Influence of Turning Operations on Waviness Characteristics of Working Surfaces of Rolling Bearings

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Abstract. The formation of micro and macro geometric parameters of conjugate cylindrical surfaces of parts is technological movements of equipment that provide the specified quality characteristics of parts. The waviness of the part's surface is one of the critical geometric characteristics, which provides the functional features of the unit as a whole, as it affects the vibration processes that occur during operation. The ripple is formed under the influence of dynamic processes of processing of details which are characteristic of metalworking machines, depending on changes in system machine-tool (cutting)-part (MTP). Mechanical perturbations during cutting occur due to forced oscillations, self-oscillations, deformation of the rings due to the action of cutting forces. Self-oscillations occur due to the loss of properties of a given motion during cutting and forced oscillations due to external factors. The undulation of the surface is formed due to forced oscillations of the metal-cutting system due to periodic perturbations that occur due to disbalances of the MTP system's parts. The ratio of the oscillation frequency for relative motions of the tool and the part can change the law of oscillating motion and the shape of the surface. The decisive factor influencing the formation of geometric errors of the part is the ratio of the frequency of harmonic oscillations of the tool and the workpiece to the frequency of rotation of the machine tool's spindle.

Keywords: Formation · Harmonic · Heredity · Roller bearing · Spectral analysis · Workpiece · Process innovation · Industrial growth

1 Introduction

Machining of parts takes place using machining operations, which provide the initial and final (finishing) processing, to varying degrees affect the final formation of the geometric characteristics of the functional surface [1].

If the ratio χ/n is an integer (χ – the ratio of the frequency of harmonic oscillations of the tool and the workpiece; n – frequency of rotation of the spindle), the harmonic oscillation does not affect the shape of the longitudinal section of the part [2]. In order to prove the technological heredity of the waviness, it is necessary to establish the

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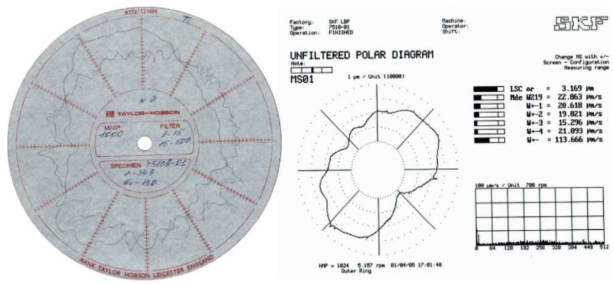
relationship between the processing modes and the microgeometry of the functional surfaces of the bearing rings. Moreover, heredity is manifested not only in the finishing operations. It also occurs during the operation of the bearing in the product because of external factors and operating conditions [3, 4].

The formation of the waviness of the functional surface begins in the provision operations, as the macrogeometric parameters of the surface are formed, and its appearance can be observed in the finishing operations (Fig. 1).



a) b)

Fig. 1. Hereditary nature of the origin of the waviness: a – round diagram of the ring's raceway after turning; b – polar diagram of the ring's raceway after grinding.

In the technological cycle, the influence of initial operations and transitions on the formation of geometric parameters of the treated surface is less than the finish, but ignoring it will be erroneous. There are irregularities with different pitches and amplitude deviations on actual rolling surfaces.

2 Literature Review

During the rotation of the inner ring of the bearing, the simultaneous interaction of deviations on the rolling surfaces of both rings and the rolling elements causes oscillations of the outer ring of the bearing, i.e., its vibrations [5–7]. A complex periodic function describes the displacement of the outer ring in the form of a Fourier series, which consists of simple harmonic oscillations with frequencies multiples of the fundamental [8]:

$$R(\phi) = \frac{a_0}{2} + \sum\nolimits_{k=1}^{\infty} A_k \sin(k\phi + \psi_{0k}) \tag{1}$$

a_0 – the constant value of the radius vector; k – is the harmonic number; A_k – is the amplitude of the k-th harmonic; ψ_{0k} – is the initial phase of the harmonic.

If the amplitude of the harmonics $a_0 = 0$, then the zero harmonics of the schedule is a constant component of the series:

$$R(\phi) = \frac{a_0}{2} = R_0 = \frac{d_0}{2} = const \tag{2}$$

For the first harmonic of the schedule ($k = 1$) the deviation of the contour L from the base circle corresponds to the dependence:

$$\delta_1(\phi) = A_1 \sin(\phi + \psi_{01}) \tag{3}$$

As the harmonics' amplitude decreases, the contour's shape approaches the base circle, and deviations are detected in the cut of the contour by the number of faces corresponding to the number of the harmonic (Fig. 2) [9, 10].

