UDC 623.482

O. Kriukov **H. Silin**

INVESTIGATION AND MATHEMATICAL MODELLING OF DEFECTS IN BARREL CHANNELS: DIAMETER WEAR, FIELD ABRASION AND THE EDGES OF THE CUTS, THE FIELD CUT

The peculiarities of the shape of defects in the barrel channels and mathematical modelling of the surfaces of damaged areas are considered.

Methods for describing the characteristic forms of defects in barrel channels, namely: diametric wear of a smooth barrel channel, as well as a pitting of the flank, abrasion of the flank and cutting edges of a rifled barrel channel, are proposed. The mathematical expressions in the form of algebraic equations were obtained, which give a formalised description of the surface areas formed in the barrel channel as a result of the occurrence of these defects.

A study of the similarity of mathematical models to their physical prototypes was carried out on the basis of graphical reproduction of the surfaces of the specified defects of the barrel channel in accordance with their equations using specialised software.

Keywords: *barrel channel, technical diagnostics, barrel channel defect, mathematical model, diameter wear, flank abrasion, flank piercing, flank abrasion, cutter face abrasion.*

Statement of the problem. An analysis of the use of firearms in modern armed conflicts shows that the increased use of fire modes, untimely maintenance, and the use of low-quality ammunition lead to faster and premature wear of the barrel channels [1]. During combat operations, there may also be improper or untimely maintenance of forms for individual weapons, which causes some uncertainty about the current technical condition of the CW [2]. The combination of these factors requires increased requirements for the quality of technical diagnostics (TD) of barrel channels and the reliability of its results.

A well-grounded and promising direction for improving the process of TD of barrel channels is the introduction of operational technical diagnostics [3] using a promising diagnostic complex based on a laser triangulation tool for measuring the geometric characteristics of the CS [laser measuring tool (LMT)].

In accordance with [4], the structure of the LZV is conditionally divided into two components: the measuring channel and the computing component. The measuring channel is used to obtain an array of CS radius values in a cylindrical coordinate system with predefined longitudinal (axial) and angular steps. Based on this measurement information and with the help of the computing component, a scan of the borehole channel surface is subsequently built in a rectangular coordinate system. The X-axis of this coordinate system is oriented parallel to the longitudinal axis of the BHA, and the Y-axis is perpendicular to the X-axis in the scan plane. The Z-axis is orthogonal to the scan plane XY and corresponds to the normal to any of the points of the CS surface in the original (cylindrical) coordinate system. Thus, a geometric 3D model of the borehole channel is created in the form of a scan of its surface in a rectangular coordinate system. According to the measured information about the coordinates of the points of the obtained surface, the computing component detects areas of the BC with geometric characteristics that deviate from their nominal values (i.e., areas containing defects), as well as assigns the detected defects to one of the predefined types (defect type identification).

Despite the existence of studies that address the issue of developing a measuring channel for the above-mentioned LZV, the problem of creating a computational component remains unresolved today. In particular, to substantiate the methods of defect type identification and further algorithmisation of this process, it is necessary to create mathematical descriptions (models) of common defects in the borehole channel, which can then form the basis of a set of indicators and criteria that will be used to decide whether the detected defect belongs to one of the predefined types.

Despite the availability of some information in the literature on the types of defects in the CS, it is mostly statistical or descriptive in nature. In this regard, at the initial stage of development of the computing component of the measuring instrument, the problematic issue of creating mathematical models of typical defects of firearms CS should be resolved.

Analysis of recent research and publications. The issues of studying the geometric shapes and modelling of borehole defects are considered in a number of domestic and foreign publications.

The textbook [5] describes the basics of representing elementary surfaces in the form of equations. However, this source does not consider the construction of complex surfaces that can describe the geometric shape of the CS defect. The authors of articles [6] and [7] proposed mathematical descriptions of the abrasion of the breech and muzzle parts of the barrel channel, as well as the swelling of the CS. These expressions are used for the analysis of longitudinal sections of the barrel channel and cannot be used for cases of processing data from three-dimensional models of the CF surface.

Paper [8] describes the use of machine learning models in the process of classifying defects in the wellbore channels based on their photographic images. However, this paper considers only a limited number of types of CS defects, and their identification is based on the analysis of photographs, which significantly complicates the acquisition and consideration of information about the depth of defects. Paper [9] investigates the mathematical modelling of artificially damaged surface areas using interstriping operators. This method of surface modelling is used only for certain areas of a mathematically defined surface, which does not satisfy the conditions for modelling the surfaces of CS defects.

The modelling of the damaged surface of the barrel channel by the mesh generation method is introduce certain terms and definitions that significantly simplify the description of surface proposed in [10]. The authors also determined the effect of rifling damage on the ballistic parameters of a bullet. However, this work covered only partial damage to the rifled part of the barrel channel and does not generalise the effect of the entire variety of defects on the geometric parameters of the CS.

The analysis shows that the available sources of information either do not consider scientific approaches to mathematical modelling of firearms barrel channel defects at all or cover them only partially and in a limited way.

