel surfaces at generally accepted technological modes leads to an underestimation of the efficiency coefficient of the process by 15–20%.

The research results will contribute to a deeper understanding of the mechanisms of energy redistribution in the process of shot blasting of metal surfaces and to the improvement of resource characteristics and coordination of technological modes of the process. This will allow optimizing technological costs and ensuring the required quality of steel surfaces of products. The obtained research results can be used to increase the productivity of the technology of shot blasting of products of the defense, agricultural, machine-building, chemical, aviation and other industries.

The obtained experimental results, which are the basis of the conclusions, concerned steel 10 and 09G2S, subjected to normalizing annealing. The studies were carried out under rational technological modes of shot blasting: attack speed 100–120 m/s; attack angle $40° < \alpha < 70°$.

Further studies should focus on the development of models that cover the influence of the spectrum of phenomena accompanying the shot blasting process on the useful work of the torch and on experimental studies of the components of the distribution of kinetic energy of the attacking torch. It seems advisable to experimentally adapt the obtained results to determine the coefficient of efficiency of the technology of shot blasting of surfaces of products made of different materials.

4. Conclusions

1. The greatest work is done by the pellets when overcoming internal friction forces. 10–15% of the torch energy is spent on plastic deformation of the holes, and the costs for overcoming external friction forces and microcutting are insignificant. The share of energy spent on elastic deformation (13) is 4–5% of the total kinetic energy of the torch in rational shot blasting modes of steel surfaces.
2. The value of the classical recovery coefficient upon impact gives underestimated performance indicators of the shot blasting process. The recovery coefficient during shot blasting cleaning according to our studies at average attack speeds of 100–120 m/s and angles of $40° < \alpha < 70°$ turned out to be 15–20% less than the classical one.
3. The coefficient of recovery of the initial energy during shot blasting directly affects the efficiency (productivity) of the technological process. The lower the recovery coefficient, the greater the work performed, aimed at a useful result – cleaning metal surfaces by reducing the work spent by the pellet on overcoming elastic forces.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship-related, or any other type that could have influenced the research and its results presented in this paper.

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Data availability

The manuscript does not include related data.

Use of artificial intelligence

The authors confirm that no artificial intelligence technologies were used in the preparation of this work.

Authors' contributions

Oleksii Goryk: Conceptualization, Methodology, Formal analysis, Writing – original draft, Supervision, Project administration; ***Oleksandr Brykun***: Formal analysis, Validation, Investigation, Writing – review and editing, Visualization, Data curation; ***Oleg Kalashnykov***: Software, Investigation, Data curation, Visualization, Writing – original draft; ***Andrii Buchynskyi***: Investigation, Resources, Data curation, Formal analysis, Writing – original draft.

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