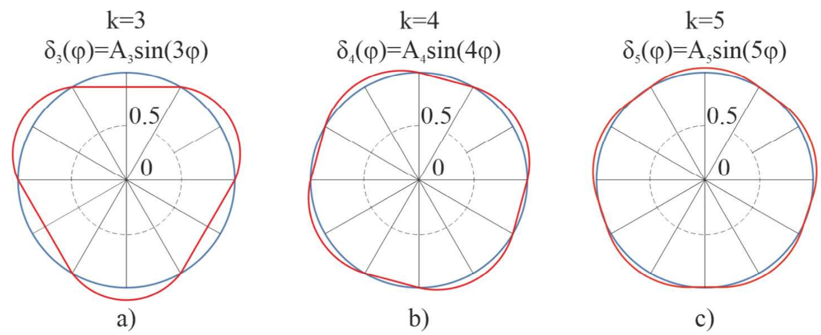


Fig. 2. Contour shapes corresponding to the third (a), fourth (b), and fifth (c) harmonics of a periodic function with period 2π Fourier series for zero initial phases and small amplitudes.

Vibroacoustic characteristics of the bearing deteriorate when the number of waves of the k-th harmonic on the track of the inner or outer rings with the number of bodies of rotation in the bearing, $f_k = qz$, where f_k is the number of waves of the main harmonic on the track [11].

Spectral analysis methods were used to diagnose the causes of technological defects of bearings [12]. The spectrum allows us to identify the predominant harmonics, which are present in the schedule of the series and depend on the number of rolling elements (Fig. 3) [13].

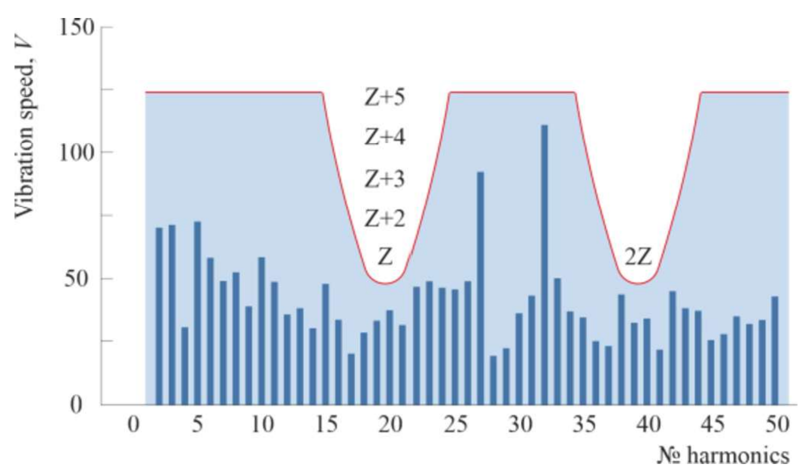


Fig. 3. Tolerances for the harmonics of the spectrum of the bearing ring with the number of rolling elements Z = 20.

This mechanism of modeling the vibroactivity of the surface allows solving applied problems of development and optimization of the technology of forming microgeometric parameters of the surfaces of rotating bodies [14].

3 Research Methodology

The modeling of topography parameters is based on the principle of multi-coordinate formation because of the relative movements of the system MTP [15]. The microrelief shape height depends on the disturbances in the MTP system and the movement of the cutting tool relative to the workpiece [16]. The microrelief step parameters depend on the ratio between the longitudinal and transverse feeds and the workpiece's rotation speed [17, 18]. Therefore the formation of vibroacoustic characteristics of the functional surfaces of friction pairs largely depends on the functional features of the technological equipment [19, 20].

The dynamic mathematical model of the turning process is shown in Fig. 4.