Evaluating the results of studies of barrel channel surfaces with defects of various types [11], it can be concluded that some of them have common features for both types of barrels – rifled and smooth, while others are different (specific): some are characteristic of rifled, others – of smooth. Defects common to both rifled and smoothbore barrels include cracks, pitting and swelling. Specific to rifled barrels are, for example, rifling field abrasion, rifling edge abrasion (especially in combat) and rifling field pitting. Uniform diametrical wear of the bore surface, especially in the immediate vicinity of the breech and muzzle, can be considered a defect that is predominantly characteristic of smooth barrels.

Given the limitations of the journal article, this paper considers only mathematical descriptions of defect surfaces that are specific to either rifled or smooth barrel channels.

The purpose of the article is to analyse the characteristic features of the shape of common specific defects of the barrel channel, namely: diametric wear of the smooth barrel channel, field pitting, field abrasion, and abrasion of the faces of the rifled barrel channel cuts. The article is also aimed at substantiating the mathematical description of the surfaces formed by these defects.

Summary of the main material. At the first stage of work in this area, a detailed study of damaged barrel channels on various types of weapons was carried out. The analysis examined the causes of defects, their nature and propagation mechanism, as well as the shape and size of actual damage in a wide range of firearms samples. The data obtained made it possible to generalise the patterns of formation and development of damaged areas of the CS, as well as to determine the ranges of typical geometric parameters of characteristic defects. The further transition to mathematical modelling of CS defects prompted the authors to sweeps and bodies formed as a result of the appearance of defective CS areas (Figure 1).

The body of the borehole defect, T, is the part of the space bounded by the surface of the defective section of the borehole and the imaginary undamaged surface of the same CS.

The base of the defect, D, is a figure on the plane formed by a curve describing the intersection of an imaginary undamaged surface of the barrel channel with a depression (defect) in it.

Defect base contour, l_D is a closed curve that describes the intersection of the undamaged surface of the borehole channel with a depression (defect) in it and forms the base of the defect.

The longitudinal axis of the *defect base, a* is a straight line connecting the two most distant points of the defect base contour.

Centre of *the defect base,* O_B is a point dividing in half the segment of the longitudinal axis of the defect base between the points of its intersection with the contour of the defect base.

The length of the defect, L, is the length of the longitudinal axis segment between the points of its intersection with the contour of the defect base.

The transverse axis of the defect base, b, is a straight line that passes through the centre of the defect base at right angles to the longitudinal axis of the defect base.

Defect width, W, is the length of the segment lying on the transverse axis of the defect base and is equal to twice the length of the perpendicular dropped on the longitudinal axis of the defect base from the point furthest from it, which belongs to the contour of the defect base.

Defect depth, a_D is the length of the perpendicular lowered to the base of the borehole channel defect from the farthest point of the defect body.

The angle of rotation of the defect base, α, is the smallest of the adjacent angles formed by the longitudinal axis of the defect base and the abscissa axis.

Displacement of the defect base centre along the abscissa and ordinate axes, $x_\Delta y_\Delta$ – coordinates of the projection of the defect base centre onto the corresponding axes of the coordinate system.

It is well known that the mathematical representation of any surface or its part can be made in the form of an algebraic equation *f*(*x*,*y*). In the Cartesian coordinate system, this equation describes the dependence of the applicativity of a point *z* belonging to the surface on its abscissa *x* and ordinate *y*. All points on the surface satisfy this equation. Let us consider separately the geometric features of the defects of the CCW, characteristic of smoothbore and rifled weapons, as well as the corresponding mathematical models of surfaces that describe them approximately.

Diametrical wear is a defect that is specific to smooth barrel channels.

Diametrical wear of the barrel channel is the abrasion of the surface layer of the metal of the barrel channel as a result of the chemical and mechanical factors of the shot, and the nature of this abrasion depends on the location of the defect.

