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Research Article

Classification of Regular Microreliefs of the Volumetric Class

V. Dzyura[1]
P. Maruschak[2,*]
R. Bytsa[2]
[1] *Department of Wheel Vehicles, Ternopil Ivan Puluj National Technical University, Ternopil, 46001, Ukraine*
[2] *Ternopil Ivan Puluj National Technical University, Ternopil, 46001, Ukraine*

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Abstract:
An analysis of the geometric features and functional purposes of different classes of regular microreliefs has been conducted. Some optimal geometric parameters for the grooves of regular microreliefs (cross-sectional and longitudinal shapes and sizes) have been determined to ensure optimal surface performance in friction pairs and facilitate relative reciprocating motion. A new classification of regular microrelief, called the volumetric class microrelief, has been presented. The groove of this microrelief and its constituent elements have been considered a basis for forming multiple microrelief options with different geometric parameters, constituent elements, and their mutual arrangement within the groove and within the microrelief. This approach will enable the creation of volumetric microreliefs, both regular and partially regular, with different functional purposes. Depending on the geometric features, these types of relief can be applied to surface elements subject to non-uniform wear at the locations of most significant dynamic loads (connecting rod liners, cylinder liner surfaces of internal combustion engines, etc.). The optimal shape of the cross-section of the microrelief grooves of the volumetric class is established under the condition of the maximum value of the residual groove area when the surface is worn by 50% of the groove depth. For a rectangular cross-sectional profile, the residual groove area relative to the initial one is 81%; for a triangular one, 50%; and for a semicircular one, 69%. The groove shape of the micro-relief has been justified using an analytical method. The main features of the classification of volumetric class microreliefs have been identified, dividing them into two groups: the first one, describing the specific geometry of the microrelief grooves, and the second one, describing the particular features of the mutual arrangement of these grooves, creating a unique pattern of microrelief on the surface.

Keywords: *Regular microrelief, Grooves, Geometric parameters, Operational properties of surfaces*

1. Introduction

Surface engineering is an essential field of science that seeks new technical solutions to meet the growing demands of production. Conventional processing methods have practically exhausted their potential for improving and ensuring the working surfaces of machine parts with the required operational properties.

Methods of surface plastic deformation and chemical and chemical-thermal treatments have been well studied and widely used in modern mechanical engineering to ensure the specified operational properties of the working surfaces of machine parts [1, 2, 3]. However, all these methods provide stable physical and mechanical properties on the working surface, and accordingly, the operational changing that requires the corresponding changes in the geometric

* Corresponding author: P. Maruschak
E-mail address: Maruschak.tu.edu@gmail.com

parameters of the surfaces to ensure the proper lubrication conditions. Solving this technical problem is possible by providing the necessary surface topography. The concept of a textured surface is synonymous with the concept of a regular microrelief created on a specific surface.

Ordered regular surface microstructures created on the working surfaces of machine parts are referred to as regular microreliefs in scientific literature, and their shape and geometric parameters are regulated by the relevant normative base [4].

According to this document, a regular microrelief (fully or partially regular) is a set of periodically repeating protrusions and depressions on the material surface to reduce the break-in period, increase reliability and durability, and improve other operational properties of the surface. The periodic arrangement of microrelief grooves allows for the provision of a specified relative area of the microrelief - one of its main parameters, which, to a large extent, determines the operational properties of the surface on which it is formed.

The application area of regular microreliefs is quite broad, encompassing almost all human activities [5]. The most common use of textured surfaces in mechanical engineering is in the production and processing of mating surfaces that operate under harsh conditions. It was found that the main parameter determining the typological properties of the surface with the formed microrelief is the ratio of the area occupied by the microstructures to the area of the surface on which they are formed. According to the authors, the optimal value of this parameter lies between 5% and 20%. However, other studies indicate that the optimal value of this parameter depends on operating conditions and ranges from 15% to 45%. Larger values of the relative area of the microrelief grooves significantly reduce the support area, while smaller values provide insufficient surface regularization and, accordingly, insufficient oil capacity.

There is a significant body of research in the scientific literature on the operational properties of surfaces with regular microrelief. In [6], the results of studies on the impact of different shapes of regular microrelief grooves formed on the surfaces of test samples on the friction coefficient, friction zone temperature, and the surface's ability to remove wear products are presented. Reducing the friction coefficient reduces energy consumption in mechanisms, particularly in the aviation industry and other transportation sectors.

In [7], studies indicate that forming an ordered microrelief on the inner cylindrical surface of a cylinder sleeve enhances the surface's ability to retain an oil film. This property of the hydraulic cylinder sleeve's working surface improves its operational performance and extends the overall service life of the hydraulic cylinder. Therefore, the search for new classes of regular and partially regular microreliefs is a crucial task for modern mechanical engineering. To ensure the specified operational properties of working surfaces, microreliefs with grooves of various shapes and sizes are formed.

Numerous studies have confirmed that forming an ordered microstructure on the working surface reduces surface roughness and increases surface microhardness. Thus, in the articles [8, 9] the influence of technological parameters on the surface roughness during ball or roller rolling was investigated. In this case, regression equations and response surfaces were obtained that describe the specified dependencies. The influence of roller rolling on the surface roughness and microhardness of aluminum alloy 6061-T6 rods was also investigated [10]. Using the analysis of variance (ANOVA) approach, it was confirmed that rolling operations improve the geometric and physical-mechanical surface quality parameters.

For example, in [11], the authors conducted comparative studies on the operational properties of flat rotating disk surfaces. Regular microreliefs were formed on these surfaces, whose elements in the first case were periodically repeating spherical dimples and, in the other case, chevron-shaped segments of varying lengths intersecting at acute angles in the range of 60° to 90°. The study's outcome was the determination of the friction coefficient of surfaces with formed microrelief features and the search for the optimal shape, size and mutual arrangement of these microrelief elements.

Similar studies were conducted in [12], where the authors investigated the surface structures with a depth of 8 nm, with traces in the vertical plane appearing as circles, ellipses, and triangles. The influence of texture shape on the friction coefficient was examined. It was also established that, given the same area, area ratio, and depth, dimples of elliptical and triangular shapes have lower load-bearing capacity compared to circular dimples.

Surface structures in the form of square dimples and grooves were investigated in [13]. The surface area covered by microrelief elements was 25%. After forming grooves and square dimples with a depth of 20 nm on the test samples' surfaces, they were subjected to friction against a similar surface to simulate wear. Each sample underwent 20,000 cycles of relative movement. After simulating the wear process, the samples were compared with a flat-surface control sample lacking a formed microrelief. The study's outcomes conclude that surfaces with formed surface structures exhibit better operational properties. Some surface operational defects were observed only on the surface, without forming microreliefs, during the study period.

In [14], the authors proposed an approach in which regular microrelief is considered from the perspective of factors that determine its characteristics, particularly: the size and shape and mutual arrangement of microrelief elements; the orientation of microrelief elements relative to the surface on which they are formed; the ratio between microrelief parameters; and hierarchical ranking. Some examples of regular microreliefs in the form of ordered microstructures in the environment have been provided, showing the sizes and orientations of their constituent elements. Factors affecting the functional properties of surfaces with regular structures have been considered.

