construction materials

*Article*
# Partially Regular Microreliefs Formed by Rotation

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**Abstract:** A new scheme for forming partially regular microreliefs by rotational rolling is proposed. A new transcendental curve-shaped, partially regular microrelief (of a trochoid type) is discussed; the shape and geometric parameters of its grooves are substantiated. Grooves discussed below proved to be technologically advanced, providing for a high performance of all types of equipment. Once combined, they act together to provide for the best in-service properties of planar, partially regular microreliefs formed by rotation, which are unparalleled among those of their kind. Analytical dependences are presented that describe the groove's shape. A relationship is established between the main technological parameters, that is, feed rate and rotation frequency of the deforming element that produces microrelief grooves of different shapes and sizes. Possible location variants for microrelief grooves are given and classified. Technological layouts and movement cyclograms are substantiated for the tool that forms regular microrelief grooves by means of rotation. A comparative analysis of the profile lengths of the grooves of rotational and sinusoidal microreliefs modeled in the MathCAD environment was conducted.

**Keywords:** regular microrelief; grooves; cycloid; geometric parameters; shape; properties

## 1. Introduction

Researchers involved in surface engineering need a powerful toolset that would help them improve the in-service properties of machine parts' working surfaces by applied methods. New surface structures are investigated that provide for the optimal in-service characteristics of working surfaces throughout their service life. Regularity is a key to obtaining the required in-service characteristics of a surface. To this end, surface irregularities are created, the shape, size, and mutual placement of which can be controlled. This helps improve the physical and mechanical properties of the surface. Surface regularization aims at reducing the number of irregularities, the shape and size of which cannot be controlled. The proportion of controlled irregularities is called the microrelief's relative area. It is defined as the ratio of the regular microrelief's area to the surface area on which they are formed. It is this parameter that defines the in-service properties of the surface. Its optimal value is determined by the operating conditions in each specific case. New types of regular and partially regular microreliefs need to be investigated to find the optimal geometry of regular surface microroughnesses. This will aid in obtaining the specified in-service parameters of machine parts' working surfaces.

In modern engineering, curves in the form of a trochoid or its variant—cycloid—have been used in the design of working surfaces of cutting tools, in particular, end mills [1]. The end mill's working surface of the shape discussed was found to wear out more slowly and evenly, thus extending the tool's life and providing for a high-quality surface treatment, even if the tool's working surface is worn out heavily.



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Working surfaces in the form of cycloidal curves are widely used in cycloidal drives [2], which are used in industrial robots, machine tools, the aerospace industry, and other industries. These drives provide for a high gear ratio, light weight, compact dimensions, high accuracy, and impact toughness [3,4]. Many scientific papers describe investigations into the shape of regular microrelief grooves. In particular, the paper in [5] presents research findings dealing with the speed at which liquid droplets roll down from surfaces with different microreliefs. Test specimens with microrelief grooves of nine different shapes were made specifically for this purpose. A surface microrelief in the form of longitudinal grooves was found to retain droplets a little longer than other microrelief types or flat surfaces.

The paper in [6] investigates the effect of microrelief grooves' shape on the friction coefficient. To obtain reliable results, the relative microrelief area was the same in each experiment. This is an important parameter that affects the contact area between surfaces and determines the friction coefficient. Research findings indicate that of all planar microreliefs, sinusoidal grooves provide for the lowest friction coefficient. At the same time, we should note that the difference between friction coefficients provided by microrelief grooves of different shapes was insignificant. Therefore, grooves' shape is not a determining factor, even though it affects the tribological characteristics of the surface.

Mathematical models of partially regular microreliefs, which have regular properties of certain parameters, are devoted to the work in [7]. The author conducted mathematical modeling of the shape of microreliefs depending on the design parameters of the microrelief grooves and the technological parameters of their formation. It was established that the parameter, that is, the pitch of the microrelief grooves in the Cartesian coordinate system is variable, and in the polar coordinate system is constant (unchangeable). Thus, a new concept was introduced—the angular pitch of the microrelief grooves, which for partially regular microreliefs formed on the end surfaces of bodies of revolution in the polar coordinate system is constant.

