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Transformation of groove area distribution non-uniformity in partially regular microrelief of the rotational type with increasing axial pitch

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Abstract

The transformation of the groove shape in a rotary-type regular micro-relief with varying degrees of groove loop overlap, simulated by an increase in the rotary tool feed rate, is considered. A search was conducted to find the optimal groove shape for partially regular micro-reliefs formed by the rotary method, subject to ensuring the optimal value of the planar heterogeneity coefficient of the groove area distribution. Graphs illustrating the planar heterogeneity of the groove area distribution were constructed for groove shapes formed at tool feed rates of f_g = 2, 2.5, and 3.5 mm/s. It was established that as the longitudinal spindle feed rate increases, the planar heterogeneity coefficient of the groove area distribution, k_g, decreases in both the axial direction and the direction perpendicular to it. Concurrently, the parameters R_{Xmax} and R_{Xaver} increase, whereas R_{Ymax} and R_{Yaver} decrease. The relative area of the micro-relief also decreases as a result. Thus, it is proven that increasing the tool feed rate at a constant rotational speed leads to an increase in the heterogeneity of the groove area distribution for a partially regular micro-relief formed by the rotary method. Optimization of the micro-relief creates a favorable profile of compressive residual stresses, preventing the propagation of microcracks. As the tool feed rate increases, the number of groove intersections decreases from 4 to 2, and the shape itself becomes elongated in the axial direction. Correspondingly, the planar heterogeneity coefficients k_{gX} decrease from 0.69 to 0.48, and k_{gY} decrease from 0.71 to 0.6. The overall relative area of the micro-relief, F_n, drops sharply from 68.48% to 45.9%, which is a critical parameter for determining the load-bearing capacity of the component surfaces.

Keywords: regular micro-reliefs; grooves; planar heterogeneity; area distribution; coefficient; quantitative assessment; parameters

Introduction

Enhancing the operational characteristics of the working surfaces of machine components through technological methods is a highly relevant objective for researchers in the field of surface engineering. In this context, novel types of surface structures capable of providing the required level of operational properties over a specified service period are being investigated. One of the effective approaches to achieving such properties is surface regularization. It involves the creation of asperities with a predetermined shape, dimensions, and spatial arrangement, which contributes to the improvement of the physical and mechanical characteristics of the surface. The primary purpose of regularization is to reduce the proportion of random asperities with uncontrolled shapes and sizes. The fraction of ordered micro-asperities is characterized by the relative area of the micro-relief, which is defined as the ratio of the area of the regular micro-asperities to the total area of the surface on which they are formed. It is this specific parameter that significantly influences the operational properties of the surface, and its optimal value is determined taking into account specific operating conditions. In this regard, investigating the features of new types of regular and partially regular micro-reliefs represents a crucial stage in the search for rational forms of regular micro-asperities capable of ensuring the specified operational characteristics for the working surfaces of machine components.

Literature review

The creation of new types of regular and partially regular micro-reliefs opens up new possibilities for ensuring enhanced operational properties of the working surfaces of machine components. Traditional micro-relief groove shapes–triangular and sinusoidal–although providing a high degree of micro-relief regularity, still remain difficult to form on general-purpose machine tools. This is associated with the challenge of ensuring the regularity of the micro-relief grooves, which is particularly evident on long surface sections. Furthermore, the mechanisms that provide a periodic groove profile with a specific amplitude and a symmetrical arrangement of the groove elements necessitate special tooling and require additional balancing, which consequently complicates the design of the respective equipment.

Working surfaces in the form of cycloidal curves are widely used in cycloidal drives [1], which are employed as actuators in industrial robots, machine tools, aerospace, and other industrial sectors. These transmissions provide a high gear ratio, low weight, compact dimensions, high precision, and impact resistance [2, 3].

As is known, the primary parameter determining the operational properties of a surface with a regular micro-relief–specifically, the coefficient of mutual friction–is the relative area of the micro-relief, which depends on the total area of the micro-relief grooves [4].

While the area of micro-relief grooves of standard shapes and their intersections can be relatively easily determined analytically [5, 6], calculating the area for complex groove shapes remains an unresolved task.

From the perspective of creating various types of micro-reliefs using a rotary tool, the study [7] is of particular interest. The authors developed a mathematical model of the tool's kinematics and the resulting micro-relief profiles formed by it, depending on its operating parameters. It has been demonstrated that face milling allows for the formation of partially regular micro-reliefs featuring various groove shapes and spatial arrangements–specifically, parallel grooves and grooves offset by a fraction of the pitch. Additionally, a 2-DOF (degrees of freedom) vibration platform was developed to provide oscillation along the feed and cross-feed directions during the micro-milling process.