An interesting work in terms of classification is [15]. It presents a classification of directions in scientific research on textured surfaces, including: technologies for creating regular microreliefs; the input/output characteristics of such surfaces; modeling their interaction; and further research in this direction. The article also provides a classification of the primary methods for creating textured surfaces, including thermal, mechanical, and electrochemical interactions, micro- and nano-finishing, and micromolding. The article presents technological schemes for forming surface microstructures with justification of the main technological parameters. The authors' research results include a table describing various tool materials, working materials, and cutting parameters used in processing with microtextured tools, as well as a table of texture generation methods, along with groove sizes and geometries.

The surface microstructure in the form of straight grooves was investigated in the work [16]. These microstructures, with depths of 80-120 nm and groove angles of 0°, 45° and 90°, were created using a laser beam. The authors studied the frictional properties of these surfaces. The studies were conducted under a load that pressed a ball against the test sample, with a force of 20-100 N, and performed 10,000 cycles of relative cyclic motion to simulate wear. The results of the change in the friction coefficient were compared with a control sample with a surface without created surface microstructures. The study also identified the mechanism of groove filling by interaction products and searched for the optimal groove placement to prevent their formation in the mating surfaces' contact zone.

The technology for creating regular microrelief was proposed in [17, 18]. Due to the use of a special tool with an indenter in the form of a ball and an adjustable interaction force, a regular microrelief with sinusoidal grooves was created on the surface. Thus, a fully regular microrelief with hexagonal cells was formed on the surface. The article presents the results of the study on the influence of the main technological parameters on the geometric parameters of the created microrelief. In addition, to form regular microreliefs, a special tool was created to provide the necessary force to deform the groove surface.

Studies confirming the ability of textured surfaces to retain liquids better are presented in [19]. The authors investigated the rolling speed of liquid droplets on surfaces with different microreliefs. Some test samples with nine classes of regular microrelief shapes were produced. It was found that surfaces with formed microreliefs, particularly longitudinal grooves, retain liquid droplets longer than flat surfaces and surfaces with other classes of microreliefs.

Surfaces with different surface structures have varying hydrophobic properties, as demonstrated in the article [20]. Depending on the surface microstructure, it can be neutral to the liquid, excessively absorb it, or repel it. These surface properties are relevant for many industries, including the food and military sectors. The authors studied several options to achieve the surface microstructure necessary to achieve the required hydrophobic properties. It was found that by controlling the chemical composition of the laser-textured surface, wettability can be modulated from extreme hydrophobicity to hydrophilicity, allowing for complex wettability cycles.

Classifications and mathematical modeling of partially regular microreliefs, whose regularity is ensured only for specific geometric parameters formed on the end surfaces of rotating bodies, are the focus of the articles [21, 22, 23]. These microreliefs are created on the end surfaces of rotating bodies, where the axial pitch of the grooves gradually decreases as they approach the center of rotation. To ensure the regularity of this parameter, the concept of the angular pitch of the groove is introduced, which is uniform for grooves located at different distances from the center of rotation of the end surface.

Exploratory research aimed at determining the optimal geometry of microrelief grooves that provide the minimum friction coefficient is presented in the work [24]. The authors conducted a significant experiment to determine the optimal microrelief geometry that yields the minimum friction coefficient. Six test samples with microrelief grooves of different geometric shapes were made for comparison.

When forming regular and partially regular microreliefs on the surfaces of machine parts, the shape of their grooves and their mutual arrangement determine the operational properties of this surface. A preliminary analysis of the operational properties of surfaces [25, 26] showed that with the same area of formed microreliefs of different types (I, II and III), their ability to retain a specific volume of lubricant (oil capacity) is practically the same.

2. Traditional approach to evaluating surfaces with regular micro-reliefs

One of the main characteristics of the regular micro-relief formed on the surface is its relative area F_n, i.e., expressed as a percentage, the ratio of the area of micro-relief grooves to the total surface area on which it is formed. Several researchers consider this parameter to be the one that determines the surface's performance properties with regular micro-relief [4, 27].

In work [27], it is noted that the relative surface area, F_n, is a parameter of partially regular micro-relief and most fully characterizes the surface's performance properties, primarily the actual contact area of the mating surfaces.

In summary, it can be concluded that, in all cases, regardless of the application patterns and modes of the "pattern," the optimal groove area of the micro-relief F_n ranged from 25% to 45%. At lower values of F_n, the mating surfaces have insufficient oil retention capacity, whereas at higher values, their load-bearing capacity significantly decreases.

Increasing the groove area of the micro-relief improves the surface's oil-retention capacity, enhancing operating conditions, though it reduces the support area, resulting in rapid wear during operation. Therefore, the optimal groove area value for surfaces with regular micro-reliefs is determined experimentally and depends on the operating conditions. Its value can vary from case to case.

The traditional approach to evaluating surfaces with regular micro-reliefs involves determining the relative area of the micro-relief as one of the main parameters characterizing the surface's performance. This parameter is defined as the ratio of the total projected area of all the grooves to the area of the surface on which the grooves are formed. However, this approach does not assess the influence of groove shape in either the longitudinal or cross-sectional directions.

The existing quantitative parameter for evaluating micro-relief, i.e., the relative area of the micro-relief, is defined as the ratio of the projected area of the micro-relief on a horizontal plane to the area of the surface on which the micro-relief is formed, expressed as a percentage. The following formula determines it:

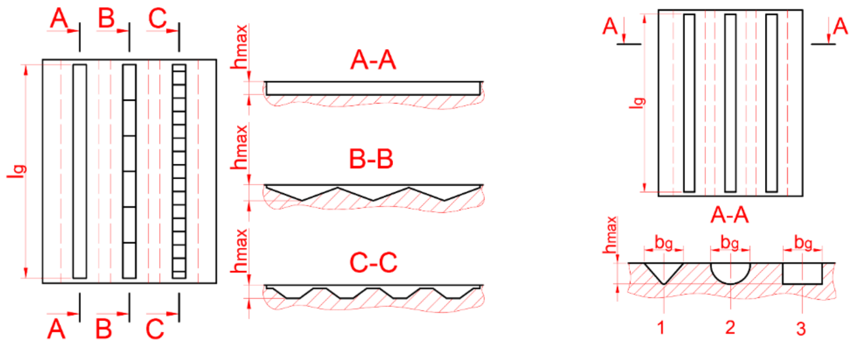
$$B = F_{g.s.} \cdot 100\% / F_s, \tag{1}$$

where $F_{g.s.}$ – is the total value of all the area projections of all micro-relief grooves; F_s – is the surface area on which the micro-relief is formed.

In the scientific literature, there is considerable evidence that an optimal value of this parameter exists, independent of the micro-relief's shape and size. This suggests that the area of the formed micro-relief, rather than its geometry, decisively influences the surface's performance properties.
In fact, the relative area of the micro-relief, as a quantitative parameter, indicates the percentage reduction in the mating surfaces' contact area.