The paper in [8] is interesting because it describes how grooves are created. The authors examine micro-grooves obtained by micro-milling. The effect of processing conditions, such as feed rate, cutting speed, and depth, on the surface roughness formation process and its numerical value was investigated. The range of optimal values of these parameters was found for different materials. To address the surface treatment quality, the authors developed a model for creating surface roughness of metallic materials by micro-milling. Micro-grooves that appeared in the process of milling were considered a negative consequence of the milling process. However, their geometric parameters were not investigated, as well as the conditions that lead to their formation.

The paper in [9] considers the in-service characteristics of the irregular microrelief formed by honing. Grooves are located in an irregular manner because the microrelief formation process does not provide for this. The abrasive mesh's parameters (grain size of the honing tool) were found to affect the oil film's thickness and the friction coefficient. This paper is interesting because it considers the effects caused by the grain size.

The paper in [10] investigates the transformation of a honing surface with irregular microrelief grooves formed on top.

The paper in [11] describes the operating conditions of cylinder liners made of Al-Si alloy and cast iron. It also discusses their tribological characteristics and resistance to scuffing. After wear and scuff tests, cast iron cylinder liners were found to have a better wear and scuff resistance but poor friction performance. Cylinder liners made of Al-Si alloy had a lower wear and scuff resistance but excellent friction performance. The paper considers the surface microstructure, grooves' geometry, and their location relative to each other. The wear mechanism inherent in the honing surfaces with grooves and the shell formation process that precedes scuffing are described.

The paper in [12] presents the scuffing hypothesis for internal combustion engine (ICE) cylinder liners. Scuffing is preceded by abrasion of the structure formed during honing and the resulting surface cracks. This leads to the appearance of a layered structure on the liner surface. Tribofilms undergo local fracture, leading to a local metallic contact between specimens. When this local fracture becomes uncontrollable and extends to the macro level, the adhesive bonds lead to the occurrence of macroscopic scratches. The authors come to a conclusion that damage caused to the cylinder liner's surface results from surface fatigue.

The paper in [13] investigates the effects caused by wear of the honing tool intended for the inner cylindrical surface of ICE cylinder liners. Only a few parameters ($S_{pk}$, $S_{sc}$, and $S_k$) were found to cause wear of the honing tool intended specifically for each cylinder. As the honing tool wears out, the surface roughness of the cylinder liner increases.

The paper in [14] presents findings concerning the irregular microreliefs formed by honing and the optimal shape of such microreliefs' grooves. Grooves of multi-directional shape proved best at providing a more uniform microstructure of the machined surface and lower surface roughness values.

All these studies confirm that a microstructure even with partially regular microrelief grooves significantly improves the in-service characteristics of the surface on which it is formed. Thus, summing up the analyzed research, it can be stated that one of the ways to improve the operational properties of the working surfaces of machine parts is the formation on their surface of partially or completely regular micro-irregularities with specified geometric parameters. It is necessary to establish the dependence between the geometric parameters of microreliefs and the modes of their formation.

## 2. Theoretical Aspects of Microrelief Formation

The analysis of the literature sources suggests that the microrelief grooves' shape does not significantly affect the in-service characteristics of the friction pair's surfaces. However, the relative microrelief's area is a crucial parameter for planar microrelief. It is expressed as the ratio of the microrelief grooves' area to the surface area on which they are formed. Therefore, the specific area of grooves per unit surface area of the friction pair is important when it comes to obtaining the required in-service characteristics of the surface.

The irregular microrelief created on the inner cylindrical surface of the ICE cylinder liner, which is called a hone, is the best testimony to that.

Therefore, to obtain the required in-service characteristic of a surface with a microrelief formed on top, we need to create grooves that occupy a certain surface area, placing them uniformly with a certain tolerance.

Similar microreliefs can be created on flat surfaces. Making grooves of a rectilinear shape appears to be the simplest solution for a flat surface, as far as manufacturability is concerned. However, such grooves do not provide for the uniformity of physico-mechanical and, accordingly, service characteristics in different directions of the surface.