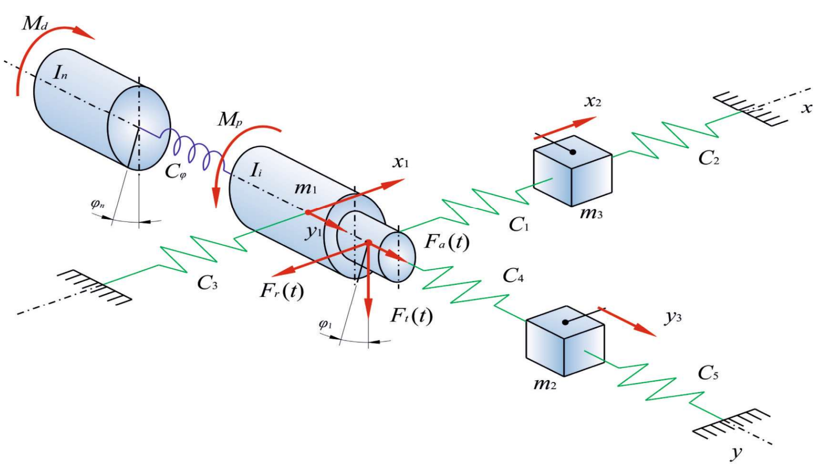


Fig. 4. The calculated scheme of the spindle.

The dynamic calculation scheme includes the masses of the spindle with the part, m_1, m_2, m_3 of transverse and longitudinal supports, the mass of the machine's drive, connected by elastic links C_1–C_5 (Table 1).

Table 1. Designations used for mathematical modeling [1].

Designation	Value
C_φ	Stiffness of the drive machine tool (angular)
M_d, M_p	Moments of cutting force
x_1, x_2	Coordinates of displacements of masses m_1 and m_2 along the x-axis
y_1, y_3	Coordinates of displacements of masses m_1 and m_3 along the y-axis
φ_1, φ_n	Coordinates of angular displacements of rotating masses machine tool
$F_t(t)$, $F_r(t)$, $F_a(t)$	Components of cutting forces

The oscillations of the support masses that take place along the perpendicular axes are connected through the workpiece, so it is necessary to consider the mutual damping of oscillations.

Formulas can describe the equation of oscillation of the masses of a dynamic spindle system in the corresponding directions of rotation:

– in the direction of movement of the transverse support along the x-axis:

$$\begin{aligned} & m_1\ddot{x}_1 + \alpha\,\dot{x}_1 + c_1(x_1 - x_2) + c_3x_1 = F_r(t)\ ; \\ & m_2\ddot{x}_2 - c_1(x_1 - x_2) + c_2x_1 = 0 \end{aligned} \tag{4}$$

– in the direction of movement of the longitudinal support along the axis in:

$$\begin{aligned} & m_1\ddot{y}_1 + \beta\,\dot{y}_1 + c_4(y_1 - y_3) = F_a(t)\ ; \\ & m_3\ddot{y}_3 - c_4(y_1 - y_3) + c_5y_5 = 0 \end{aligned} \tag{5}$$

– spindle oscillations:

$$\begin{aligned} & I_1\ddot{\phi}_1 + c_\phi(\phi_1 - \phi_n) = M_p(t); \\ & I_n\ddot{\phi}_n - c_\phi(\phi_1 - \phi_n) = 0 \end{aligned} \tag{6}$$

In (4) and (5), α and β are the damping coefficients of the transverse and longitudinal support, respectively, and $F_\alpha(t)$, $F_r(t)$, $F_t(t)$ are the forces acting on the respective links.

4 Results

In the course of research works, dependencies of waviness on processing parameters at various frequencies of rotation of a spindle were established (Table 2). Theoretical studies have been confirmed experimentally with 15–20% error.

Table 2. Dependence of spindle oscillation amplitudes on speed rotation.

Spindle speed, rpm	The amplitude of oscillations along the X-axis, μm		The amplitude of oscillations along the Y-axis, μm	
	Theory	Experiment	Theory	Experiment
1800	1,453	1,336	1,115	0,924
1200	2,863	2,376	1,862	1,645
800	5,121	5,349	3,241	3,702
560	1,125	1,093	0,907	0,756
280	3,985	4,366	2,912	3,023

Graphs of dependence of the amplitude of oscillations of the cutting tool during the processing of rings of bearings on the spindle speed are built (Fig. 5, Fig. 6).

These figures show the formation of the waviness of functional surfaces of parts such as “body of rotation” considering theoretical calculations (theory) and their approximation with experimental studies (experiment) to confirm the oscillations of the forming system of the machine, which significantly affects the formation of operational of the waviness roller bearings.