Properties of grooves of regular micro-reliefs

As an illustrative example, we present images of micro-reliefs with the same total projected groove area (Fig. 1). According to the statement proposed in work [2], their performance properties should be identical. Under the same operating conditions, these surfaces should wear to the same extent. However, it is evident that grooves with different longitudinal (Fig. 1a) and cross-sectional (Fig. 1b) shapes will have different performance properties.



(a) (b)

Fig. 1. Variety of longitudinal and cross-sections of microrelief grooves with the same area of projection of the groove onto the plane: a – longitudinal section of grooves (hollow, triangular and complex profile); b – cross-section of hollow grooves (1 – triangle; 2 – semicircular; 3 – rectangular)

Thus, evaluating the performance properties of a surface based on the projected area of grooves, without considering their geometric features (shape in longitudinal and cross sections), is only possible when comparing micro-reliefs with grooves of the same depth. This is because a reduction in the projection area is directly proportional to a decrease in the mating-surface contact area. Therefore, to evaluate the geometric characteristics of grooves in regular micro-reliefs, a quantitative parameter is needed that accounts for these characteristics.

Let us consider the change in the projected area of grooves with different cross sections, depicted as 1, 2 and 3 in Fig. 1b. The groove depth, denoted h_{max}, ranges from 0.1 to 0.8 mm, depending on the surface's purpose and operating conditions. With significant surface wear, the groove depth may decrease, reducing the groove area and its projection on the micro-relief plane. At the initial stage, before the start of operation (segment I) at time T_0, the projection areas of grooves 1, 2 and 3 are equal and are denoted on the graph (Fig. 2) by the corresponding notation S_{g0}.

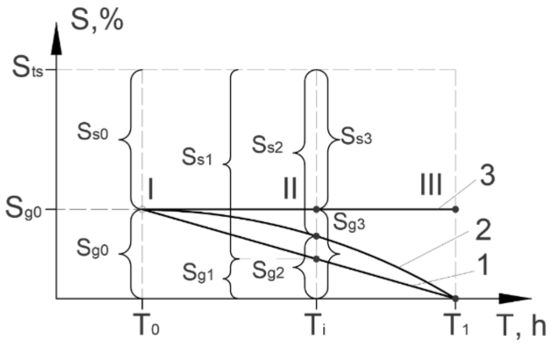


Fig. 2. Graphs of changes in surface area and groove area of the micro-relief under the same operating conditions.

After a specific period of surface operation (segment II) at time T_i, the projection areas of grooves 1, 2 and 3 will decrease depending on the shape of their cross-section. The triangular groove, numbered 1, will change according to the linear law in the projection area (curve 1). The projection area of the grooves will then be S_{g1}. The projection area of the semi-circular groove, numbered 2, will gradually decrease (curve 2) to S_{g2}. The area of the rectangular groove, numbered 3, will remain unchanged until the groove depth decreases to 0 (curve 3).

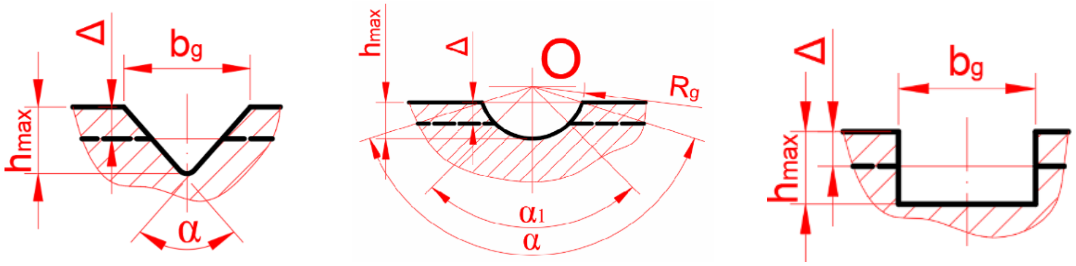
Given that the groove area will decrease while the surface area on which they are formed increases during operation, a parameter can be proposed that accounts for both areas.

Therefore, it has been proposed to evaluate the grooves of the micro-relief using the parameter "groove degradation intensity," defined as the percentage change in the total projected area of the micro-relief grooves divided by the time over which this change occurs.

The following formula determines the groove degradation intensity:

$$k = \frac{S_{gi} - S_{g0}}{T_1 - T_0} \tag{2}$$

To assess the degree of reduction in the area of a triangular groove with width b_g and depth h_{max} as the surface wears by an amount Δ, consider Fig. 3a.



(a) (b) (c)

Fig. 3. Calculation diagrams of cross-sections of grooves of volumetric microreliefs of various profiles to determine the degree of reduction in their area during wear simulation: a – triangle; b – semicircular; c – rectangular.

Since the groove length and depth remain constant, we will compare the groove profile lengths in the cross-section, limited by the angle α and the groove depth h_{max} before operation, and by $h_{max} - \Delta$ after a specific period of operation. The formula will find angle α

$$\alpha = 2arctg\left(\frac{b_g}{2h_{\max}}\right) \tag{3}$$

The following dependency will determine the groove profile length:

$$l = \frac{h_{\max}}{\cos \alpha / 2} \tag{4}$$

or

$$l = \frac{h_{\max}}{\cos\left(arctg\left(\frac{b_g}{2h_{\max}}\right)\right)} \tag{5}$$

When the surface wears by an amount Δ, the groove profile length will be determined by the following dependency:

$$l_1 = \frac{h_{\max} - \Delta}{\cos\left(arctg\left(\frac{b_g}{2h_{\max}}\right)\right)} \tag{6}$$

To assess the degree of reduction in the area of a semicircular groove with radius R_g and depth h_{max} due to surface wear by the amount Δ, let's refer to Figure 3b.

For the semicircular groove, we will compare the arc lengths of the circle spanning the angle α on the groove surface before operation and after a specific period of operation, accounting for surface wear by the amount h_{max}.

The relationship between the value of h_{max} and the angle can be described by the following expression:

$$h_{\max} = R_g\left(1-\cos\frac{\alpha}{2}\right) \tag{7}$$

Therefore,

$$\alpha = 2\arccos\left(1-\frac{h_{\max}}{R_g}\right) \tag{8}$$

The arc length will be determined from the following equation:

$$l = \frac{\pi \cdot R_g \cdot 2\arccos\left(1-\frac{h_{\max}}{R_g}\right)}{180^\circ} \tag{9}$$

With surface wear by the amount Δ, the coverage angle will be α_1, and the following equation will determine the arc length of the groove profile:

$$l_1 = \frac{\pi \cdot R \cdot 2\arccos\left(1-\frac{h_{\max}-\Delta}{R_g}\right)}{180^\circ} \tag{10}$$

For a rectangular groove, we will compare the profile lengths in the cross-section, limited by the groove depth h_{max} before operation and h_{max}-Δ after a certain period of use.
The profile length of the rectangular groove before operation will be determined from the following dependency:

$$l = b_g + 2 \cdot h_{\max} \tag{11}$$

The profile length of the rectangular groove after a certain period of operation will be determined from the following dependency:

$$l_1 = b_g + 2 \cdot \left(h_{\max} - \Delta\right) \tag{12}$$

The obtained dependencies for the known total length of the micro-relief grooves and the amount of surface wear will allow determining the degradation intensity of the groove surfaces of the partially regular micro-relief.
To compensate for the loss of groove surface area during operation, a new groove shape for the partially regular micro-relief has been proposed.