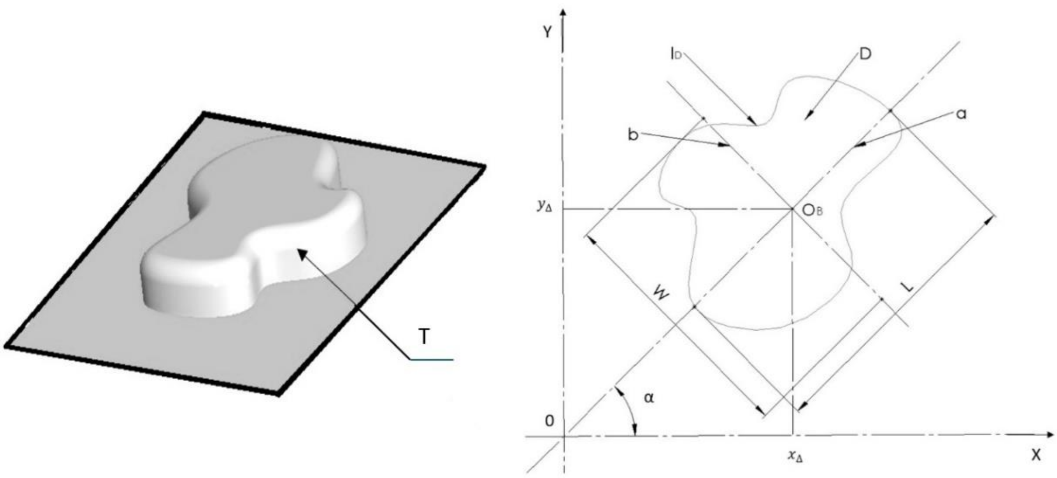


Figure 1 – Arbitrary defect in the barrel channel and its base

Thus, in the case of wear in the breech (muzzle).part, it is a local monotonically decreasing (increasing) increase in the diameter of the CS in the muzzle direction, and in the case of wear in the middle part of the CS, it is uniform. Considering that significant abrasion in the middle part of the barrel channel most often occurs when the abrasion in the breech and muzzle parts of the barrel reaches a size that is generally unacceptable for further use of the firearm, this case will not be considered further. According to previous studies of the sections of the borehole channel with such a defect [6], it is known that on the graph of the dependence of the increase in the CS radius on the longitudinal coordinate of its cross section, the curves of this function have variable angles of inclination and non-zero derivatives. However, at the initial and final points, the derivatives are still equal to zero, which indicates a smooth adjacency of the surface of the defect to the undamaged part of the CS. Taking into account these geometric features of this defect, it is advisable to describe its surface by the decreasing and increasing parts of a cosine for cases of diametric wear in the breech and muzzle parts, respectively. Thus, the surface formed as a result of the diameter wear of the barrel channel can be represented by a cosine function of the *x* coordinate (along the longitudinal X-axis) in a certain area of definition with the origin in the centre of the coordinate system:

$$z = \cos\left(\frac{x}{a_x}\right), \tag{1}$$

where a_x is the surface compression coefficient along the X-axis.

As noted above, the surface of a defect is described by a cosine function only in the area of its descent or in the area of its ascent, depending on the location of the worn surface (breech or muzzle). In both cases, these will be the sections of the function curves between the two nearest points *x* where their derivatives are zero. Then, for the case of a defect located in the breech part of the barrel channel, the area of the function $D(f)$ will be as follows:

$$D(f_{bre.\ part}) = \left\{(x,y) \in R^2 \mid -\pi \geq \frac{x}{a_x} \leq 0\right\}, \tag{2}$$

and in the case of a defect in the muzzle area

$$D(f_{muz.\ part}) = \left\{(x,y) \in R^2 \mid 0 \geq \frac{x}{a_x} \leq \pi\right\}. \tag{3}$$

Let us also take into account the need to move (raise) the surface of the defect base to the level of $f(x,y)=0$ to ensure its smooth transition to the undamaged part of the CS surface. In this case, the amplitude of the cosine wave a_A will be defined as half the depth of the diameter wear. As a result, the surface of this defect can be described by the following function:

$$z_{bre.\ part} = \begin{cases} a_A\left(\cos\left(\frac{x}{a_x}\right)+1\right),\ at -\pi \leq \left|\frac{x}{a_x}\right| \leq 0; \\ 0,\ at \left|\frac{x}{a_x}\right| < -\pi \bigcup \left|\frac{x}{a_x}\right| > 0. \end{cases} \tag{4}$$

$$z_{muz.\ part} = \begin{cases} a_A\left(\cos\left(\frac{x}{a_x}\right)+1\right),\ at\ 0 \leq \left|\frac{x}{a_x}\right| \leq \pi; \\ 0,\ at \left|\frac{x}{a_x}\right| < 0 \bigcup \left|\frac{x}{a_x}\right| > \pi. \end{cases} \tag{5}$$

The range of values of the above function covers the range from zero, which corresponds to the level of the undamaged surface of the borehole channel, to twice the amplitude of the unshifted cosine wave. Consequently,

$$E(f) = [0;\ f(0;y)]. \tag{6}$$

In most cases, the diameter wear is normal to the longitudinal axis of the CS, i.e., the function $z = \cos\left(\frac{x}{a_x}\right)+1$ depends only on *x* and does not depend on *y*. Thus, at $x \to 0$, the function $z = \cos\left(\frac{x}{a_x}\right)+1$ has a boundary $\lim_{x\to 0}\left(\cos\left(\frac{x}{a_x}\right)+1\right) = 2$, and at $x \to \infty$ it has no boundary due to its periodicity. However, provided that the surfaces of the defect and the undamaged part of the barrel channel are smoothly adjacent, the functions from system (5) at $\left|\frac{x}{a_x}\right| \leq \pi$ and $\left|\frac{x}{a_x}\right| > \pi$ have a common (one-sided) boundary at the point located on the boundary of their definition areas, which confirms the continuity of the CS surface:

$$\lim_{x\to\infty}\left(f_{bre.\ part}\right) = \lim_{x\to\infty}\left(f_{without\ def.}\right) = 0, \quad (7)$$

$$\lim_{x\to\infty}\left(f_{muz.\ part}\right) = \lim_{x\to\infty}\left(f_{without\ def.}\right) = 0. \quad (8)$$

When rotating the base of this surface around a vector normal to the XOY plane and directed from the point O_B , it is advisable to apply a well-known formula for calculating the coordinates of a point when the coordinate system is rotated [12]:

$$x' = x\cos(\alpha) - y\sin(\alpha)\,, \quad (9)$$

$$y' = x\sin(\alpha) + y\cos(\alpha)\,, \quad (10)$$

where x', y' are the coordinates of the plane points after rotating the coordinate axis;

