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TWO-STAGE OPTIMIZATION OF OSCILLATORY BURNISHING PARAMETERS

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A b s t r a c t

The paper presents an issue of optimal parameters selection of oscillatory burnishing operation in terms of coverage surface with microgrooves S_r and time of the operation t for the I-st type system of after-machining marks (not intersecting each other). It has been evaluated a range of rotational speeds of a workpiece n_p, number of oscillations of burnishing element n_{osc}, and values of feedrate f, for which the coverage surface with microgrooves amounts to $S_r = 34 \pm 0.5\%$. Next, it has been performed selection of such association of the above parameters for which oscillatory burnishing time t of a selected surface is the shortest. A system of microgrooves, which was verified in the test bench, has been modeled for optimal parameters of the oscillatory burnishing.

Keywords: burnishing operation, oscillatory burnishing, parametric optimization

Dwustopniowa optymalizacja parametrów nagniatania oscylacyjnego

S t r e s z c z e n i e

W pracy przedstawiono zagadnienie doboru optymalnych wartości parametrów nagniatania oscylacyjnego z uwzględnieniem kryterium powierzchni pokrycia mikrorowkami Sr oraz w czasie obróbki t dla I. rodzaju układu śladów poobróbkowych (nieprzecinających się). Określono zakres wartości prędkości obrotowej przedmiotu n_p, liczby oscylacji elementu nagniatającego n_{osc} oraz wartości posuwu f, dla których powierzchnia pokrycia mikrorowkami $S_r = 34 \pm 0.5\%$. Dokonano następnie wyboru skojarzenia wartości parametrów, dla których czas nagniatania oscylacyjnego t zadanej powierzchni jest najmniejszy. Dla ustalonych wartości parametrów nagniatania oscylacyjnego opracowano model układu mikrorowków i prowadzono jego weryfikację na stanowisku badawczym.

Słowa kluczowe: kulkowanie oscylacyjne, mikrorowki, modelowanie i symulacja

1. Introduction

The burnishing operation is most often used to assure low surface roughness and strengthening of the surface layer. It is less used to formation of lubricating microgrooves on mating surfaces in conditions of friction (journals, bearings, slideways) in order to increase resistance for seizure and abrasive wear [1-3]. Such type of burnishing operation is called an oscillatory burnishing.

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Constant depth of sinusoid after-machining marks in perpendicular plane to direction of motion of the tool is a characteristic feature of this method. By changing value of feedrate, amplitude and velocity of oscillations, and value of rotational speed of the workpiece, we can obtain a very diverse, depending on needs, character of the after-machining marks on a machined surface [2-4].

Abrasive wear of a surface during oscillatory burnishing operation depends on conditions of the burnishing, and in result on the relative surface of the microgrooves S_r on machined surface, and type of microgroove system. Optimal, in terms of abrasive wear, relative surface area of the microgrooves depends on, among others, type of friction pair and kinematics of its motion. This value, in case of different friction pairs, changes within limits of $S_r = 28 \div 43\%$. The lowest wear of cylinder liners occurs for the $S_r = 30 \div 37\%$ and for the I-st type system of microgrooves, i.e. system of the microgrooves not intersecting each other [2, 3].

Therefore, objective of the present study is the selection of optimal parameters of the oscillatory burnishing operation of a cylinder liner, i.e. rotational speed of the workpiece n_p, number of oscillations of the burnishing element n_{osc} and value of the feedrate f, for which the surface covered with microgrooves amounts to $S_r = 34 \pm 0.5\%$. And in the next step, selection of such association of the above parameters, for which burnishing time of the selected surface is the shortest.

2. Characteristics of the oscillatory burnishing

Oscillatory burnishing consist of plastic forming of continuous groove on a machined surface with use of hard ball, which oscillating in plane of longitudinal feed under predetermined pressure, displaces together with burnishing feedrate along machined surface [2-4]. Principle of operation and kinetics of the oscillatory burnishing is presented in the Fig. 1. Sinusoidal shape of the after-machining marks on the machined surface of the workpiece is a characteristic feature of the oscillatory burnishing operation.

System of after-machining marks on surface results from superposition of there basic movements:

- oscillating motion of the burnishing element (ball) in plane of the feed n_{osc}, 1/min,
- rotational motion of the workpiece n_p, rpm,
- feed of the burnishing element with respect to the workpiece f, mm/rotation.

Moreover, the pressure force F_n expressed in N, amplitude of the oscillations $2e$ expressed in mm, diameter of the burnishing element d_k

expressed in mm and diameter of the hole D expressed in mm [2, 6] are parameters of the oscillatory burnishing.