The study [8] investigates the characteristics of forming trochoidal and elliptical grooves. Trochoidal and elliptical modified trochoidal tool trajectories were analyzed, along with the distance between loops, overlap, feed rate, and spindle speed. The proposed method for forming a micro-relief with such groove shapes allows for the optimization of the tool trajectory in order to reduce surface roughness.

The formation of trochoidal micro-relief grooves ensures enhanced operational parameters of the surface, specifically its microhardness [9], which can be increased by 60% relative to the initial value. This machining method yields lower surface roughness parameters compared to conventional milling.

The positive impact on the uniformity of the distribution of surface micro-asperities during machining with a rotary tool utilizing spherical deforming elements is presented in [10]. It has been proven that a radical improvement in the degree of surface isotropy–specifically, an increase of over 80% – could be achieved by employing tools that, in addition to the primary burnishing feed motion, feature an additional rotational movement of the burnishing head (equipped with a greater number of burnishing balls or rollers).

The aim of this work is to determine the variation in the heterogeneity of the groove area distribution for a rotary-type partially regular micro-relief with an increase in the axial pitch, as well as to identify the optimal groove shape of a partially regular micro-relief formed by a rotary method, for which the value of the groove area distribution uniformity coefficient is as close to the optimum as possible, i.e., to 1.

Research materials and methodology

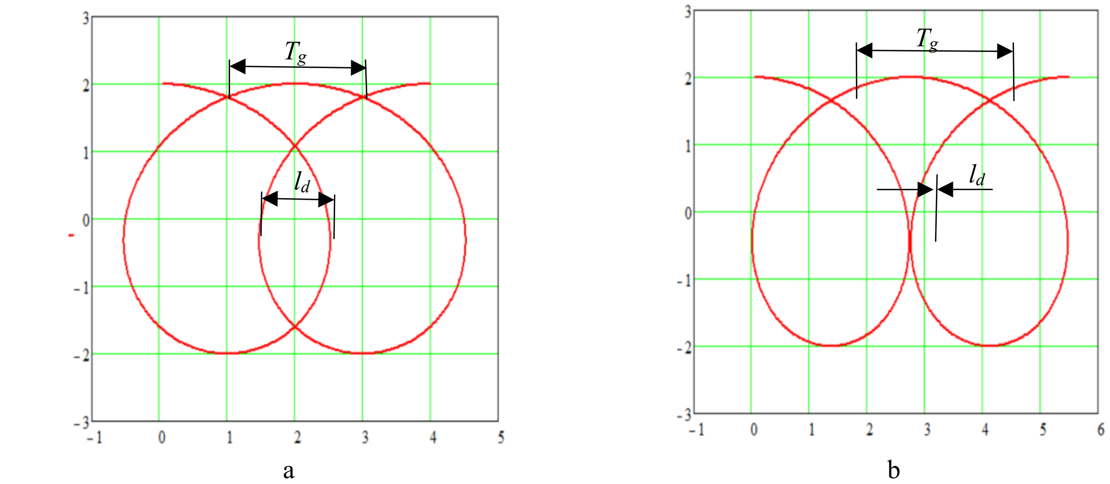
An increase in the productivity of forming partially regular micro-reliefs is associated with an increase in the feed rate of the deforming tool f. Increasing the feed rate while maintaining a constant tool rotational speed leads to a change in the groove shape of the partially regular micro-relief formed by the rotary method. Altering the micro-relief groove shape results in a redistribution of microhardness in the vicinity of the groove, which significantly affects the uniformity of the groove distribution across the plane where the micro-relief is formed. Thus, the uniformity of the groove area distribution across the plane leads to a uniform distribution of surface microhardness. With a dense arrangement of grooves, corresponding to low feed rate values, the plastic deformation zones from adjacent indenter passes overlap. This leads to the formation of a continuous or more uniformly hardened layer with increased microhardness. When the loops are stretched, corresponding to high feed rate values, the hardening becomes local (only within the zone of the grooves themselves), while areas with the initial hardness remain between them.

Plastic deformation generates beneficial compressive residual stresses in the surface layer. Modifying the shape of the groove mesh allows for the formation of a specific framework of compressive stresses. The optimal loop density creates a favorable stress distribution profile that prevents the initiation and propagation of microcracks.