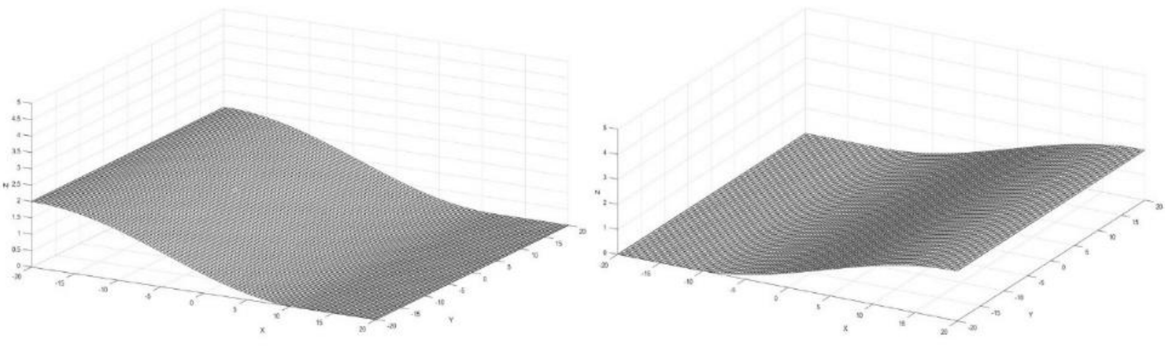
x, y are the coordinates of the plane points before the coordinate axis are rotated;

α is the angle of rotation of the base.

When substituting formulas (8) and (9) into system (5) and adding the displacement, x_Δ y_Δ of the centre of the defect model base along the X and Y-axis, the expression for the surface describing the diameter wear in the breech and muzzle parts of the CCW will take the form

$$z_{bre.\ part} = \begin{cases} a_A(\cos\left(\dfrac{x\cos(\alpha) - y\sin(\alpha) + x_\Delta}{a_x}\right) + 1 \ at \ -\pi \le \dfrac{x\cos(\alpha) - y\sin(\alpha) + x_\Delta}{a_x} \le 0; \\ 0 \ at \ \dfrac{x\cos(\alpha) - y\sin(\alpha) + x_\Delta}{a_x} > 0. \end{cases} \quad (11)$$

$$z_{muz.\ part} = \begin{cases} a_A(\cos\left(\dfrac{x\cos(\alpha) - y\sin(\alpha) + x_\Delta}{a_x}\right) + 1 \ at \ 0 \le \dfrac{x\cos(\alpha) - y\sin(\alpha) + x_\Delta}{a_x} \le \pi; \\ 0 \ at \ \dfrac{x\cos(\alpha) - y\sin(\alpha) + x_\Delta}{a_x} > \pi. \end{cases} \quad (12)$$



a *b*

Figure 2 – Surface view corresponding to the mathematical model of the diameter wear of a smooth barrel channel: *a* – breech part of the barrel channel; *b* – muzzle part of the barrel channel

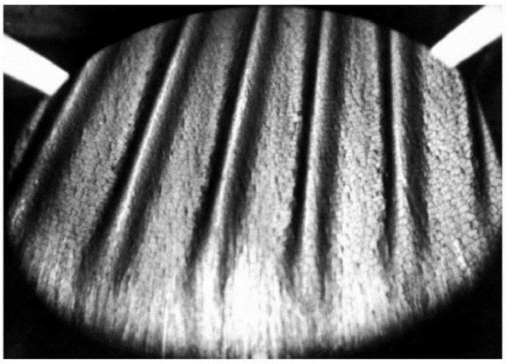
Figure 2 shows an example of a graphical representation of the surface of a smooth barrel channel in the areas of its diameter wear according to formulas (11), (12) using MATLAB software.

Defects specific to rifled guns include: abrasion of rifling fields, abrasion of rifling edges (especially combat rifling) and rifling field pitting. In contrast to smoothbore barrels, the surface of rifled barrels has a more complex and varied shape. It depends on the production technology and design parameters of the rifled barrel. It is also worth adding the specific shape of individual rifling sections and flutes, which depend on their location relative to the breech. Thus, the shape of the rifling differs significantly in two areas: the first is the connecting cone, where the fields have an increasing height to ensure smooth penetration of the projectile into the rifling; the second is the rifling part, where the fields initially have the same height, and the angle of inclination of the rifling gradually decreases as it approaches the muzzle (in the most common case, the progressive steepness of the rifling is used). Due to the limited scope of the article, this publication considers defects (pitting, abrasion of rifling margins and rifling edges) only in the part of the barrel channel most susceptible to degradation [13] – the breech rifling part and only for the example of a rectangular rifling shape with a constant rifling steepness.

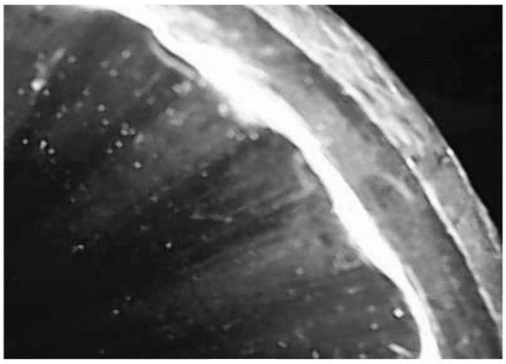
In addition to the diversity of the initial geometry of the rifled barrel channel cuts, an important factor influencing the nature of the formation of the shape of the defects in the rifled CS is the process of wear of the rifled barrel channel, which results in an unevenly (in the cross-section) worn surface of the CS with some features. For example, studies [14] and [15] show that during the movement of a projectile element (PE) along a rifled CS, the fields and edges of the rifling are subject to the greatest friction due to the increased (compared to the bottom of the rifling) pressure on their surface created when the PE is inserted into the rifling.