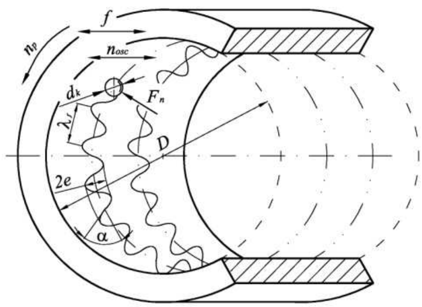

Fig. 1. Kinematics of the oscillatory burnishing of the holes through burnishing [5-7]

By changing values of individual motions, especially feeding motion of burnishing element and rotational motion of workpiece, it is possible to produce on machined surface a different systems of the microgrooves, and also totally new micro-geometry of surface irregularities in case of superposition of the after-machining marks. There are the following main types of the after-machining marks: I-st type – not intersecting each other; II-nd type – being in contact; III-rd type – intersecting each other; IV-th type – superimposed; V-th type – tetragonal; VI-th type – hexagonal [2-4].

Detailed model and burnishing mechanism of a given type of the microgrooves is presented in the publications [2-5].

Creation of various microgroove systems on machined surface should be considered with the following boundary conditions [5]:

- radius of the sphere of the burnishing element is much smaller than the radius of the workpiece,
- amplitude of oscillations of the burnishing element is equal to the double value of eccentric of the system which changes rotational motion of the shaft of electric motor to reciprocal motion,
- course of burnished grooves, creating regular pattern, features shape of sine curve.

Condition of obtainment of the I-type microgrooves, i.e. the microgrooves not intersecting each other, is such that during the oscillatory burnishing operation, value of the feedrate f which satisfies the dependency (1), and ratio of the number of burnishing element's oscillations n_{osc} to the number of the workpiece's rotations n_p is assured. Additionally, for the microgrooves not intersecting each other and simultaneously not shifted in phase, the requirement is such that the ratio n_{osc}/n_p should be an integer value, i.e. a fractional part of the number i should be equal to zero – $\{i\} = 0$.

In station to the oscillatory burnishing stepless adjustment of oscillations of the burnishing element and number of the workpiece rotations is used, what enables easy selection of the ratio n_{osc} / n_p required due to system of the microgrooves with predetermined parameters [5].

The station to oscillatory burnishing comprises high capacity, adjustable frequency of a converter to controlling operation of the a.c. motor, a crankshaft assembly, changing rotational motion to reciprocating motion, a slideway to guide a rigid blade ended with a head comprising a ball to oscillatory burnishing, and special fixture to attachment of the workpiece in 3-jaw lathe chunk. Required burnishing force is assured by tension of the spring through rotation of the screw with angle ψ.

The station to oscillatory burnishing operation is installed in the turning lathe of the TUG-40 type. The turning lathe is equipped with d.c. motor with thyristor control, enabling rotational speed of the workpiece in range of $n_p = 16 \div 1400$ rpm. During operation of the oscillatory burnishing it is important to have a possibility of setting a given rotational speed of the ball located in the head, and to assure its constant speed in time. High accuracy of the developed control system results from setting of resolution of the frequency converter amounting to: in digital values – $0{,}1\,\mathrm{Hz}\ (1 \sim 99{,}9\ \mathrm{Hz})$; $1\,\mathrm{Hz}\ (100 \sim 200\ \mathrm{Hz})$ or in analog values – $1\,\mathrm{Hz} / 60\,\mathrm{Hz}$.

The following conditions of the experimental research were taken due to parametric characteristics of the station to oscillatory burnishing operation: number of oscillations of the burnishing head $n_{osc} = 1350 \div 1850\ \ 1/\mathrm{min}$ and number of rotations of the cylindrical liner $n_p = 16 \div 100$ rpm. Oscillatory burnishing was performed on the bore $\phi 90H6$ after honing process in cylinder of the 1CA90 engine, made of cast iron having hardness of $HB = 240 - 285$.

3. Selection of optimal parameters of the oscillatory burnishing in terms of coverage surface and duration of the machining

In case of oscillatory burnishing of a cylinder liner, the most advantageous conditions of this operation are [2, 6]:

- microgroove system of the I-st type,
- lacking shift of the microgrooves in phase – $\{i\} = 0$,
- relative coverage surface with the microgrooves $S_r = 34 \pm 0.5\%$.