Table 1: Properties of grooves of regular micro-reliefs

Grooves form / **Parameters**	**Triangle**	**Semicircular**	**Rectangular**	**Volumetric**
Change in groove width during operation	+	+	+	–
Uniformity of the distribution of the bearing surface and oil pockets along the groove surface	–	–	–	+
Possibility of compensating for the loss of groove area due to surface wear	–	–	–	+

Practical implementation of the proposed solutions.

To understand the degree of surface area reduction in the grooves that occurs during the operation of a working surface with a regular microrelief and its wear, we will conduct some simulations.

To ensure identical initial conditions, the geometric parameters of the groove, specifically its depth and width, are the same for all three forms of microrelief grooves: h_{max} = 0.3 mm; b_g = 1 mm. We will simulate changes in the geometric parameters of the microrelief grooves due to surface wear of Δ = 0.15 mm. The calculations will use dependencies (5) – (12).

Table 2: Geometric parameters of microrelief grooves with different cross-sections before use and at a certain level of surface wear.

№ з/п	Groove profile / Parameters	Triangular profile	Semi-circular profile	Rectangular profile
1	Groove width b_g, mm	1.00	1.00	1.00
2	Groove depth h_{max}, mm	0.30	0.30	0.30
3	Profile length of the groove before operation l, mm	1.166	1.225	1.60
4	Profile length of the groove at surface wear 0.15 mm l, mm	0.58	0.84	1.30
5	Residual in % of the groove surface area about the initial value	0.5	68.89	81.25
6	Groove width after operation b_g, mm	0.77	0.58	1.00

As shown by the obtained values, the triangular shape of the microrelief grooves is the least optimal, as the most significant loss of geometric parameters is observed in this case. The groove width and, accordingly, the groove's projection area will decrease by 42%. At the same time, the groove's surface area will decrease by 31.11%.

The optimal shape is a rectangular groove. The surface area of the rectangular-profile groove will decrease by 18.75%, while the projection area will remain unchanged. In real conditions, forming a groove of rectangular cross-section with a depth of 5 to 15 microns by plastic deformation methods is technologically complex. The difficulty lies in the fact that microrelief is usually formed with a tool that uses a ball or roller as a deforming element. This results in surface plastic deformation by rolling. With this processing scheme, the ball or roller "indents" the processed surface, creating a groove. This prevents the formation of metal inflows, which occur during the processing scheme when the deforming element slides over the surface. Therefore, in real conditions, the most approximate to a rectangular groove shape may be a trapezoidal cross-sectional shape of the groove (Fig. 9e). In fact, considering the capabilities of regular and partially regular microreliefs formed on the working surfaces of machine parts [1], we can state their certain limitations regarding the geometric shapes and uniqueness of the patterns created by their grooves. It is also worth noting their technological imperfections, which are due to the complex shape of the grooves, whose axial symmetry line exhibits continuous, regular, and irregular variation and is described by a periodic function. This leads to the fact that the geometric shape of the grooves in planar microreliefs has so-called "peaks," during the formation of which the tool must change direction and, accordingly, stop. This significantly reduces the productivity of forming the microrelief grooves.

If regular and partially regular microreliefs formed on the plane have a constant groove depth, such microreliefs can be called planar. In contrast, microreliefs with variable groove depths are called volumetric-class microreliefs.
In planar microreliefs, the groove depth is a constant value in all grooves of the microrelief. That is, the operational properties of the surface are provided only by changing the area occupied by the microrelief (relative area of the microrelief). If the groove depth is a variable value, it is evident that this will lead to a change in the operational properties of the surface on which such a microrelief is formed. Thus, the provision of the operational properties of the surface can be achieved not only by changing the area occupied by the microrelief (its relative area) but also by altering the depth of its grooves. The general view of the longitudinal section of the groove of a regular volumetric class microrelief with a rectangular cross-section is shown in Fig. 4.

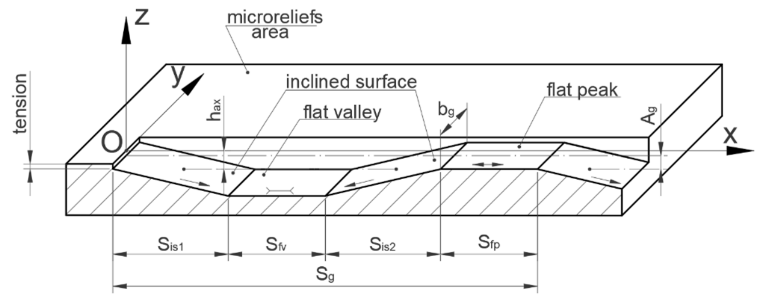


Fig. 4. Longitudinal section of the groove of a regular volumetric class microrelief with a rectangular cross-section

For a complete and accurate understanding of the classification, let's consider the main elements of the profile of a volumetric microrelief groove (Fig. 5).

Accepted notations:

b_g – width of the microrelief groove;
L_g – length of the microrelief groove;
h_{ax} – distance from the surface on which the microrelief is formed to the longitudinal axis of the microrelief groove;
A – amplitude of the irregularities of the microrelief grooves;
S_o – interaxial pitch of the microrelief grooves (for microrelief with parallel grooves);
S_g – pitch of the irregularities of the microrelief grooves;
S_{is1} – length of the 1st inclined element of the profile;
S_{is2} – length of the 2nd inclined element of the profile;
S_{fv} – length of the flat valley;
S_{fp} – length of the flat peak;
b_{lk}, b_{bk} – distances from the boundaries of the microrelief groove to the boundaries of the area on which the microrelief is formed.

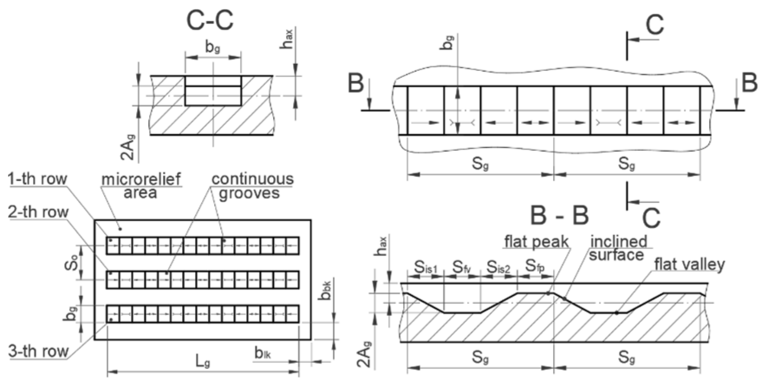


Fig. 5. A groove of a volumetric class microrelief and its main elements

A new class of regular microreliefs has been proposed, where the grooves of the microrelief ensure regularity both in the horizontal and vertical planes.