Accordig to the results of the conducted studies, it is advisable to combine and consider the abrasion of the field and the faces of the cuts in the aggregate, but to separately distinguish such a defect as a field puncture, which can form on the surface of the CS regardless of other defects.

In addition, the complex shape of the barrel channel cuts causes corresponding differences in the approaches to the process of processing the measurement information obtained after scanning with the help of LWD. Thus, when scanning smooth barrel channels, the body and surface of the defect (e.g., sinks, cracks) are formed by a depression formed in the damaged area of the CS. In contrast, when scanning rifled barrel channels, a "differential" approach is used: the body and surface of the defect are reproduced by points whose appliers are the differences in the radii of the scanned (real) CS and the conditional "new", undamaged CS. At the same time, the description (model) of the undamaged barrel channel can be determined empirically with the help of LWD – using a new CS that has no traces of operation or obtained from the manufacturer. These circumstances determine some features of the study of functions that describe defect surfaces, for example, the inexpediency of their study for continuity at the extreme points of the area of their definition.



a



b

Figure 3 – Photo of the profile of the worn out cutter field: *a* – the image given in [16]; *b* – a sample of a worn rifled barrel channel, which was available to the authors during previous studies

Abrasion of the rim and rifling edges. According to the analysis of the images of the worn rifled barrel channel (Figure 3), the process of abrasion of the field and rifling edges during the operation of the BHA changes the rectangular profile of the field protrusion to a rounded one. In combination with the uneven wear along the longitudinal axis of the BHA, a surface with unidirectional, unevenly raised "troughs" is formed.

To describe this surface, the authors of the article propose to use the equation $z = f(x, y)$, in which the variable *x is* raised to the fourth power. Under this condition, in the lumbar section of the barrel channel, the line describing the cutting field is a parabola with a flattened top. It is advisable to apply a cosine function to the variable *y* in the interval [0; π], which gives an inclined longitudinal profile of the field in the breech part of the barrel channel, which smoothly adjoins the middle part of the CS. Eventually, the above equation takes the following form:

$$z = (\frac{x}{a_x})^4 + \cos(\frac{y}{a_y}), \qquad (13)$$

where a_y is the surface compression coefficient along the Y-axis.

It should be noted that the abrasion of each field and its adjacent faces is considered as a separate defect (separate surface), and its propagation along the Y-axis is limited only by the width of the field W_n. Taking into account all the restrictions, the domain of the function that describes the defect in the form of abrasion of the field and the faces of the cuts can be represented as follows:

$$D(f) = \left\{ (x, y) \in R^2 \mid \frac{y}{a_y} > 0 \cap \frac{y}{a_y} < \pi \cap |x| < \frac{W_n}{2} \right\}. \qquad (14)$$

Taking into account the need to align the surface with the level z = 0, the displacement of the centre of the defect base and its rotation by the angle α, which corresponds to the steepness of the cuts, the mathematical model of the surface of the barrel channel section in the presence of abrasion of the field and the adjacent faces of the cuts will be as follows

$$z = \begin{cases} \left(\frac{((x - x_\Delta)\cos(\alpha) - (y - y_\Delta)\sin(\alpha))}{a_x} \right)^4 + \cos\left(\frac{((x - x_\Delta)\sin(\alpha) + (y - y_\Delta)\cos(\alpha))}{a_y} \right) + 1 \\ at \left| \frac{((x - x_\Delta)\cos(\alpha) - (y - y_\Delta)\sin(\alpha))}{a_x} \right| < \frac{W_n}{2} \cap \frac{((x - x_\Delta)\sin(\alpha) + (y - y_\Delta)\cos(\alpha))}{a_y} < \pi \cap \frac{((x - x_\Delta)\sin(\alpha) + (y - y_\Delta)\cos(\alpha))}{a_y} < 0; \\ 0, \quad otherwise. \end{cases} \qquad (15)$$

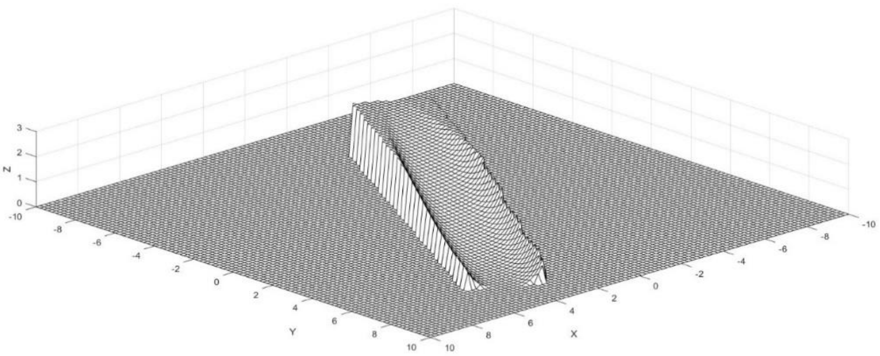


Figure 4 – Surface view corresponding to the mathematical model of the barrel channel surface in the presence of abrasion of the field and the adjacent faces of the cut

Figure 4 shows an example of a graphical representation of the surface of the barrel channel in the presence of field abrasion and adjacent cut edges in accordance with system (15) using MATLAB software.