Condition of creation of the I-st system of the microgrooves (not intersecting each other) is [2-5]:

$$f > 2 \cdot \rho + 2 \cdot e \cdot \sin\left(\pi \cdot \{i\}\right) \tag{1}$$

where: f – feedrate of the burnishing element; ρ – half-width of the microgroove; e – eccentricity of the device generating the oscillations (half-amplitude of oscillations of the burnishing element); i – ratio of oscillations frequency of the burnishing element n_{osc} to number of rotations of the workpiece n_p (number of oscillations during a single rotation of the workpiece); $\{i\}$ – fractional part of the number i.

The number i shows how many times the wavelength of the microgroove λ_f is positioned on circumference of the workpiece. Fractional part from this ratio $\{i\}$ shows value of mutual displacement of the microgrooves on machined surface during each successive rotation. The wavelength λ_f of the microgrooves is described by the following dependency [3]:

$$\lambda_f = v_c \cdot T_{osc} \tag{2}$$

where: v_c – peripheral speed of the workpiece (cylinder liner); T_{osc} – period of oscillating motion of the burnishing element.

$$v_c = \pi \cdot D \cdot n_p; \quad T_{osc} = \frac{1}{n_{osc}} \tag{3}$$

where: D – diameter of the cylinder liner.

After substitution of the dependency expressed by the formula (3) to the equation (2), we receive:

$$\lambda_f = \pi \cdot D \cdot \frac{n_p}{n_{osc}} \tag{4}$$

Because

$$\frac{n_p}{n_{osc}} = \frac{1}{i} \tag{5}$$

Hence

$$\lambda_f = \pi \cdot \frac{D}{i} \tag{6}$$

To calculations of the surface area of the workpiece covered with the microgrooves, it is necessary to determine how much the surface is occupied by microgroove with wave length λ_f (machined in time of a single period of oscillations T_{osc}). The trajectory L_o of motion of the ball's imprint centre $C(x, y)$ – (Fig. 2) analyzed on development plane of the workpiece's surface in Cartesian co-ordinate system, is described by the parametric system of equations:

$$\left.\begin{aligned} x &= v_c \cdot t \\ y &= f_t \cdot t + e \cdot \sin\left(\frac{2\pi}{T_{osc}} \cdot t\right) \end{aligned}\right\} \tag{7}$$

where: t – time of burnishing of the microgrooves; $f_t \equiv v_f$ – velocity of motion of centre of the imprint along generating line of the bore (federate).

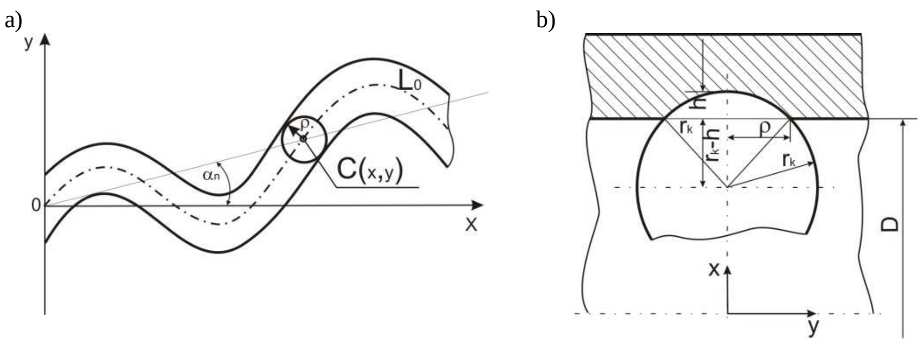

Fig. 2. Scheme of burnishing of the microgroove in development plane of cylindrical surface of the bore burnished oscillatory: a) microgroove in Cartesian co-ordinate system, b) cross-section through imprint of the ball produced on surface of the bore

The surface area S of the microgroove burnished during one period T_{osc} of oscillating motion is determined with use of the equation [2]:

$$S = \frac{2 \cdot \pi \cdot \rho}{3 \cdot i}\left(2 \cdot D + \sqrt{D^2 + 4 \cdot e^2 \cdot i^2}\right) \tag{8}$$

Half-width of the microgroove [2]:

$$\rho = \sqrt{d_k \cdot h} \tag{9}$$

where: d_k – diameter of the burnishing ball; h – depth of imprint of the ball (microgroove).

Relative surface of coverage with the microgrooves S_r expressed in percent, for the I-st type system of the microgrooves, is described by the following dependency [2]:

$$S_r = \frac{i \cdot S}{\pi \cdot D \cdot f} \cdot 100\% \tag{10}$$

The dependencies (8) and (10) are true for the microgrooves of the I-st type system only, i.e. not intersecting each other. In case of the marks being in contact or intersecting each other, from calculated surface area S we need to subtract surface area of contacts, or intersections (respectively S_1 and S_2).