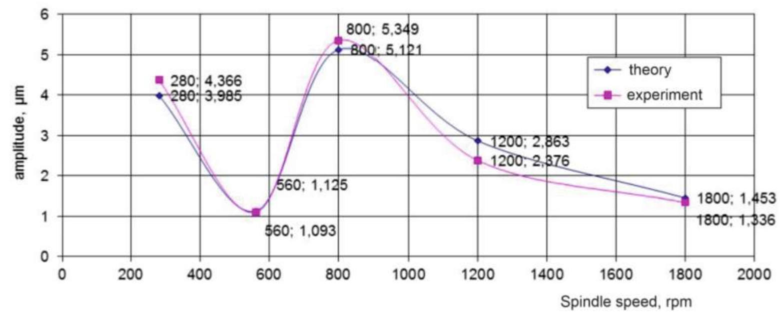


Fig. 5. Dependence of the amplitude of transverse oscillations on the machine’s spindle speed.

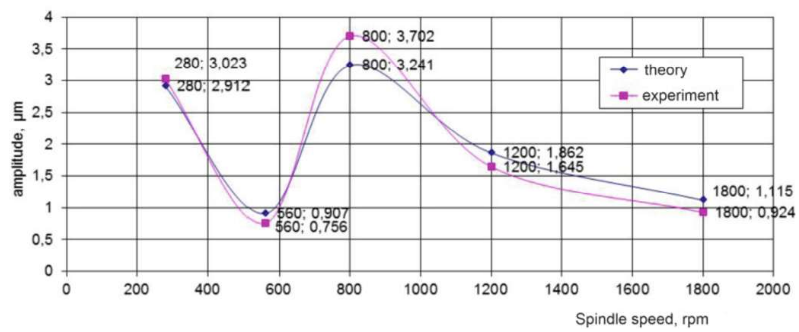


Fig. 6. Dependence of the amplitude of longitudinal oscillations on the machine’s spindle speed.

To interpret the influence of technological factors on the formation of microgeometry of functional surfaces, the complex Talyskan was used (Fig. 7).

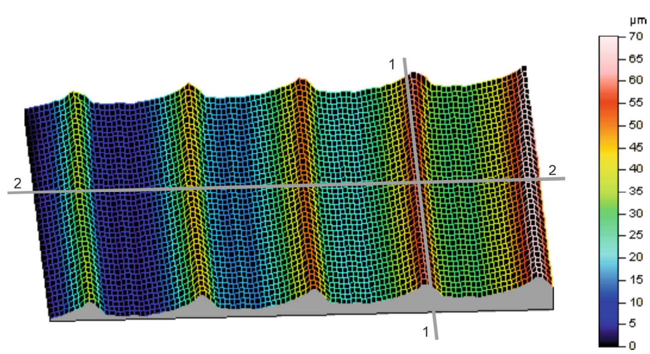


Fig. 7. The working surface of the roller-bearing ring after turning.

The waviness of the functional surface changes during its operation and takes the form obtained during processing in the initial operations, including turning.

Thus, the change in surface geometry at finishing operations leads to the formation of "technological" geometry, which is erroneous in its macrogeometric parameters. After running-in, the surface takes the form of "operational" geometry, which reflects the geometry of the initial machining operations. Forming the necessary geometric parameters of functional surfaces in the initial (rough) machining operations is an essential task to ensure the quality of operation of machine parts.

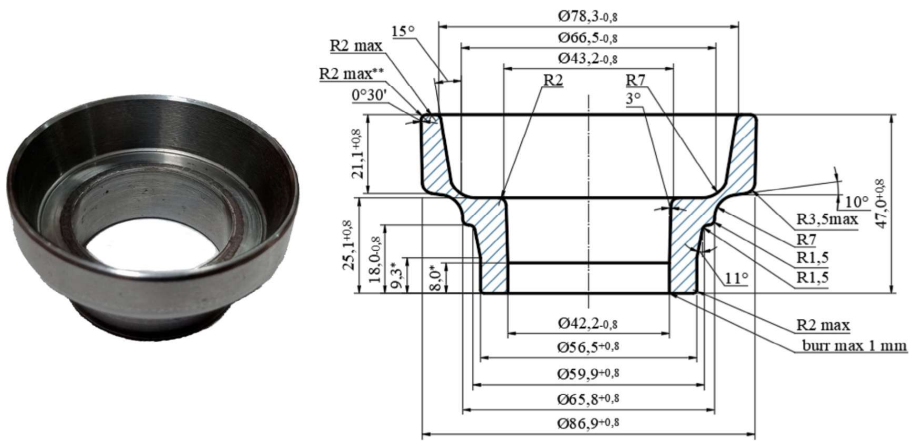


Fig. 8. The prototype and design of the blank set of rings on a roller bearing 7509.