A *cutter field puncture* is a defect in the barrel canal that is formed as a result of the destruction, separation and subsequent loss of a limited (lengthwise) part of the cutter field body. When scanning a section of the CS with such a defect with the help of an ultrasound scanner, the defect body resembles a convex polyhedron (Figure 5)

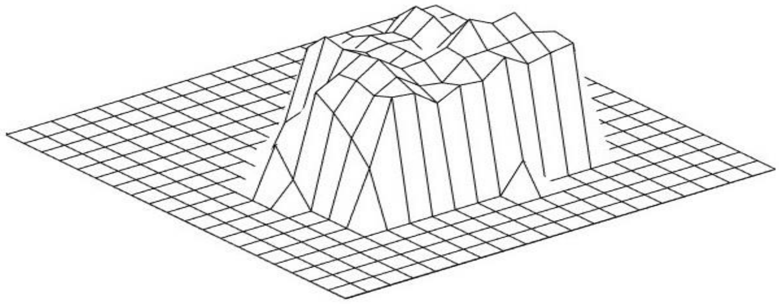


Figure 5 – Depiction of a defect as a combination of a broken and lost body part fields of the barrel channel cut

Taking into account the similarity and limited width W_n and height of the casing cut fields, it is advisable to reduce the resulting polyhedron to an obelisk. In this case, the model of the borehole channel cutout field will be considered as a combination of the four side and top faces of the specified obelisk and the undamaged surface of the BHA. In practice, there may be cases when the angles between the faces and the base of the obelisk (defect) are up to 90º, in which case the shape of the obelisk itself is close to a parallelepiped. However, in this case, the specified faces of such a parallelepiped cannot be described by the equation $z = f(x, y)$, since the values of the arguments in the domain of defining the faces will not correspond to a single value of the function. Therefore, to generalise the cases of formation of various forms of such a defect, the authors propose to describe the surface formed as a result of a field breakdown by the following equation:

$$z = a_{D,} \tag{16}$$

in the definition area:

$$D(f) = \left\{(x, y) \in R^2 \mid -\frac{L}{2} \le x \le \frac{L}{2} \cap -\frac{W}{2} \le y \le \frac{W}{2}\right\}. \tag{17}$$

It should be added that the discontinuity of the function at points belonging to the boundary of the function definition area may cause an error when calculating the area of the defect base. However, this factor does not affect the content of the algorithm for implementing the outlined method of diagnosing the barrel channel and is insignificant due to the discreteness of surface scanning, which is inevitable during measurements using the LWD.

Taking into account the rotation and displacement of the centre of the defect base, the final model of the field excavation looks like this:

$$z = \begin{cases} a_D \ \ at \ -\frac{L}{2} \le (x - x_\Delta)cos(\alpha) - (y - y_\Delta)sin(\alpha) \le \frac{L}{2} \cap -\frac{W}{2} \le (x - x_\Delta)sin(\alpha) + (y - y_\Delta)cos(\alpha) \le \frac{W}{2} \\ 0, \ otherwise. \end{cases}; \tag{18}$$

Figure 6 shows an example of a graphical representation of the surface formed by the cutout of the cut field in accordance with system (18) using MATLAB software.

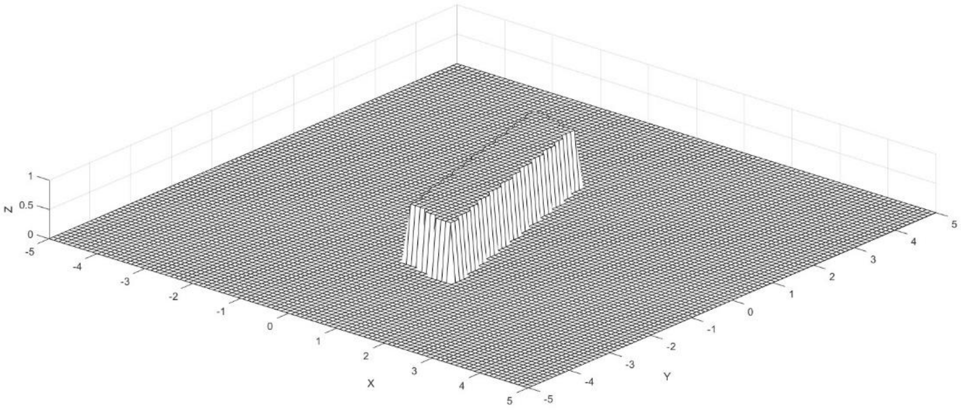


Figure 6 – Surface view corresponding to the mathematical model of the cutter field barrel channel

Thus, as a result of the work performed, mathematical models of the diametrical wear of the smooth channel of the barrel in its breech and muzzle parts, abrasion of the field and adjacent rifling edges, and the piercing of the rifling field of the rifled CS were obtained, which are presented in the form of mathematical expressions describing these defects as three-dimensional surfaces.