In case of a surface with system of the microgrooves not intersecting each other, the inclination angle of the grid belongs to significant parameters (Fig. 1). This angle depends on oscillatory burnishing parameters and can be determined from the following approximate dependency:

$$\mathrm{tg}\alpha = \frac{2e \cdot n_{osc}}{D \cdot n_p} \tag{11}$$

or, after substitution of the dependency (5):

$$\mathrm{tg}\alpha = \frac{2e \cdot i}{D} \tag{12}$$

Relative coverage surface, as a parameter describing microgrooves system, in the best way characterizes operational parameters of the surface, including oil capacity of the surface, and also capability of deposition of foreign particles on the surface [2-4].

The following variables were taken in course of the performed investigations:

$$x_1 = n_{osc} - 1350 \div 1850\, 1/\min,$$

$$x_2 = n_p - 16 \div 100 \text{ obr/min},$$

$$x_3 = f - 1.32; 1.92; 2.25; 2.5; 3.5; 4.0; 4.5 \text{ mm/rotation}$$

As a constants there were accepted: pressure force of the ball $F_n = 332\ N$, assuring that for the ball diameter $d_k = 3$ mm, width of the microgroove burnished in the cast iron amounts to $2\rho \cong 0.49$ mm, $e = 1.8$ mm – half amplitude of oscillations equal to the value of crank throw and the diameter of the cylinder bore D = 90 mm.

To determine a possible relation of the rotational speed n_p of the 1CA90 engine's cylinder and frequency of oscillations of the ball burnishing the microgroove n_{osc}, in order to obtain a degree of coverage surface on machined bore consistent with, or close to intended degree, the following dependency $n_p = g(n_{osc})$ was elaborated.

Substituting the dependency (8) to the equation (10) which describes relative surface of coverage S, the following equation was obtained:

$$S_r = \frac{2 \cdot \rho}{3 \cdot D \cdot f}(2 \cdot D + \sqrt{D^2 + 4 \cdot e^2 \cdot i^2}) \cdot 100\% \tag{13}$$

From the equation (13) value of the i was determined

$$i = \sqrt{\frac{\left(\frac{S_r \cdot f \cdot 3 \cdot D}{200 \cdot \rho} - 2 \cdot D\right)^2 - D^2}{4 \cdot e^2}} \tag{14}$$

Substituting for $i = \frac{n_{osc}}{n_p}$, the following equation was obtained:

$$n_p = \frac{n_{osc} \cdot 2 \cdot e}{\sqrt{\left(\frac{S_r \cdot f \cdot 3 \cdot D}{200 \cdot \rho} - 2 \cdot D\right)^2 - D^2}} \tag{15}$$

where:

$$\rho = \sqrt{d_k \cdot h}; \quad d_k = 3 \text{ mm} \quad \text{and} \quad h = 0.02 \text{ mm}$$

It has been verified condition (1) of formation of the I-st type system of the microgrooves (not intersecting each other).

In the next stage a computer program has been developed, which on the base of a suitable algorithm, generates results of the calculations. Objective of the algorithm is search after a possible relationships between the feedrate f of the ball burnishing the microgroove, rotational speed of the cylinder n_p, and oscillations frequency of the ball n_{osc}, in order to obtain surface coverage ratio of the machined bore consistent with, or close to the intended one (in case of the cylinder bore of the above mentioned engine $S_r = 34 \pm 0.5\%$).

For a preset values, selected from possible to be obtained on the turning lathe of the TUG-40 type, feedrate values f of the burnishing ball are: 1.32, 1.92, 2.25, 2.5, 3.5, 4.0 and 4.5 mm/rot., and number of oscillations $n_{osc} = 1350 \div 1850$ 1/min as well as number of rotations of the workpiece $n_p = 16 \div 100$ rpm, it have been determined optimal values of n_p, n_{osc} and f with respect to coverage surface with the microgrooves $S_r \cong 34 \pm 0.5\%$.

For width purpose, using scanning method, it has been created a table of the values n_p and n_{osc} giving integer quotient $\frac{n_{osc}}{n_p}$ and it has been created a table of values S_r enabling selection of pairs n_{osc} and n_p, for which the value S_r satisfies predetermined condition (Table 1).