There is an optimal value for the relative groove area (typically within the range of 25–40%, depending on operating conditions). Deviations from the optimal trajectory shape (excessive overlap or, conversely, an excessively sparse mesh) lead to a reduction in wear resistance due to decreased load-bearing capacity or insufficient lubrication, respectively.

As is evident, an increase in the feed rate results in a decrease in the number of micro-relief groove intersections. In Fig. 1a, the number of intersections is 4; in Fig. 1b, it is 3; and in Fig. 1c, it is 2. The number of groove intersections and the distance between them, l_d (Fig. 1), constitute some of the most critical parameters determining the surface topology. At the intersection points of the tool trajectories, specific nodes are formed where the material is subjected to a dual deforming impact. This creates distinct conditions that differ significantly from areas featuring isolated grooves. At the groove intersection points, the indenter passes twice, which leads to more intensive plastic deformation. Consequently, at the intersection nodes, the microhardness of the material reaches its maximum values, and the depth of the hardened layer is the greatest compared to other regions of the surface. If the number of intersections is excessively high (indicating a very dense mesh), the repeated plastic deformation of the same metal micro-volumes can lead to the exhaustion of its plasticity – a phenomenon known as over-work hardening. This causes the formation of microcracks, the flaking of the surface layer, and a sharp reduction in fatigue strength.

To determine the variation in the uniformity parameters of the groove area distribution on the plane where the partially regular micro-relief is formed, we will simulate an increase in the tool's traverse speed – that is, an increase in its feed rate – which will result in a corresponding increase in the axial pitch T_g of the micro-relief grooves. The formed grooves possess an identical amplitude value, A_g, but differ in their axial groove pitch values, T_g. The coordinate grid in the figure is specified in millimeters (Fig. 1).



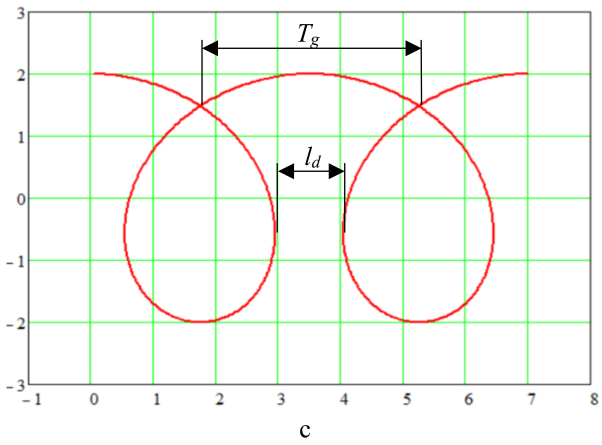


Fig. 1. Transformation of the groove centerline trajectory of a rotary-type regular micro-relief with an increase in feed rate: a – f_g = 2 mm/s; b – f_g = 2.75 mm/s; c – f_g = 3.5 mm/s.

The essence of the method for determining the planar heterogeneity of the groove area distribution in regular or partially regular micro-reliefs is described in detail in [11]. This method allows for determining the optimal mutual arrangement of the micro-relief grooves, at which their area will be distributed most uniformly. This will ensure consistent operational properties of the surface with a regular micro-relief across any of its regions.

The method for determining the planar heterogeneity of the groove area distribution involves determining several parameters, specifically the planar heterogeneity coefficient k_g, and the parameters R_{max} and R_{aver}.

The heterogeneity coefficient k_g is defined as the ratio of the average value R_{aver} to the maximum groove height R_{max}.

$$k_g = \frac{R_{aver}}{R_{\max}} \tag{1}$$

The value of this coefficient is determined in the axial or transverse directions. Under the condition of a completely uniform distribution of the groove area, the value of the coefficient will be 1. The degree of proximity to this value reflects the level of uniformity of the groove area distribution in the selected direction.

The average value of the groove cross-section is determined by the formula:

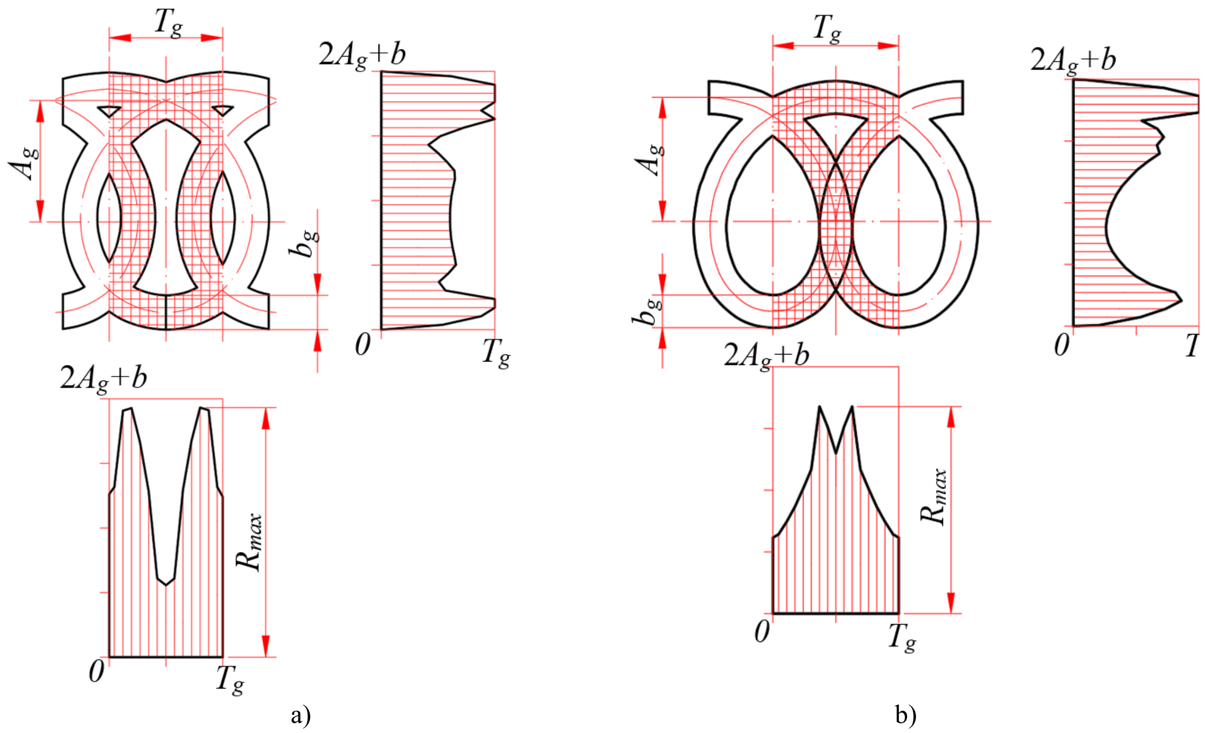
$$R_{aver} = \frac{\sum_{i=1}^{n} h_{gi}}{n} \tag{2}$$

where h_{Ygi} (h_{Xgi}) – height of the *i*-th segment on the corresponding planar heterogeneity graph, mm.

The calculated height values h_{Ygi} are determined within the axial pitch T_g for the axial planar heterogeneity graph, whereas the height values h_{Xgi} are determined within the transverse pitch of magnitude $2A_g$+b_g for the transverse planar heterogeneity graphs. The value A_g corresponds to the groove amplitude, and b_g to its width.

For comparison, we will simulate the groove shape of a rotary micro-relief during its transformation as the feed rate increases. The parameters of the micro-relief groove are as follows: R_g = 2 mm; n_g = 1 rev/s, and groove width b_g= 0.5 mm.

To determine the main parameters of the uniformity of the groove area distribution, it is necessary to construct graphs of their planar distribution (Fig. 2).



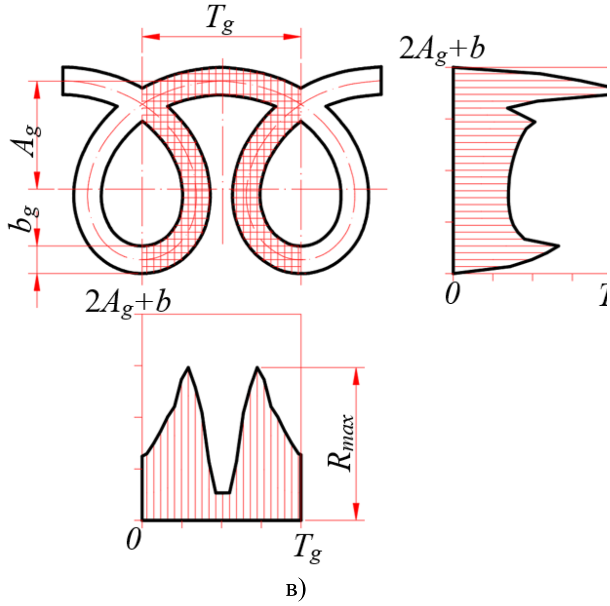


Fig. 2. Graphs of planar heterogeneity of the groove surface area distribution of a rotary-type partially regular micro-relief, obtained for a feed rate: а – f_g =2 mm/s; б – f_g =2,75 mm/s; в – f_g=3,5 mm/s

The results of determining the parameters of the graphs of planar heterogeneity of their area distribution, obtained by increasing the axial pitch through an increased tool feed rate, are presented in Table 1.