A groove of a periodically repeating complex shape allows us to obtain uniform in-service surface characteristics. This is because its midline has an optimal shape for a continuous regular micro-roughness. This may be a trochoid or its variants—elongated, shortened, and ordinary cycloids. They can be formed by rotating a deformable element in a circle with radius $R_g$, gradually moving it along the axis. Forming microreliefs by rotation is a highly productive technology since it coordinates only two movements, that is, the rotational movement $D_r$ and feed movement $D_s$ of the deforming element. This makes it possible to form rotary microreliefs on any equipment that can adjust feed rate or the number of revolutions.

Once combined, feed and rotation rates of the deforming element make it possible to create partially regular microreliefs of different shapes and sizes.

There are two schemes for creating partially regular microreliefs by rotation. Depending on the scheme chosen, the shape of grooves may be similar, but the formation process' kinematics are completely different.

In the first case, the deforming element's movement describes a cycloid—the dynamic trajectory of any point that belongs to a circle with radius $R_g$, which rolls without slipping along a straight line (Figure 1b). When a circle with radius $R_g$ rolls along a straight line, its instantaneous center of rotation, that is, the point of the lower quadrant, will constantly change. In other words, per one complete revolution of the circle, it will move along the axis by a value equal to its length $2{\cdot}\pi{\cdot}R_g$.

(**a**) (**b**) (**c**) (**d**) (**e**)