Table 1. Values of relative surface of coverage with the microgrooves S_r – boundary conditions: S_r = 33.64÷34.52%, D = 90 mm, e = 1.8 mm, d_k = 3 mm, h = 0.02 mm, ρ = 0.2449 mm, f = = 1.92 mm/rotation

	n_p, obr/min													
	31	32	33	34	35	36	37	38	39	40	41	42	43	44
S_r, %	34,23	33,93	33,35	33,06	32,77	32,49	32,20	31,92	31,64	31,37	31,10	31,10	30,83	30,56
	34,52	34,23	33,64	33,35	33,06	32,77	32,49	32,20	31,92	31,64	31,37	31,37	31,10	30,83
	34,82	34,52	33,93	33,64	33,35	33,06	32,77	32,49	32,20	31,92	31,64	31,64	31,37	31,10
	35,12	34,82	34,23	33,93	33,64	33,35	33,06	32,77	32,49	32,20	31,92	31,92	31,64	31,37
	35,42	35,12	34,52	34,23	33,93	33,64	33,35	33,06	32,77	32,49	32,20	32,20	31,92	31,64
	35,72	35,42	34,82	34,52	34,23	33,93	33,64	33,35	33,06	32,77	32,49	32,49	32,20	31,92
	36,03	35,72	35,12	34,82	34,52	34,23	33,93	33,64	33,35	33,06	32,77	32,77	32,49	32,20
	36,33	36,03	35,42	35,12	34,82	34,52	34,23	33,93	33,64	33,35	33,06	33,06	32,77	32,49
	36,64	36,33	35,72	35,42	35,12	34,82	34,52	34,23	33,93	33,64	33,35	33,35	33,06	32,77
	36,95	36,64	36,03	35,72	35,42	35,12	34,82	34,52	34,23	33,93	33,64	33,64	33,35	33,06
	37,25	36,95	36,33	36,03	35,72	35,42	35,12	34,82	34,52	34,23	33,93	33,93	33,64	33,35
	37,56	37,25	36,64	36,33	36,03	35,72	35,42	35,12	34,82	34,52	34,23	34,23	33,93	33,64
	37,87	37,56	36,95	36,64	36,33	36,03	35,72	35,42	35,12	34,82	34,52			
	38,19	37,87	37,25	36,95	36,64	36,33	36,03							
	38,50	38,19	37,56	37,25										
	38,81		37,87											

For calculated values $S_r = 33.64 \div 34.52\%$, it has been created the table with pairs of rotations' value of the workpiece n_p and number of oscillations of the burnishing element n_{osc}. Using highlighting, there were marked such pairs which satisfy the boundary conditions and enable formation of the I-st type system of the microgrooves with assumed value of relative surface coverage with the microgrooves (Table 2).

Table 2. Associations (pairs) of values of number of rotations of the workpiece np and number of oscillations of the burnishing element n_{osc} for relative surface of coverage S_r = 33.64÷34.52%

	n_p, obr/min													
	31	32	33	34	35	36	37	38	39	40	41	42	43	44
n_{osc}, 1/min	1364	1376	1353	1360	1365	1368	1369	1368	1365	1360	1353	1386	1376	1364
	1395	1408	1386	1394	1400	1404	1406	1406	1404	1400	1394	1428	1419	1408
	1426	1440	1419	1428	1435	1440	1443	1444	1443	1440	1435	1470	1462	1452
	1457	1472	1452	1462	1470	1476	1480	1482	1482	1480	1476	1512	1505	1496
	1488	1504	1485	1496	1505	1512	1517	1520	1521	1520	1517	1554	1548	1540
	1519	1536	1518	1530	1540	1548	1554	1558	1560	1560	1558	1596	1591	1584
	1550	1568	1551	1564	1575	1584	1591	1596	1599	1600	1599	1638	1634	1628
	1581	1600	1584	1598	1610	1620	1628	1634	1638	1640	1640	1680	1677	1672
	1612	1632	1617	1632	1645	1656	1665	1672	1677	1680	1681	1722	1720	1716
	1643	1664	1650	1666	1680	1692	1702	1710	1716	1720	1722	1764	1763	1760
	1674	1696	1683	1700	1715	1728	1739	1748	1755	1760	1763	1806	1806	1804
	1705	1728	1716	1734	1750	1764	1776	1786	1794	1800	1804	1848	1849	1848
	1736	1760	1749	1768	1785	1800	1813	1824	1833	1840	1845			
	1767	1792	1782	1802	1820	1836	1850							
	1798	1824	1815	1836										
	1829		1848											

Moreover, there is a possibility to change the boundary conditions for S_r and a possibility to change burnishing feedrate f. Next, in the developed program, for the new boundary conditions it is possible to generate a new table with values of the n_p and n_{osc}.