The research results are realized in the form of engineering methods of designing tool adjustments of lathes with a subroutine of adjustment waviness at the stage of determining the forming modes. The design of a continuous billet of a set of 2 rings of a roller bearing (Fig. 8) is offered. The structure of the technological process of manufacturing rings is changed.

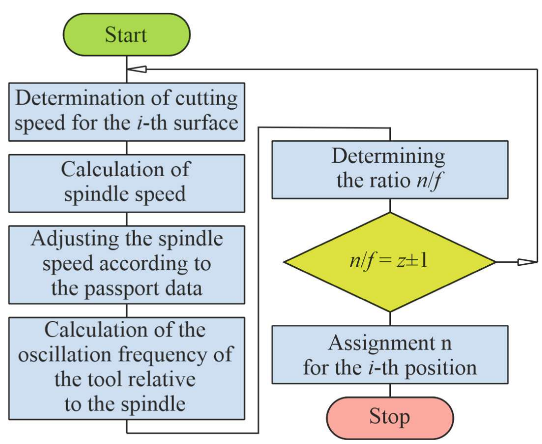


Fig. 9. Algorithm for correcting the waviness of the ring machining process on automatic turning operations: n/f – the ratio of the rotational frequencies of the workpiece n and the oscillation frequency of the tool f.

Due to the introduction of the proposed design of the workpiece, it was possible to avoid systematic defects in the turning of the outer rings associated with the deformation of the clamping elements of the spindle chucks [21–24]. Technological requirements: diameter inconsistency – up to 0.6 mm; width inconsistency – up to 0.6 mm; cracks are not allowed; *dimensions for references; burr is allowed in the axial direction - max 1 mm with a maximum thickness of 1 mm; hardness of forging HB 179…207. Surface defects: protrusions from wear and chipping of the tool - up to 0.5 mm.

The engineering technique of adjusting lathes in the conditions of multi-nomenclature bearing production allowed the machine to optimize the machine's productivity due to the change of structure of the technological process of manufacturing rings of roller bearings (Fig. 9).

This allowed us to offer optimal cutting modes for tools with different values of the predicted stability. An algorithm for automated design of structures and parameters of tool adjustments of lathes was developed, which allowed predicting the optimal parameters of waviness at the stage of technological design. To do this, a procedure for adjusting the waviness of the working surface of the bearing ring, which allowed to stabilize the performance of roller bearings.

5 Conclusions

To assess the impact of geometric parameters of the surfaces of rotation of bearing parts on its performance, a complex functional-parametric indicator – vibroactivity of the surface allowed during the technological design of molding operations to predict vibroacoustic characteristics of annular surfaces and bearing performance. The waviness and deviations of the shape of the working surfaces of the rings are hereditary. They begin with procurement (10…15%), transformation into mold (40…55%), heat treatment (10…15%), and operation, finally formed on the final operations of roughing and finishing (20…25%). The control of the waviness and accuracy of the working surfaces of the bearing rings must be carried out throughout the life cycle of the rings, starting from the workpiece, turning, shaping operations, and ending with the final grinding.

The leading causes of waviness and deviations of the shape of the functional surfaces of bearing rings are the imperfection of the workpieces and forming processes, the presence of residual deformations from the clamping elements of machines, dynamic oscillations of forming elements of machines, devices, and tools (self-oscillations). The step parameters of the critical harmonic ripple are related to the ratio between the workpiece's rotational frequencies and the oscillations of the forming instruments, and the amplitude parameters – with the amplitude of their oscillating motions. Thus, at the ratio 1/2 of the workpiece's rotational frequencies n and the tool's oscillation frequency k, the shape deviation is close to the oval one. At the ratio of 1/6, the shape deviation is close to the hexagonal one. The waviness of the 12th harmonic results from the frequency ratio of 1/12.

For preventing technological defects during the formation of the rings' working surfaces, it is necessary to avoid exceeding the specified tolerances on waviness for harmonics equal to or multiples of the number of bodies of rotation in the bearing. The harmonics of the waviness should dominant be considered by $h_1 = z \pm 2$ $h_2 = z \pm 3$; $h_3 = z \pm 4$; $h_4 = z \pm 5$ where z is the number of bodies of rotation in the bearing.

It is planned to offer a field of tolerances for the dynamic waviness of rings' working surfaces (wavy spectrogram) for the spectrum of harmonics from 0 to 500 depending on the ratios of bodies of bearing's rotation and the waviness (number of critical harmonics). This will make it possible to optimize the limit of economically feasible values of vibration velocities of critical harmonics and, hence, the ripple's amplitudes within the specified spectrum.

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