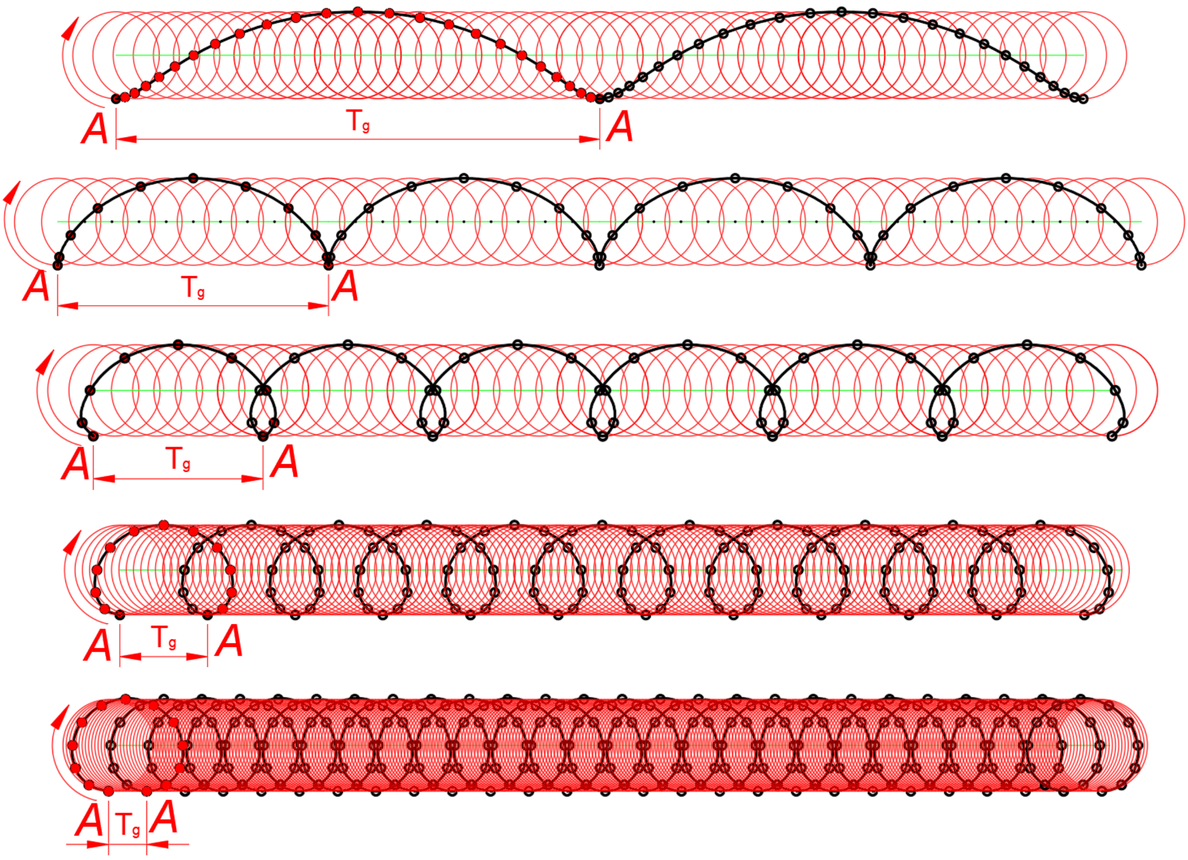


**Figure 1.** Transformation of the deforming element's trajectory when it rotates around a circle with radius $R_g$ at different rotation rates. (**a**) shortened cycloid; (**b**) cycloid (**c**–**e**) elongated cycloids.

A similar curve can also be modeled by rotating a circle with radius $R_g$ around its center. However, a mandatory condition is that for one complete revolution of the deformable element placed on a circle with radius $R_g$, its longitudinal movement (feed) should be equal to the length of the circle, that is, $f_d = 2{\cdot}\pi{\cdot}R_g$. The resulting shape of the groove's centerline will also have the shape of a cycloid. The length of the cycloid arch is $8R_g$.

In the second case, the rotation rate of the deforming element around the center of a circle with radius $R_g$ and the speed of its translational motion along the axis (feed) are independent values. Their combination makes it possible to obtain curves that are different in shape (Figure 1a,c–e).

In practice, both schemes can be implemented on the same equipment.

Basic geometric characteristics of a regular microrelief formed by rotation:

$A_g$ is the groove's amplitude;

$L_{g1}$ is the projection length of the groove's axial part;

$L_{g2}$ is the projection length of the groove's subaxial part;

$T_g$ is the groove's step;

$b_g$ is the groove's width;

$S_o$ is the interaxial distance between microrelief grooves;

$R_g$ is the cycloid radius.

Cycloidal grooves of a regular microrelief formed by rotation are created by rolling along a straight line per one revolution of any point, for example point $A_0$, which is found on a circle with diameter $R_g$ (Figure 2a). In this case, point $A_0$ will move to point $A_2$.

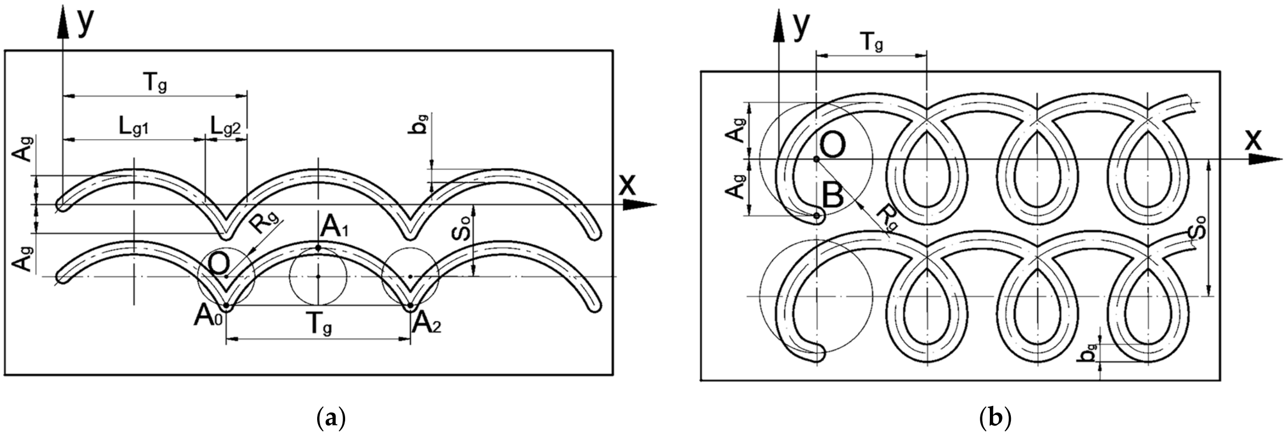


**Figure 2.** Basic geometric parameters of grooves and their location on a regular microrelief formed by rotation. (**a**) cycloid; (**b**) elongated cycloid.