In the next step, for already evaluated pairs of values of the n_p and n_{osc}, which are optimal in terms of value of relative coverage surface with the microgrooves $S_r = 33.64 \div 34.52\%$ (Table 2), for the values of feedrate f = 1.92 mm/rotation, it has been selected such pair of the values n_p and n_{osc} for which time t of embossing the microgrooves is the shortest. In order to do it, it has been analyzed motion of the center of the ball's imprint $C(x, y)$ in a selected position of the trajectory (Fig. 2). Each point of the center of the ball's imprint is created in result of superposition of three velocities: constant peripheral speed v_c of the workpiece, constant feedrate of the ball embossing the microgrooves $v_f = f \cdot n_p$ and changing speed of oscillating motion of the ball v_{osc}.

Scheme of crankshaft assembly used in the device to oscillatory burnishing is presented in Fig. 3 [6, 8].

To characteristic values belong: $l = AB$ – length of the conrod, $r = e = BO$ – crank throw equal to eccentricity of the device generating oscillations, and equal to half-stroke of the ball $s/2 = r = e$, ratio of these two values $\lambda = r/l = e/l$, in this case $\lambda = 1.8/66 = 0.027$.

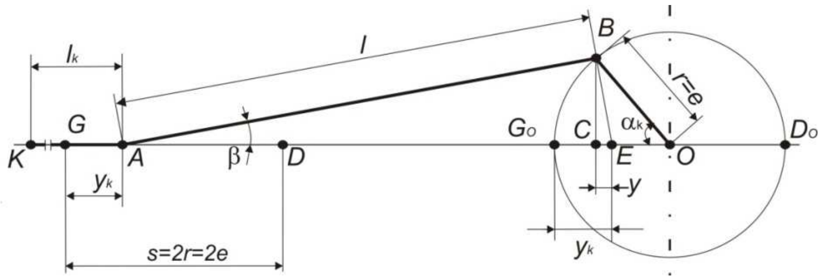

Fig. 3. Scheme of crankshaft assembly used in device to oscillatory burnishing

The ball embossing the microgroove is located in the burnishing head positioned at the end of rigid slideway having length of l_k. To determine displacement value of the ball in function of the clearance angle α_k of the crankshaft, it was assumed that the ball is located in the point A, what doesn't have any effect on the result of calculations.

$$y_k = OG - OA = OG - (OC + CA) = l + e - (l \cdot \cos\beta + e \cdot \cos\alpha_k) \qquad (16)$$

Making use of $\Delta\ AOB$ the following dependencies were determined:

$$\frac{BC}{l} = \sin\beta \quad \text{and} \quad \frac{BC}{e} = \sin\alpha_k \qquad (17)$$

$$BC = l \cdot \sin\beta \quad \text{and} \quad BC = e \cdot \sin\alpha_k \qquad (18)$$

hence

$$l \cdot \sin\beta = e \cdot \sin\alpha_k \qquad (19)$$

$$\frac{\sin\beta}{\sin\alpha_k} = \frac{e}{l} = \lambda \qquad (20)$$

and the same

$$\sin\beta = \lambda \cdot \sin\alpha_k \qquad (21)$$

Making use of known equation:

$$\cos\beta = \sqrt{1-\sin^2\beta} = \sqrt{1-\lambda^2\cdot\sin^2\alpha_k} \tag{22}$$

and developing its RH side into the power series, we obtain:

$$\cos\beta \approx 1-\frac{\lambda^2\cdot\sin^2\alpha_k}{2}-\frac{\lambda^4\cdot\sin^4\alpha_k}{8}-\dots \tag{23}$$

For the value $\lambda = 0.027$ it can be assumed with the satisfactory accuracy, that:

$$\cos\beta \approx 1-\frac{\lambda^2\cdot\sin^2\alpha_k}{2} \tag{24}$$

Substituting this dependency to the formula for y_k (equation (16)) it has been obtained:

$$\left.\begin{aligned} y_k &\approx l+e-l+\frac{l\cdot\lambda^2\cdot\sin^2\alpha_k}{2}-e\cdot\cos\alpha_k \approx \\ &\approx e-e\cdot\cos\alpha_k+\frac{l\cdot\lambda^2\cdot\sin^2\alpha_k}{2} \approx \\ &\approx e\cdot(1-\cos\alpha_k)+\frac{l\cdot\lambda^2\cdot\sin^2\alpha_k}{2} \approx \\ &\approx e\cdot\left[(1-\cos\alpha_k)+\frac{\lambda\cdot\sin^2\alpha_k}{2}\right] \end{aligned}\right\} \tag{25}$$

If length of the conrod amounts to $l = \infty$, then displacement of the ball would be equal to $G_O C$, while in case of the finite length of the conrod, the path of the ball y_k at rotation of the crank throw with angle α_k will increase with the segment $CE = y$. From the expression for the y_k (equation (25)) is is seen than in a real cranking system, motion of the ball is not strictly harmonic, as evidenced by the expression $\left(\lambda/2\right)\cdot\sin^2\alpha_k$.