As is evident from Table 1, the coefficients of planar heterogeneity of the groove area distribution decrease with an increase in the tool feed rate and the axial groove pitch.

Table 1

Values of parameters and coefficients of planar heterogeneity for grooves of a rotary-type partially regular micro-relief

Measurement parameters	Feed rate		
	f_g =2 mm/s	f_g =2,75 mm/s	f_g=3,5 mm/s
R_{Xmax}	1,71	1,99	2,97
R_{Xaver}	1,18	1,08	1,41
k_{gX}	**0,69**	**0,54**	**0,48**
R_{Ymax}	3,76	3,26	2,86
R_{Yaver}	2,66	2,11	1,72
k_{gY}	**0,71**	**0,65**	**0,6**
F_n, %	68,48	54,33	45,9

Moreover, this decrease occurs both along the axial line of the groove and in the perpendicular direction. This indicates that, despite the groove amplitude remaining constant at 0.5 mm, the heterogeneity coefficient of the groove area distribution along the Y-axis, k_{gX}, decreased from 0.69 to 0.48. At the same time, the increase in the tool feed rate led to an increase in the axial groove pitch. As a result, its shape stretched in the axial direction, which also led to a decrease in the uniformity coefficient of the groove area distribution, k_{gY}, from 0.71 to 0.6. Accordingly, the relative area of the micro-relief, F_n, also decreased from 68.48% to 45.9%.

Conclusions

Based on the text of the provided article, the following conclusions can be formulated:

With an increase in the feed rate of the rotary tool (from 2 to 3.5 mm/s) at a constant rotational speed, the heterogeneity of the groove area distribution for the partially regular micro-relief formed by the rotary method increases.

As the longitudinal spindle feed rate increases, with a corresponding increase in the axial groove pitch, the coefficients of planar heterogeneity of the groove area distribution decrease both in the perpendicular direction, k_{gX}, from 0.69 to 0.48, and in the axial direction, k_{gY}, from 0.71 to 0.6. The increase in the tool feed rate affects the uniformity parameters of the groove area distribution; specifically, R_{Xmax} increases from 1.71 to 2.97, and R_{Xaver} grows from 1.18 to 1.41. Conversely, R_{Ymax} decreases from 3.76 to 2.86, and R_{Yaver} decreases from 2.66 to 1.72.

An increase in the feed rate from f_g = 2 to 3.5 mm/s leads to a reduction in the number of micro-relief groove intersections from 4 to 2. However, this simultaneously causes the groove shape to stretch in the axial direction, which results in a substantial decrease in the overall relative area of the micro-relief, F_n, from 68.48% to 45.9%.

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Зінченко І.Б., Савчук А.М., Федів В.Я., Крук О.Ю. Трансформація неоднорідності розподілу площі канавок частково регулярного мікрорельєфу ротаційного типу зі збільшенням осьового кроку

Розглянуто трансформації форми канавок ротаційного РМР із різним ступенем перекриття витків канавки, яке змодельовано збільшенням швидкості подачі ротаційного інструменту. Проведено пошук оптимальної форми канавок частково регулярних мікрорельєфів сформованих ротаційним способом, за умови забезпечення оптимального значення коефіцієнта площинної нерівномірності розподілу площі канавок. Побудовано графіки площинної нерівномірності розподілу площі канавок для форм канавок сформованих при подачі інструменту f_g = 2, 2,5 та 3,5 мм/с. Встановлено, що із зростанням величини повздовжньої подачі шпинделя коефіцієнт площинної нерівномірності розподілу площі канавок k_g зменшується як в осьовому так і в перпендикулярному до нього напрямку. При цьому параметри R_{Xmax} та R_{Xaver} зростають, а R_{Ymax} та R_{Yaver} зменшуються. Відносна площа мікрорельєфу при цьому також зменшується. Таким чином доведено, що при збільшенні швидкості подачі інструменту при незмінній частоті обертання нерівномірність розподілу площі канавок частково регулярного мікрорельєфу, сформованого ротаційним способом збільшується.

Ключові слова: регулярні мікрорельєфи; канавки; площинна неоднорідність; розподіл площин; коефіцієнт; кількісна оцінка; параметри