In the classification of microreliefs, the "volumetric" microreliefs class will be at the same level as the "planar" regular and partially regular microreliefs.
The width of the microrelief groove is the most significant distance of the microrelief groove trace measured in the horizontal plane in the direction perpendicular to the longitudinal axis of the groove.

Pitch of the microrelief groove irregularities – is the distance at which the microrelief groove completely repeats its profile. For volumetric-class microreliefs, the groove profile will vary in one or two planes, depending on the formation technology. However, the central plane of profile change is the plane perpendicular to the surface plane on which this microrelief is formed. Therefore, the profile change and, hence, the pitch should be determined in this plane.

The amplitude of the microrelief groove irregularities is half the distance between the peak and the valley of the microrelief groove in the plane of the surface on which they are formed.

Area of the microrelief groove – is the total area of all surfaces of the microrelief groove.

Profile elements are the surfaces that form a unique profile of the microrelief in the longitudinal section in the plane perpendicular to the one on which the microrelief is formed. The lengths of the profile elements in the groove can be either the same or different. To better understand the slope of the microrelief groove surface relative to its longitudinal axis, we use appropriate notation with arrows (Fig. 4, Fig. 5).

Surfaces in the grooves of volumetric microreliefs can be of three classes:
- inclined ↗ ↘
- plane peak ↔;
- plane valley >–<

The classification features of regular microrelief are divided into two groups:
- those that describe the geometric parameters of the microrelief grooves;
- those that describe the arrangement of the microrelief grooves.

The group describing the geometric parameters of the microrelief grooves includes the following classification features:
- filling of grooves with profile elements;
- shape of profile elements in the groove;
- shape of groove profile elements along the axis;
- shape of the cross-sectional profile of the groove;
- shape of the groove axis;
- uniformity of grooves;
- length of groove profile elements.

The group describing the mutual arrangement of the microrelief grooves includes the following classification features:
- uniformity of microrelief;
- arrangement of profile elements in uniform grooves;
- arrangement of grooves along the axis;
- number of microrelief grooves in a row;

Description of the geometric parameters of grooves:

Filling of grooves with profile elements. Based on the filling of grooves with profile elements, microrelief grooves are divided into four groups:
- 1^{st} group – grooves with descending and ascending surfaces;
- 2^{nd} group – grooves with descending, ascending surfaces, and flat valleys;
- 3^{rd} group – grooves with descending, ascending surfaces, and flat peaks;
- 4^{th} group – grooves with descending, ascending surfaces, flat peaks, and flat valleys;
- 5^{th} group – combined (any number of descending, ascending surfaces, flat valleys, and flat peaks).

The microrelief grooves of the different groups are shown graphically in Fig. 7.