In general, the parametric equations of this curve are described by the following equations:

$$\begin{cases} x = R_g\alpha - h \cdot \sin(\alpha) \\ y = R_g - h \cdot \cos(\alpha) \end{cases} \quad (1)$$

where $h$ is the distance between a point and the circle center;

$\alpha$ is the rotation angle of the deforming element;

$R_g$ is the circle radius.

If $h = R_g$, the resulting curve will be a cycloid. If $h > R_g$, the resulting curve will be an elongated cycloid. If $h < R_g$, the resulting curve will be a shortened cycloid.

Microrelief of this type has a certain feature. In particular, the axial line of a continuous irregularity has a different length on both sides of the groove's axis (Figure 3). Thus, projection length $L_{g1}$ is longer than projection length $L_{g2}$. At the same time, amplitudes $A_{g1}$ and $A_{g2}$ of the microrelief groove are the same. Given this, we can suggest that this microrelief is similar to planar microreliefs with grooves of different shapes (sinusoidal, triangular, etc.).

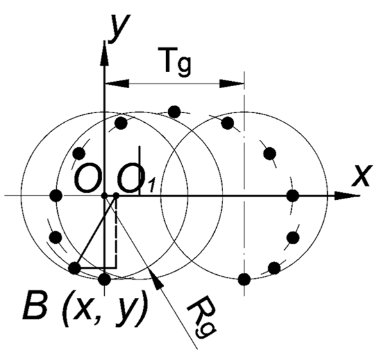


**Figure 3.** Calculation scheme for determining the deformable element's movement.

## 3. New Microrelief Technology

To determine the deforming element's coordinates, that is, point B, and to construct mathematical models, consider the calculation scheme shown in Figure 3.

Equation for determining coordinates $x$, $y$ of the deforming element:

$$\begin{cases} x = -R_g \cdot \sin\alpha + \frac{T_g \cdot \alpha}{360^\circ} \\ y = R_g \cdot \cos\alpha \end{cases} \tag{2}$$

We express these values by technological parameters: feed rate $f_g$ and rotation rate $n_g$. Feed rate $f_g$ is equal to the groove's step $T_g$, provided that it is determined in one revolution of the deforming element.

$$T_g = f_g / n_g. \tag{3}$$

Taking into account the rotation rate of the machine spindle $n_g$, which is defined as rev/sec, and feed rate $f_g$ measured in mm/sec, the groove's step will be determined from the following equation:

Thus, expression (2) will take the following form:

$$\begin{cases} x = -R_g \cdot \sin\alpha + \frac{f_g \cdot \alpha}{n_g \cdot 360^\circ} \\ y = R_g \cdot \cos\alpha \end{cases} \tag{4}$$

where $n_g$ is the rotation rate of the deforming element, in rpm.

The resulting dependencies can be used to model the microrelief's profile with the required geometric parameters.

Figure 4 shows the results of modeling sinusoidal and rotational microreliefs with identical parameters, that is, amplitude $A_g$ for sinusoidal profile ($R_g$ for rotary profile) and step $T_g$.