The proposed mathematical descriptions can serve as the basis for developing a system of indicators and criteria for automated identification of types of defects in the barrel channel during their technical diagnosis using a laser triangulation tool for measuring the geometric characteristics of the CS.

Conclusions

The study of the damaged areas of the barrel channels of firearms samples shows that defects of certain types are characterised by a characteristic combination of geometric parameters. This makes it possible to classify barrel channel defects into three categories: those characteristic of rifled barrel channels, those inherent in smooth barrel channels, and those common to both types. The article presents a mathematical modelling of defects inherent exclusively to one of the barrel channel types, in particular, diametric wear of a smooth barrel in the breech and muzzle parts, as well as abrasion of the field and adjacent edges of the rifling and a cut-out of the rifling field in the rifled barrel channel.

It has been established that mathematical models of borehole defects should be presented in the form of algebraic equations of the form $z = f(x, y)$, each of which describes the surface of the defect body. Such a model determines the dependence of the height z of a surface point on the coordinates x and y in the Cartesian coordinate system and contains equations for the surfaces of both damaged and undamaged sections of the barrel channel with their respective areas of definition.

In order to simplify further calculations using mathematical models, the concepts of the base and contour of the defect and its model were introduced and formalised, and definitions of their characteristics were proposed: length, width, longitudinal and transverse axes.

The synthesis of the expression for the mathematical description of the diametrical wear of a smooth barrel channel was performed taking into account the more pronounced manifestation of this defect in the muzzle and breech parts of the barrel channel, which is reflected in the use of the cosine function in the areas of its decrease and increase, respectively.

Taking into account the condition of simultaneous occurrence of abrasion of the field and abrasion of the adjacent faces of the cuts, the joint manifestation of these defects is described by a single function. To reproduce the shape of the cross-section of the abraded field and the adjacent faces of the cuts, the mathematical model of this defect is based on the use of a power function, which fully corresponds to the nature of the rounding of the field edges during the operation of the barrel channel.

When describing the field cut, the shape of the body surface of such a defect, as obtained by laser scanning, was simplified to an obelisk. Thus, this surface is described as an obelisk with a constant height in the area of definition, which is limited by the width of the field of cut of the corresponding barrel channel and the length of the damaged area.

The three-dimensional visualisation of the constructed mathematical models demonstrates a high degree of their correspondence to the surfaces of real defects in the barrel channel.

Further research in this area should be directed to the creation of a system of indicators that will make it possible to quantify the degree of discrepancy between the characteristics of the section of the borehole channel containing a real defect and the corresponding characteristics of the mathematical model of such a defect.

References

1. Ji-sheng Ma. (2018). The law of barrel wear and its application. *Defence Technology*. June, no. 14 (6), pp. 674–676. DOI: http://dx.doi.org/10.1016/j.dt.2018.06.012 [in English].

2. Kriukov O. M., Florin O. P. (2010). *Osnovy metrolohichnoho zabezpechennia* [Basics of metrological support]. Kharkiv : KhNADU [in Ukrainian].

3. Kriukov O. M., Mihura O. O. (2023). *Metod tekhnichnoho diahnostuvannia kanaliv stvoliv vohnepalnoi zbroi na osnovi vyznachennia ikh heometrychnykh kharakterystyk* [Method of technical diagnosing of the bores of firearms based on the determination of their geometric characteristics]. *Chest i zakon*, no. 3 (86), pp. 101–109. DOI: https://doi.org/10.33405/2078-7480/2023/3/86/287124 [in Ukrainian].

4. DSTU 2681:1994. *Metrolohiia. Terminy ta vyznachennia State Standart 2681:1994* [Metrology. Terms and definitions]. (1995, January 1). Kyiv : Derzhstandart Ukraine [in Ukrainian].

5. Klepko V. Yu., Holets V. L. (2009). *Vyshcha matematyka v prykladakh i zadachakh* [Higher Mathematics in Examples and Problems]. Kyiv : TsUL [in Ukrainian].

6. Kriukov O. M., Melnikov R. S. (2021). *Matematychne modeliuvannia protsesu postrilu dlia ekspluatatsiinoho diahnostuvannia styrannia vnutrishnoi poverkhni kanalu stvola pid chas vykonannia zavdan zabezpechennia derzhavnoi bezpeky* [Mathematical modelling of the shot process for operational diagnostics of abrasion of the inner surface of the barrel channel during the performance of state security tasks]. *Chest i zakon*, no. 1 (76), pp. 46–57. DOI: https://doi.org/10.33405/2078-7480/2021/1/76/229507 [in Ukrainian].

7. Kriukov O. M., Melnikov R. S. (2020). *Matematychne modeliuvannia protsesu postrilu z urakhuvanniam rozduttia kanalu stvola vohnepalnoi zbroi yak zasib vplyvu na efektyvnist vykonannia sluzhbovo-boiovykh zavdan sylamy bezpeky* [Mathematical modelling of the shot process taking into account the swelling of the firearm barrel channel as a means of influencing the effectiveness of performing service and combat tasks by security forces.]. *Chest i zakon*, no. 2 (73), pp. 61–73. DOI: https://doi.org/10.33405/2078-7480/2020/2/73/207146 [in Ukrainian].