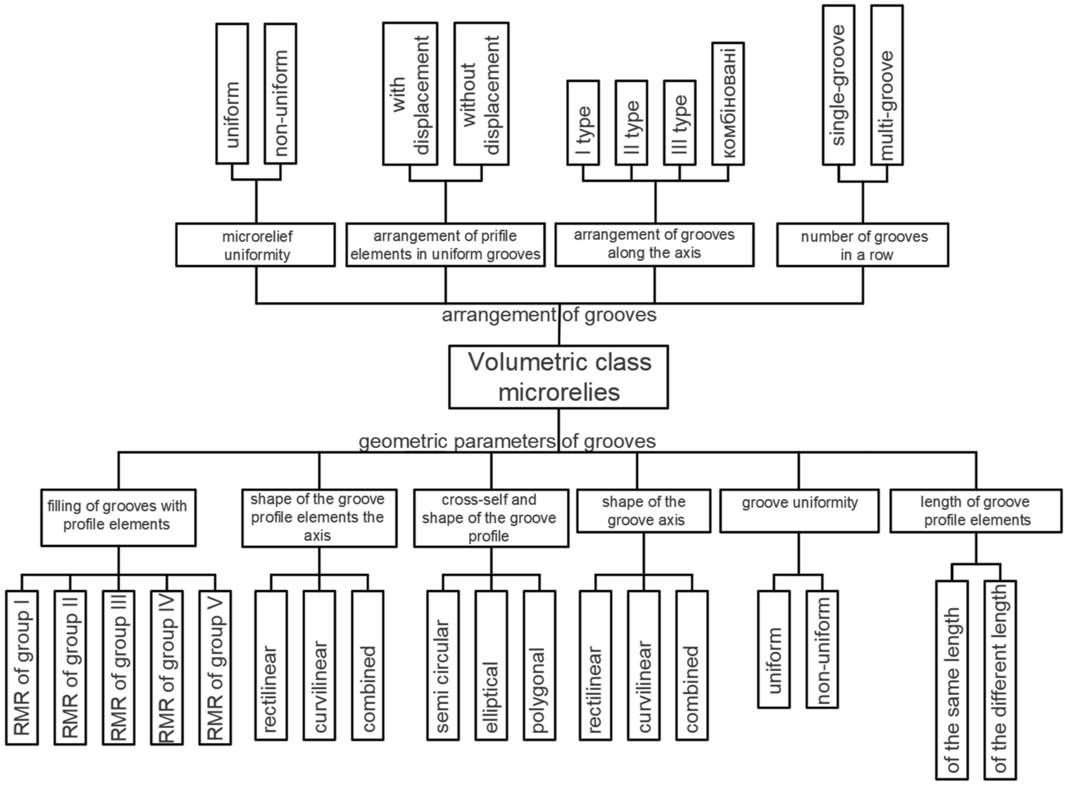


Fig. 6. Classification of volumetric microreliefs by classification features

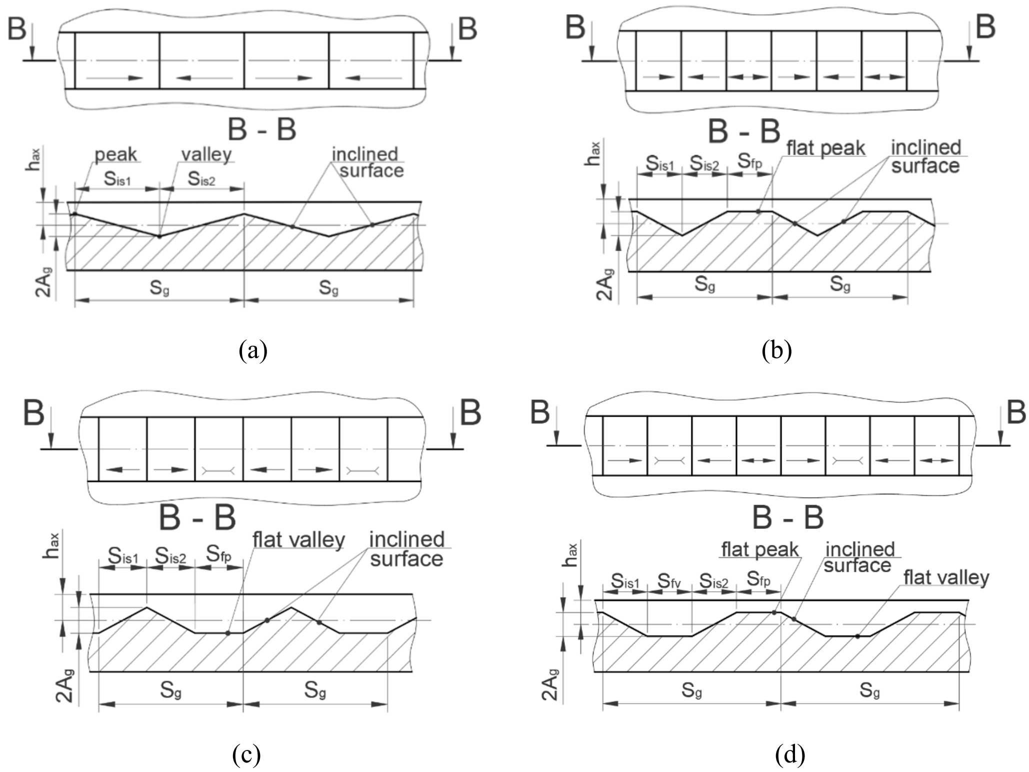


Fig. 7. Varieties of the volumetric class of microrelief with different filling of grooves by profile elements:
a – I group; b – II group; c – III group; d – IV group; e – V group

The profile elements can be either straight or curved, but still belong to the same group. This case will be discussed further in this article.

The shape of the groove profile elements along the axis. The micro-relief groove elements can have a rectilinear (Fig. 7), curvilinear, or combined shapes (Fig. 8). These grooves may not include all surface groups, but rising and descending surfaces are essential to ensure the regularity of the micro-relief along its axis.

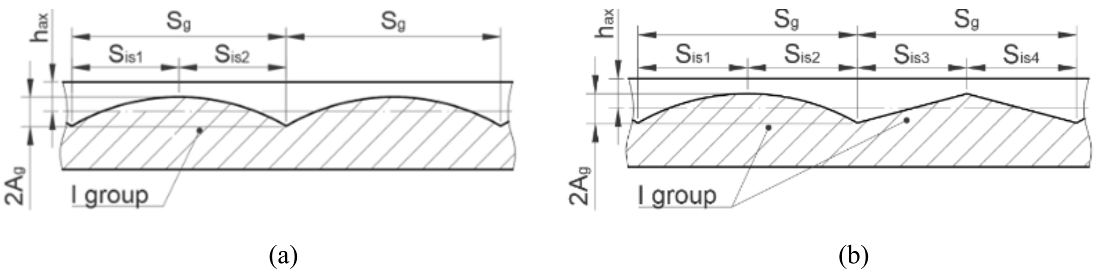


Fig. 8. Volumetric class microrelief grooves with inclined elements:
a – of curvilinear shape; b – of curvilinear and rectilinear shapes

The grooves shown in Fig. 7a and Figs. 8a and 8b belong to Group I, yet the shape of the profile elements in these grooves differs. From a technological perspective, it is quite challenging to ensure a straight groove profile, as microrelief grooves are primarily formed using deforming elements in the shape of spheres.

Cross-sectional Shape of the Groove Profile. The cross-sectional shape of volumetric microrelief grooves can vary depending on the shape of the tool used to form them. The most common cross-sectional shapes of microrelief grooves include semicircular, formed by a ball; elliptical, formed by a roller; and polygonal (triangular, rectangular, trapezoidal, etc.), formed by a tool with a specially shaped indenter (Fig. 9).

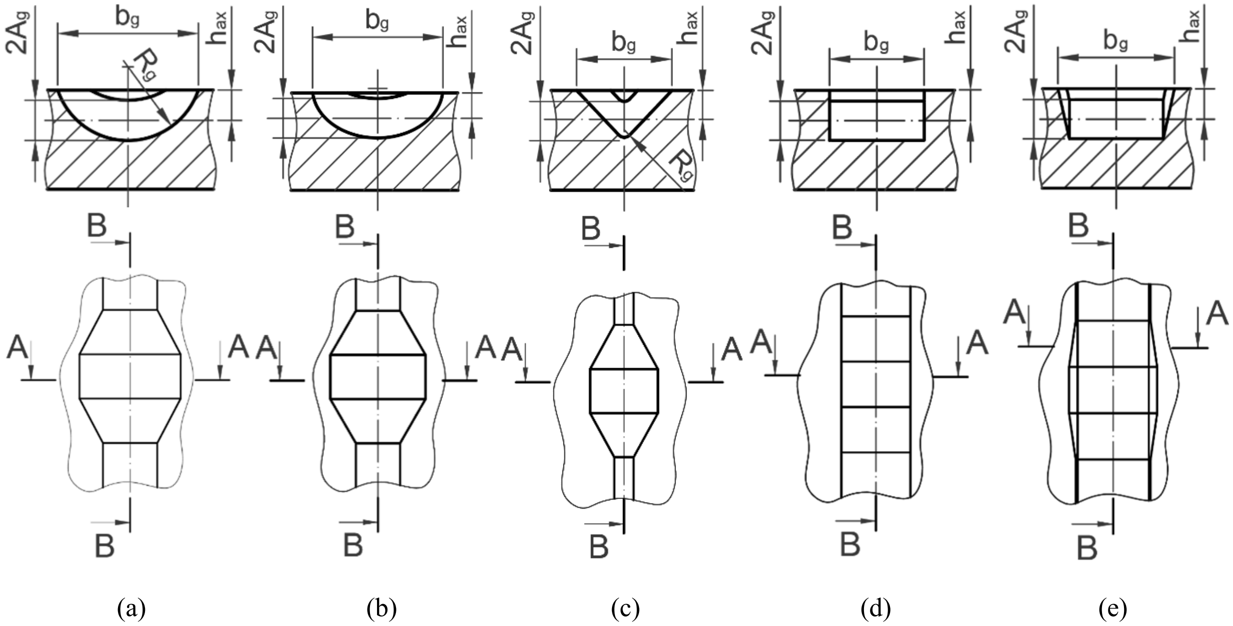


Fig. 9. Longitudinal and cross-sectional profile of the groove and its projection onto the horizontal plane:
a – semicircular; b – elliptical; c, d, e – polygonal

Variation in cross-sectional shapes of profile elements in volumetric microrelief grooves. When grooves have the same width b_g and their profile elements are identical in shape and size, different cross-sectional shapes of these elements will result in varying projections of the groove areas onto the horizontal plane. This phenomenon is unique to volumetric class microreliefs and has not occurred in planar microreliefs with grooves of equal depth, highlighting a distinctive feature of volumetric microreliefs.