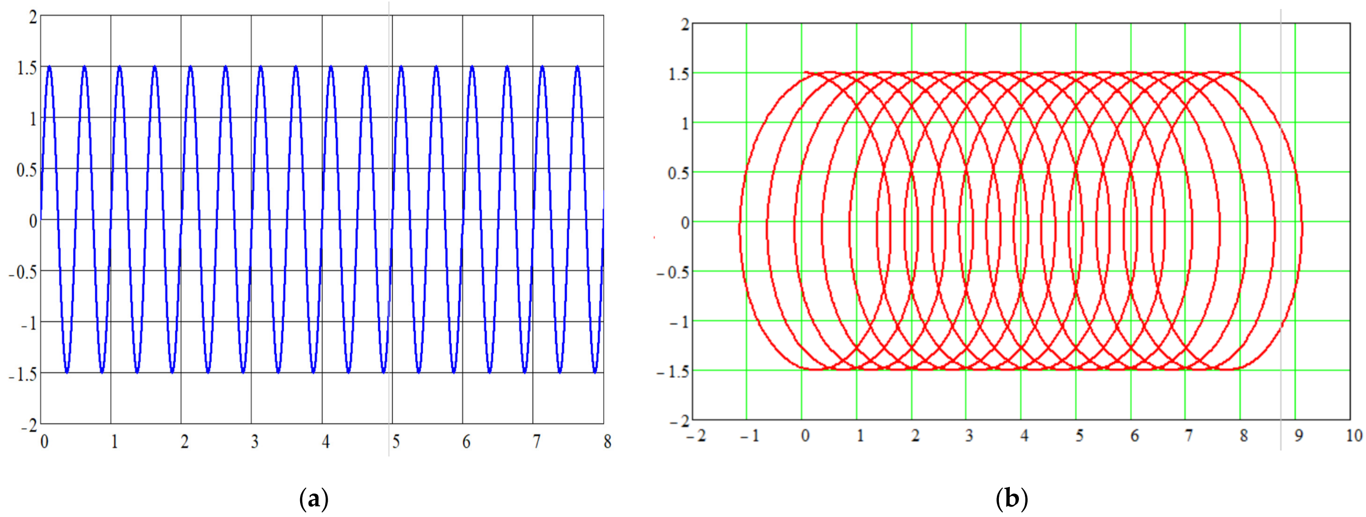


**Figure 4.** Microrelief profile with identical geometric parameters, according to Table 1: (**a**) sinusoidal profile; (**b**) rotary profile.

**Table 1.** Comparative characteristics of microrelief parameters.

| Parameters | Sinusoidal | Rotational |
|---|---|---|
| Amplitude $A_g$, $R_g$, mm | 1.5 | 1.5 |
| Step $T_g$, mm | 0.5 | 0.5 |
| Length of profile grooves per 1 step, mm | 5.98 | 9.40 |

As is seen from Figure 4, a rotary microrelief has many more grooves per unit surface area. This microrelief has its advantages and disadvantages.

Advantages:

- Significantly reduced formation time per one pass;
- Almost the same deformation rate of the surface material, which is high enough;
- No dead points at which the deforming element stops;
- Versatility of the equipment used.

Disadvantages:

- Non-uniform regularity of grooves of certain shapes in the central part and on the periphery;
- Grooves can be formed only on flat surfaces.

The depth of the microrelief grooves is set taking into account the elastic properties of the surface material. At the same time, it should be noted that the deformation rate has a significant impact on the magnitude of elastic deformations during the formation of grooves. When forming sinusoidal microrelief grooves (Figure 4a), the deforming element changes the direction of movement at their vertices. In this case, the speed of its movement will be equal to 0. Thus, the deformation rate during the formation of sinusoidal grooves will constantly vary from 0 at the vertices of the grooves to the maximum value in the middle of the distance between the vertices. When forming rotational microrelief grooves (Figure 4b), the deformation rate will be practically the same. The depth of the microrelief grooves should be set to $h_k$ = 20–40 µm [15,16].

The classification of regular microreliefs formed by rotation is presented in Figure 5.