8. Shanmugamani R., Sadique M., Ramamoorthy B. (2015). Detection and classification of surface defects of gun barrels using computer vision and machine learning. *Measurement*, vol. 60, pp. 222–230. DOI: https://doi.org/10.1016/j.measurement.2014.10.009 [in English].

9. Lytvyn O. M. (2020). *Matematychne modeliuvannia poverkhon operatoramy interstripatsii* [Mathematical modelling of surfaces by interstriping operators]. *Proceedings of the 9th International scientific and technical "Informatsiini systemy ta tekhnolohii IST-2020"* (Ukraine, Kharkiv, November 17-20, 2020). Kharkiv : KhNURE, pp. 52–55 [in Ukrainian].

10. Shen Chao & Zhou Kedong & Lu Ye & Li Jun-song (2019). Modeling and simulation of bullet-barrel interaction process for the damaged gun barrel. *Defence Technology*, August, no. 15, pp. 972–986. DOI: https://doi.org/10.1016/j.dt.2019.07.009 [in English].

11. Evaluation of cannon tubes. Technical manual 22 February 2005. Army TM 9-1000-202-14. Washington, pp. 164. Retrieved from: https://www.scribd.com/doc/252584622/TM-9-1000 -202-14 (accessed 2 March 2025) [in English].

12. Habrusiev H. V. (2014). *Konspekt lektsii iz vyshchoi matematyky (chastyna 2: vektorna alhebra)* [Lecture notes on higher mathematics (part 2: vector algebra)]. Ternopil : TNTU [in Ukrainian].

13. Li, Xiaolong & Mu, Lei & Zang, Yong & Qin, Qin. (2019). Study on performance degradation and failure analysis of large caliber gun barrel. *Defence Technology*, May, no. 16, pp. 362–373. DOI: https://doi.org/10.1016/j.dt.2019.05.008 [in English].

14. Krzysztof Łęczycki (2017). Analysis of Premature Wear-Out of Aircraft Gun Barrel by Applying a Transmission Electron Microscopy (TEM). *Aviation Advances & Maintenance*, vol. 40, no. 1, pp. 67–87. DOI: https://doi.org/10.1515/afit-2017-0003 [in English].

15. Chen P.C.T., Leach M. (2001). Modeling of barrel/projectile interaction in a rotating band. Watervliet, NY : US Army Armament Research, Development and Engineering Center, Benet Laboratories (Technical Report ARCCB-TR-01011) [in English].

The article was submitted to the editorial office on 12 March 2025

УДК 623.482

О. М. Крюков, Г. В. Сілін

ДОСЛІДЖЕННЯ ТА МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ДЕФЕКТІВ КАНАЛІВ СТВОЛІВ: ДІАМЕТРАЛЬНИЙ ЗНОС, СТИРАННЯ ПОЛЯ І ГРАНЕЙ НАРІЗІВ, ВИКОЛ ПОЛЯ

Розглянуто поточний стан розвитку методів технічного діагностування каналів стволів вогнепальної зброї. Описано переваги застосування перспективного діагностичного комплексу на базі лазерного тріангуляційного засобу вимірювання геометричних характеристик каналу ствола. Відзначено, що попри наявність деяких підходів до побудови такого засобу вимірювання, досі залишається невирішеною проблема браку наукових основ створення його обчислювального компонента, що забезпечуватиме автоматизоване виявлення пошкоджених ділянок каналу ствола та ідентифікацію наявних дефектів.

У статті наведено результати дослідження таких дефектів каналу ствола, як діаметральний знос, стирання поля і граней нарізів, викол поля. Встановлено, що ці дефекти мають характерні геометричні ознаки, які доцільно описувати алгебраїчними рівняннями поверхонь у декартовій системі координат. Описано відмінності у підходах до лазерного сканування гладкого та нарізного каналів стволів, зокрема необхідність у наявності моделі поверхні непошкодженого (нового) нарізного каналу ствола, що сканується. Отримано математичні моделі дефектів каналу ствола. В основі математичної моделі діаметрального зносу гладкого каналу ствола покладено функцію косинуса, що забезпечує плавність переходу між пошкодженою та непошкодженою ділянками. Обґрунтовано доцільність синтезу (об'єднання) під час моделювання таких дефектів нарізного каналу ствола, як стирання поля і прилеглих до нього граней. Узагальнений дефект описано поєднанням степеневої функції та функції косинуса, що надає утвореній моделі поверхі округлення, притаманне профілю зношеного поля нарізу. Форму частини поля нарізу, якої не вистачає, за наявності виколу поля приведено до обеліска та описано лінійною функцією в області визначення, що обмежена параметрами поля нарізу.

Для перевірки відповідності форм поверхонь, які відтворюються під час застосування запропонованих математичних моделей дефектів каналу ствола, формам реальних пошкоджень було виконано їх тривимірну візуалізацію.

Ключові слова: *канал ствола, технічне діагностування, дефект каналу ствола, математична модель, діаметральний знос, стирання поля, викол поля, стирання граней нарізу.*

Kriukov Oleksandr – Doctor of Technical Sciences, Professor, Professor of the Department of Logistics Management, National Academy of the National Guard of Ukraine
https://orcid.org/0000-0003-4194-6081

Silin Hryhorii – Associate Professor, National Academy of the National Guard of Ukraine
https://orcid.org/0009-0008-2059-3962