Making differentiation of the expression for the displacement y_k with respect to time, it has been received expression describing velocity of the ball in function of the clearance angle α_k of the crankshaft [8]:

$$v_{osc} \approx \frac{\mathrm{d}y_k}{\mathrm{d}t} \approx \frac{\mathrm{d}y_k}{\mathrm{d}\alpha_k} \cdot \frac{\mathrm{d}\alpha_k}{\mathrm{d}t} = e \cdot \left(\sin\alpha_k + \frac{\lambda}{2} \cdot \sin 2\alpha_k \right) \cdot \frac{\mathrm{d}\alpha_k}{\mathrm{d}t} \tag{26}$$

where: l – length of the conrod, $\frac{\mathrm{d}\alpha_k}{\mathrm{d}t}$ – the first derivative of the rotation angle of crank's arm with respect to time (angular velocity).

$$\frac{\mathrm{d}\alpha_k}{\mathrm{d}t} = \omega = \frac{\pi \cdot n_{osc}}{30} \tag{27}$$

After substitution the following was obtained:

$$v_{osc} \cong e \cdot \omega \cdot (\sin\alpha_k + \frac{e}{2l} \cdot \sin 2\alpha_k) \tag{28}$$

Velocity of the ball coming from oscillating motion is the sum of two expressions: $e \cdot \omega \cdot \sin\alpha_k$ – velocity of the ball of the first order (sinusoid with argument α_k) and $\frac{e^2 \cdot \omega}{2l} \cdot \sin 2\alpha_k$ – velocity of the ball of the second order (sinusoid with argument $2\alpha_k$). From the analysis of the equations (3), (27) and (28) it is seen, that the shortest burnishing time t of the microgrooves occurs for the highest average velocity of oscillations $v_{śr}$ ($v_{śr} = 2e \cdot n_{osc}/30$ for n_{osc} w 1/min). In case of the t_{min} it occurs for maximal number of oscillations n_{osc}=1849 1/min (Table 2), ensuring obtainment of the relative coverage surface of $S_r = 33.93\%$ (Table 1). Hence, for the following constant values n_{osc} = 1849 l/min, e = 1.8 mm and l = 66 mm it has been determined the diagram of velocity of the ball in the oscillating motion (Fig. 4). Whereas in the Fig. 5 are shown component velocities (from rotational motion of the cylinder liner v_c, from feeding motion of the ball v_f, and from changing oscillating motion v_{osc}), and resultant velocity v_w of contact point (position) of the ball with burnished microgroove.

Inclination angle of the grid α of the burnished microgrooves depends in particular on the ratio of the oscillations velocity v_{osc} to the peripheral speed of the cylinder liner v_c, whereas the inclination angle of the microgroove system α_n depends on the feedrate v_f.