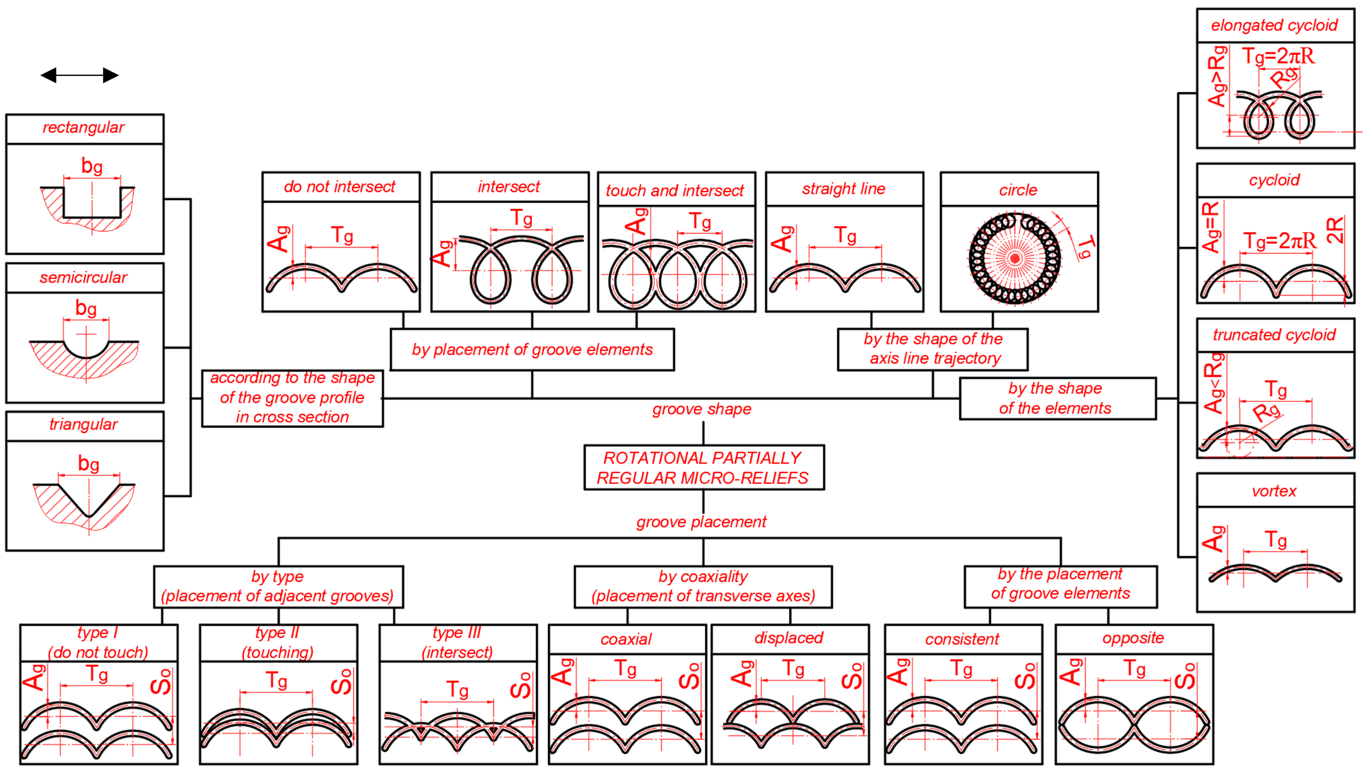


**Figure 5.** Classification of regular microreliefs of rotational type.

## 4. Discussion

Regular microreliefs formed by rotation are classified by two major factors:

- Shape of grooves;

- Location of grooves.

The classification by the shape of grooves determines the geometric parameters of a groove, that is, the shape of its axial line and the shape of its profile in the transverse and longitudinal cross-section. Based on this criterion, grooves are classified in the following ways:

- By the groove profile's shape in the cross-section: semicircular, triangular, and rectangular;
- By the location of the groove's elements: non-intersecting, intersecting, intersecting, and tangent;
- By the shape of the centerline's trajectory: straight line and circle;
- By the shape of the groove's elements: cycloid, elongated cycloid, shortened cycloid, and vortex.

The classification by location characterizes the location of microrelief grooves relative to each other. Based on this criterion, grooves are classified in the following ways:

- By type: with non-tangent grooves (type I); with tangent grooves (type II); with intersecting grooves (type III);
- By alignment (placement of transverse axes): coaxial; offset;
- By location of groove elements: sequential; opposed.

Classification makes it possible to create a set of 432 possible variants of partially regular microrelief grooves formed by rotation. Schematically, a set of variants of microrelief grooves is presented in Figure 6.