Shape of the microrelief groove axis. The axis of volumetric microrelief grooves can be either rectilinear or curvilinear. To maximize groove-formation efficiency, a straight axis is generally preferred. However, when dealing with complex-profile surfaces, forming volumetric microreliefs with curved grooves becomes more justified.

Uniformity of microrelief grooves. Microrelief grooves are considered uniform if, along the entire length of the groove within a pitch S_g, their profile elements are absolutely identical in shape and periodically repeat (Fig. 10a).

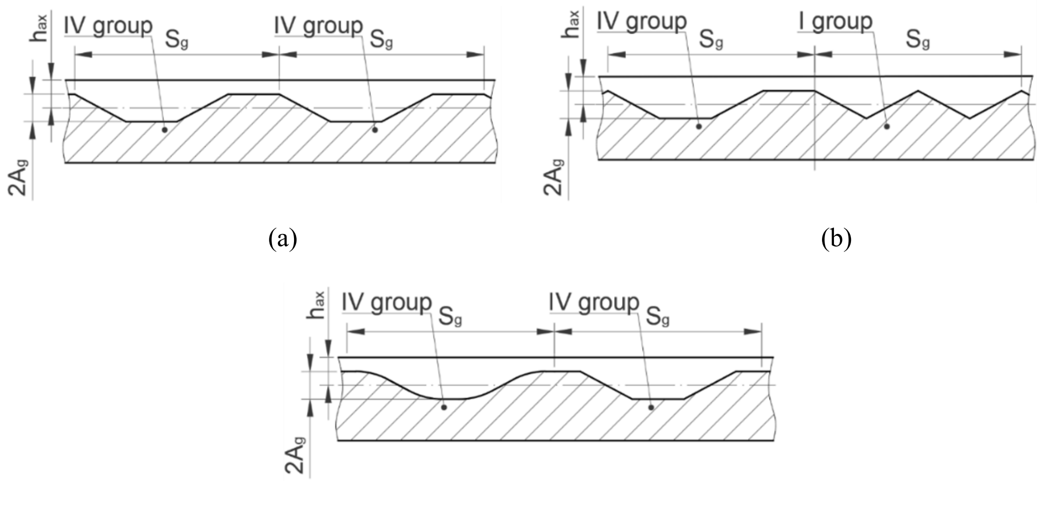


Fig. 10. Cross-section of volumetric class microrelief groove: a – uniform groove; b, c – non-uniform grooves

Grooves are considered non-uniform when, along their entire length within the pitch S_g, they are filled with profile elements that differ in shape and periodically repeat (Fig. 10b). For example, a groove may consist of elements from the same group (Fig. 10c) with similar surfaces (inclined surfaces, a flat peak, and a flat valley). However, if the profile elements differ in shape, the groove will be classified as non-uniform.

Length of groove profile elements. The length of the profile elements within a microrelief groove can either be the same or vary. The lengths of these elements are denoted as S_{is1}, S_{is2}, S_{isn}. Different lengths of profile elements result in a varying groove profile in the longitudinal section.

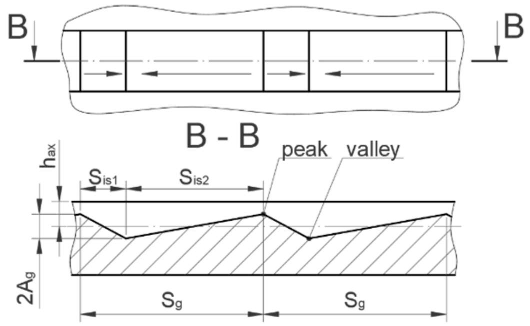


Fig. 11. Longitudinal profile of a volumetric microrelief groove with unequal profile element lengths

Despite the fact that grooves may belong to the same group based on the filling of profile elements, variations in the groove profiles can lead to non-uniformity in the micro-relief grooves.

Description of the features of microrelief groove placement:

Uniformity of microrelief. The uniformity of the microrelief is determined by the consistency of the grooves' profiles. Based on this feature, microrelief is classified as uniform if all grooves have exactly the same profile, and non-uniform if the grooves on the same surface differ in profile along their entire length. It is also possible for the grooves within a single groove to be non-uniform while still maintaining overall uniformity across the micro-relief formed on the surface.

Placement of profile elements in uniform grooves. According to the proposed classification, the placement of profile elements in uniform grooves can be either displacement-free or displacement-based.

Various options for placing profile elements in uniform grooves are illustrated in Table 1. The longitudinal profile of a groove can be described using a morphological expression by sequentially denoting its elements: S_{is1}, S_{is2}, S_{fp}, S_{fv}.

Table 3: A set of options for the arrangement of profile elements in homogeneous continuous grooves

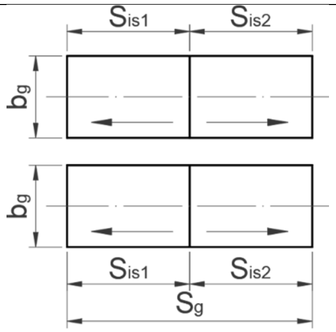
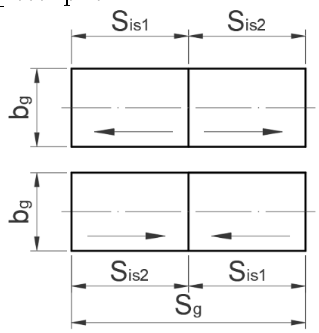
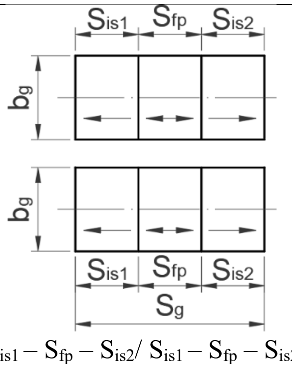
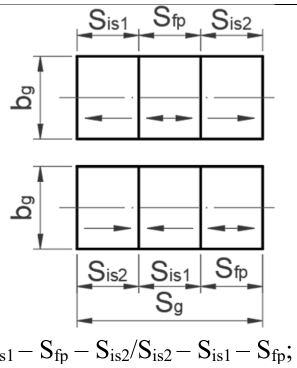
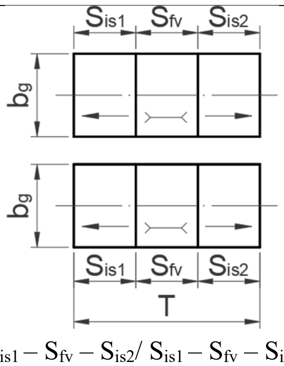
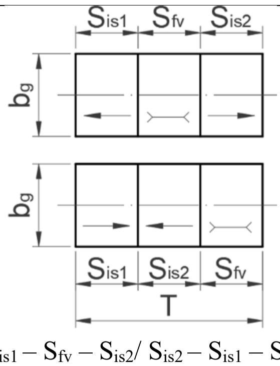
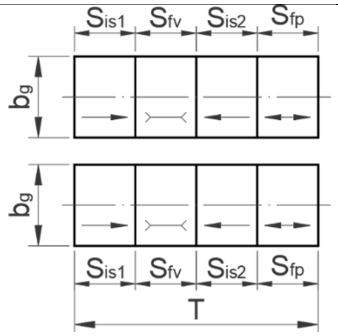
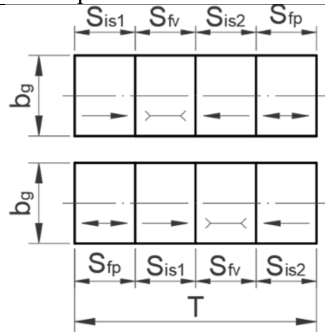
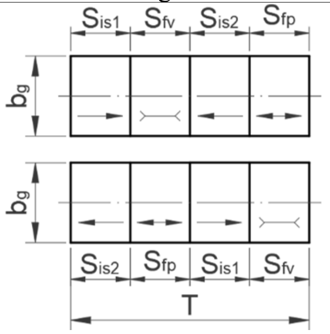
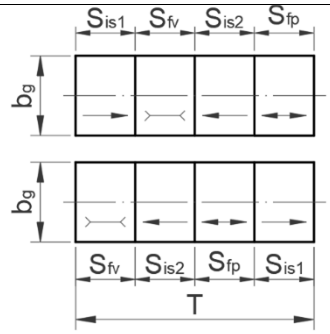
Graphical Representation of the Projections of Groove Areas of the Formed Microrelief on the Horizontal Plane and Their Conditional Morphological Description	
 S_{is1} –S_{is2}/ S_{is1} –S_{is2} a	 S_{is1} –S_{is2}/ S_{is2} –S_{is1} b
 $S_{is1} – S_{fp} – S_{is2}$/ $S_{is1} – S_{fp} – S_{is2}$ c	 $S_{is1} – S_{fp} – S_{is2}$/$S_{is2} – S_{is1} – S_{fp}$; d
 $S_{is1} – S_{fv} – S_{is2}$/ $S_{is1} – S_{fv} – S_{is2}$ e	 $S_{is1} – S_{fv} – S_{is2}$/ $S_{is2} – S_{is1} – S_{fv}$ f