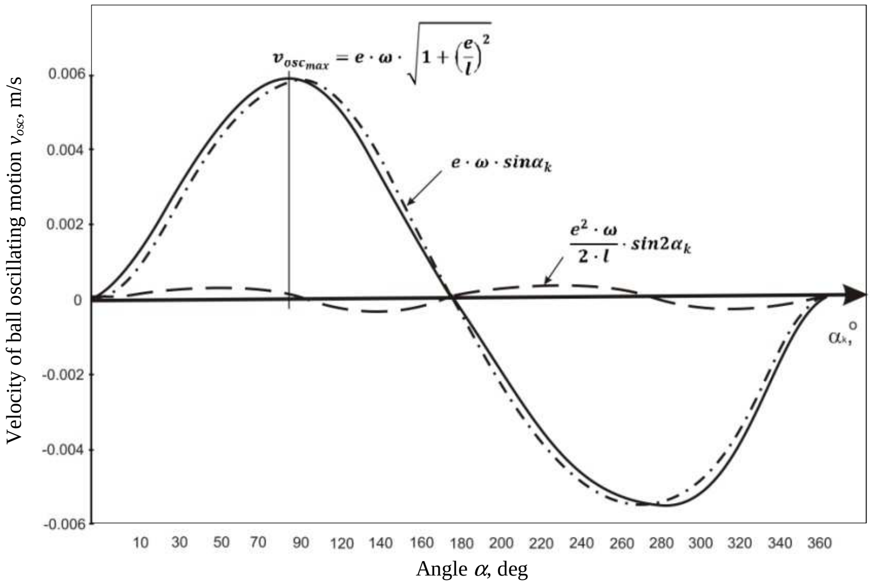

Fig. 4. Diagram of velocity of the ball in oscillating motion v_{osc} in function of rotation angle for the e = 1.8 mm, l = 66.0 mm, n_{osc} = 1849 1/min

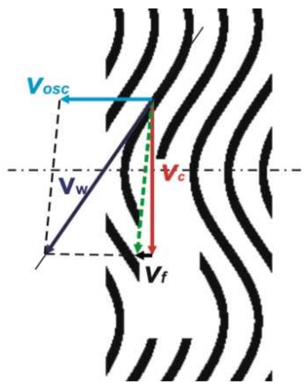

Fig. 5. Component velocities of the contact point (position) of the ball with burnished microgroove for constant values of: n_{osc} = 1849 1/min, n_p = 43 rpm, f = 1.92 mm/rot., e = 1.8 mm, l = 66 mm, D = 90 mm, a_k = 45°

For optimal oscillatory burnishing parameters with respect to coverage surface with the microgrooves $S_r = 33.93\%$ and the shortest burnishing time t_{min} of the microgrooves, i.e. n_p = 43 rpm, n_{osc} = 1849 1/min and f = 1.92 mm/rotation there were modeled microgrooves not intersecting each other. For this purpose it has been used the computer program in C# language developed earlier [5, 9]. Modeled diagram of the microgrooves of the I-st type (not intersecting each other) for optimal values of the oscillatory burnishing parameters is presented in the Fig. 6a, while the real system of the microgrooves obtained with use of a special device installed on the TUG-40 turning lathe is presented in Fig. 6b.

a) b)

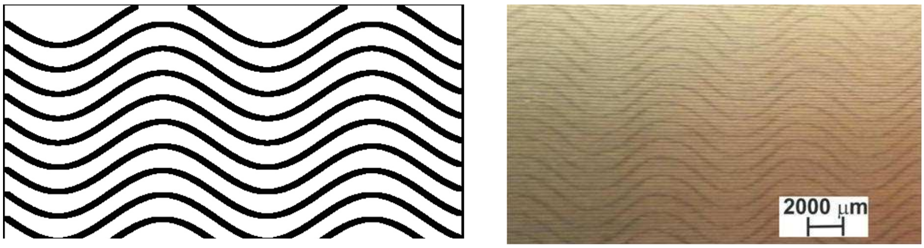

Fig. 6. Diagrams of the I-st type system of microgrooves (not intersecting each other) for optimal values of oscillatory burnishing parameters n_p = 43 rpm and n_{osc} = 1849 1/min and f = = 1.92 mm/rotation: a) computer modeled (inflicted input parameters: e = 1.8 mm, D = 90 mm, $\{i\}$ = 0, S_r = 34±0.5%, h = 0.020 mm; output parameters: F_n = 332 N, S_r = 33.93%, λ = 6.58 mm, α = 59.83°, i = 43, ρ = 1.51 mm), b) real system of the microgrooves

Summary

Performed optimization of oscillatory burnishing operation in terms of coverage surface with the microgrooves S_r, and burnishing time of the microgrooves t allows to draw the following conclusions:

- selection of optimal oscillatory burnishing parameters when values of many parameters are preset, inclusive of parameters of the microgrooves, is possible to be performed owing to computer program to simulation of the machining. A large number of variables and volume of calculations when selecting proper correlation of rotational speed of the workpiece n_p, number of oscillations n_{osc} and the feedrate f, in order to obtain predetermined system of the microgrooves, shift in phase i, relative surface of coverage S_r, it is required to implement computer with installed suitable simulation application,
- the highest capacity of oscillatory burnishing operation (burnishing of the microgrooves) occurs for the highest average velocity of the oscillations,
- devices to oscillatory burnishing should ensure obtainment of constant, planned value of the number i, through appropriate association of oscillating motion of the burnishing element with rotational motion of the workpiece.

Verification of modeled microgroove systems performed on the test bench has confirmed a possibility of their obtainment when constancy in time of calculated oscillatory burnishing parameters is ensured in real conditions.

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