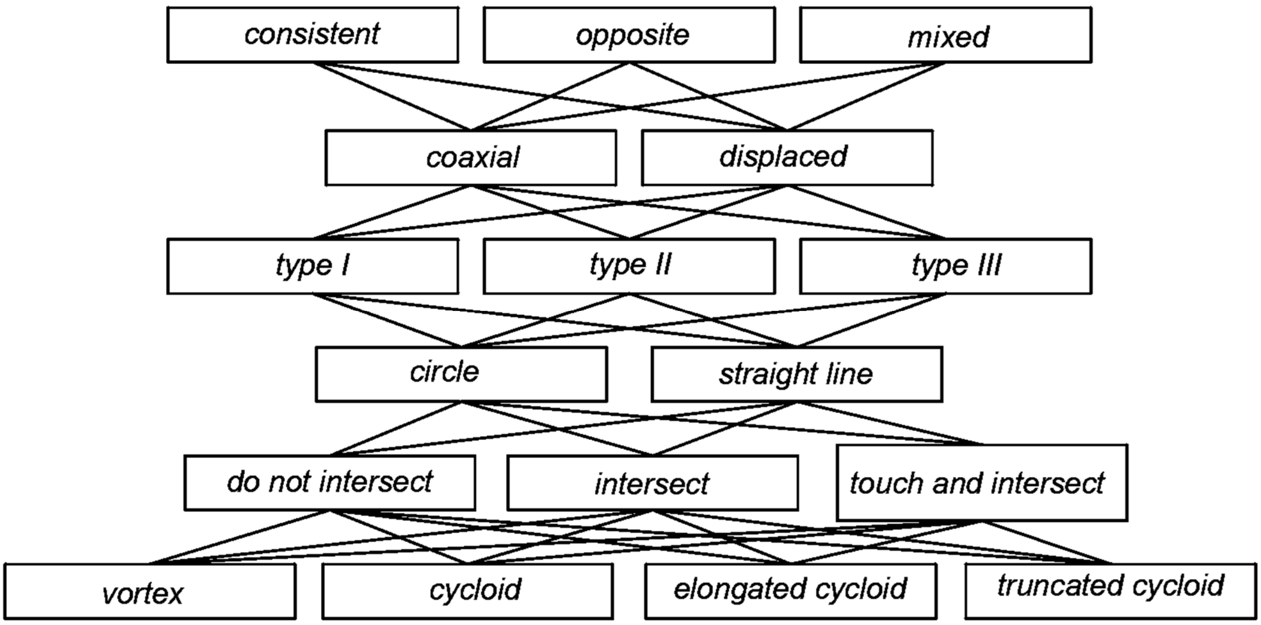


**Figure 6.** A set of variants of partially regular microrelief grooves formed by rotation.

Further research will determine the conditions for obtaining regular microrelief grooves, calculate their area, and find the conditions that provide for the necessary value of the microrelief's relative area.

A new mechanism for forming microrelief grooves is proposed, in which the rate of deformation of the groove surface will be practically the same at any point. Most metalworking machines provide rotational movements, which significantly expand the manufacturability of forming a microrelief of this shape. The combination of different values of rotation speed and feed motion will allow the formation of microrelief grooves not only of different sizes but also of different shapes.

## 5. Conclusions

1. The analysis of surfaces with regular microreliefs suggests that microrelief grooves' shape does not have a significant effect on the in-service characteristics of such surfaces. Given this, the authors propose to form partially regular microreliefs by rotation. This is a high-tech method that does not require special equipment and can be implemented on any machine without numerical program control. One of the advantages of the microrelief from the shape of the grooves in the appearance of the cycloid is that the fluidity of the grooves is formed, and, consequently, the amount of plastic deformation during their formation at any point in the grooves will be practically the same.
2. A classification of grooves of a rotational microrelief was carried out, and based on it, a scheme for the formation of a set of variants of grooves of a partially regular rotational microrelief was developed. It provides the ability to generate more than 400 groove variants with different geometric parameters and, accordingly, operational properties.
3. The grooves of the rotational microrelief were modeled in the MathCAD environment, and it was found that with the same geometric parameters of the microrelief grooves (step and amplitude), the length of the groove profile in the rotational microreliefs is twice as long as the length of the groove profile in the sinusoidal microrelief.

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