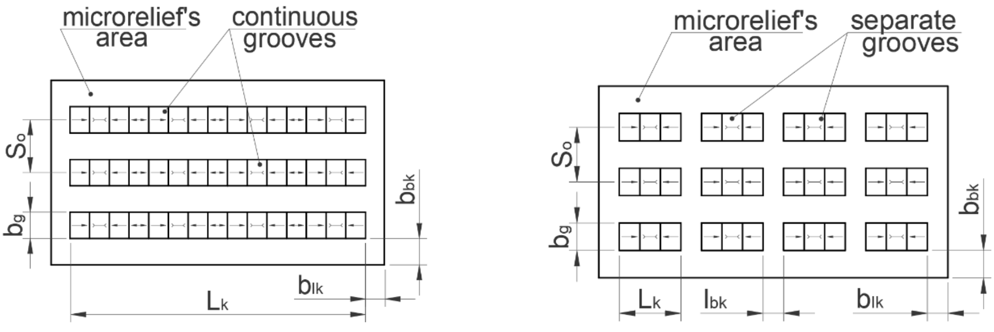
Table 3: (Continued) A set of options for the arrangement of profile elements in homogeneous continuous grooves

Graphical Representation of the Projections of Groove Areas of the Formed Microrelief on the Horizontal Plane and Their Conditional Morphological Description	
 $S_{is1} – S_{fv} – S_{is2} – S_{fp}$ / $S_{is1} – S_{fv} – S_{is2} – S_{fp}$ g	 $S_{is1} – S_{fv} – S_{is2} – S_{fp}$ / $S_{fp} – S_{is1} – S_{fv} – S_{is2}$ h
 $S_{is1} – S_{fv} – S_{is2} – S_{fp}$ / $S_{is2} – S_{fp} – S_{is1} – S_{fv}$ i	 $S_{is1} – S_{fv} – S_{is2} – S_{fp}$ / $S_{fv} – S_{is2} – S_{fp} – S_{is1}$ j

Arrangement of grooves along the axis. Volumetric microreliefs can be classified as follows:
are divided into four groups:

- type I: with parallel grooves that do not touch,
- type II: with parallel grooves that touch,
- type III: with intersecting grooves,
- combined: with grooves that are not parallel but either do not touch or do touch. For this class of microrelief, the most characteristic arrangements of the grooves' longitudinal axes are Types I and II, according to the classification [26].

Number of grooves in a row. Based on groove continuity, microreliefs are divided into continuous and discontinuous grooves. If a groove within one area of the formed microrelief is continuous, such a groove is defined as a continuous one (see Fig. 12a).



(a) (b)

Fig. 12. Classification of microrelief by the number of grooves in a row: a – single-groove; b – multi-groove

The use of volumetric class microreliefs can be practical on surfaces operating under challenging conditions. For example, wear on internal combustion engine cylinders does not occur across the entire liner surface, but only in narrow areas on the opposite side. It is on such surfaces that it is proposed to form a volumetric class of microreliefs with a higher oil capacity. The straight-line shape of the grooves will be more technological in conditions of limited tool access. Another possible application of this class of microreliefs is the surface of connecting rod liners of internal combustion engines. Under critical loads, the lubricating film is destroyed between the liner surface and the crankshaft journal, and the friction mode changes to the limit one. This leads to the formation of galling. Creating a microrelief of a volumetric class, where the depressions of adjacent grooves are shifted by a small amount in the direction of rotation of the shaft neck, will create a guaranteed oil layer that provides a hydrodynamic friction mode. Thus, this class of microrelief has significant potential to improve the operational properties of machine parts.

3. Conclusions

The proposed new class of partially regular microrelief allows varying a wide range of geometric parameter values. Regular microreliefs with variable groove depth and plastically deformed groove protrusions are proposed for the first time. Such microreliefs allow a significant increase in the relative area of the microrelief, up to 100% without losing the supporting surface area. The rectangular shape of the cross-section of the microrelief grooves provides the lowest degree of groove degradation and the least loss of groove area during surface grinding. Thus, the residual groove area for a rectangular cross-sectional profile relative to the initial value is 81%, for a triangular one, 50%, and for a semicircular one, 69%.

This will improve the operational properties of machine part surfaces. The proposed classification serves as a foundation for the mathematical modeling of grooves in partially regular volumetric microrelief classes. This will enable the development of control programs for CNC machines to form these on working surfaces and to research their operational properties.

Further research on volumetric class microreliefs will focus on their mathematical modeling and the determination of the geometric parameters of their grooves, ensuring the necessary operational properties of surfaces with such microreliefs. An important objective will be to determine the areas of microrelief grooves with different cross-sections, as well as the growth area coefficients. This will allow calculating the necessary coordinates for control programs for CNC machines when forming microrelief grooves.

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