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RESEARCH NOTE

Analysis of Inner Surface Roughness Parameters of Load-carrying and Support Elements of Mechanical Systems

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A B S T R A C T

This paper is based on the concept of physical mesomechanics, which allows any plastic shear in the stressed body to be considered as a loss of shear stability of the material in local stress concentration zones. This approach, which is physically very well-grounded, allowed us to consider from one standpoint the processes of machining by cutting and wear of steels. Physical and mechanical regularities in the effect of certain processing operations on the shape and roughness of the hydraulic cylinder surface are found. The mechanisms of the spatial self-organization of the relief and surface of bearings under conditions of false brinelling are summarized and analyzed. The data obtained can be used for further scientific generalization or prediction and diagnostics of the surface condition of load-carrying and support elements of mechanical systems under study.

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1. INTRODUCTION

There are a number of physical prerequisites for the occurrence of the ordered relief, including the principle of the self-organized formation [1, 2]. One of the best known is the effect of "chess-board" – an orderly distribution of stresses and strains in surface layers and at interfaces within solid bodies and between external (mechanical, thermal, electrical) fields. This physical phenomenon is due to incompatibility of strains of two connected environments, and it occurs in any multilevel system: on the interface "surface layer – material volume", "coating – base" within multilayered thin-filmed materials, and on grain boundaries in polycrystals [1].

At present, an increased interest is shown in the optimization of the surface properties of parts, both at the manufacturing stage and during operation. It is especially important, in our opinion, to control the processes occurring in the contact zone of friction pairs to improve wear resistance, and also to optimize the surface roughness of parts with a view to improving the durability of machines and mechanisms.

The formation of the surface during machining is a complex process of self-organization, which is analyzed using the methods of the stochastic processes theory [3]. Most informative is the method of assessing the quality of microprofile by the discrete ordinate values obtained by laser scanning measuring [4]. These methods make it possible to find common quality assessments of the microprofile (Ra, Rz, etc.). Similar approaches have been used by the authors to evaluate surface topography parameters after different modes of laser shock wave treatment. It also allowed performing their mathematical description as a cyclic random process.

There are three-dimensional stochastic models of distribution of stresses and strains at the interface "surface layer – base", which theoretically justify a special role of the surface layer in the loaded solids, and the development of nonlinear wave processes at the meso- and macrolevels [1]. Such methods can predict a "chess" distribution of normal and shear stresses in the surface layers and on the internal boundaries of the material. The practical value of this phenomenon

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consists in the possibility of adjusting the properties of such surfaces with a high degree of orderliness of their relief [5]. In previous works, the basic modes of the surface formation process of the power cylinder truck crane were found [6]. The approaches that explain the nature of degradation and wear of bearings of the oscillating mechanism of the varietal CBCM were proposed and physically grounded [4].

The aim of this work is to study the relief and the methods of its technological and operational formation.

2. OBJECTS AND METHODS OF RESEARCH

Hydraulic cylinder liner. The main elements of the power truck crane with a telescopic boom are hydraulic cylinders (Table 1). The object of experimental studies was hydraulic cylinder KS-4574.63.900 of a truck crane with a telescopic boom KTA-25 produced in Drogobych truck crane plant (Ukraine).

Optimization of the production technology will provide:

- giving recommendations on monitoring basic parameters of shape and roughness of working surfaces;
- reducing the cost of manufacturing hydraulic cylinder liners with desired characteristics, by excluding process operations that do not have a significant impact on quality indicators of the inner cylindrical surface or worsen them;
- reducing the impact of technological inheritance, i.e. reducing the cross section of the inner cylindrical surface of the hydraulic cylinders, obtained in previous process operations;
- using advanced processing methods of hydraulic cylinders to obtain the best physical and mechanical properties of the surface, which would provide an increased service life.

For the statistical evaluation of the impact of process operations on quality indicators of machining the internal cylindrical surfaces, including surface roughness parameters R_a and surface accuracy indicators, which are evaluated by the average value of deviation from roundness, we created 3 samples consisting of 5 test specimens each. The first sample included specimens after the first process operation - rough boring. The second sample was formed after the second process operation – semi-finish boring. The third sample consisted of specimens after the third process operation – rolling inner cylindrical surfaces by the method of plastic deformation of the surface using a special head.

Bearing. A spherical roller bearing 22316 (domestic analogue 53616, GOST 24696-81) with the size of 80 × 170 × 58 mm was investigated. Bearing material was chrome steel (domestic analogue ShH-15). Chemical composition: C = 0.95…1.05; Si = 0.17…0.37; Mn = 0.2…0.4; Ni < 0.3; Cr = 1.3…1.65; Cu < 0.25; S < 0.02; P < 0.027.

The bearing was part of the lever mechanism for rocking the mold caster of the varietal continuous casting machine (CCM) installed in the converter shop of PJSC "Yenakiyevo Steel Plant", and was withdrawn from service after three months of work. Bearing damage led to changes in the technical condition of the swing mechanism, parameters of vibrational motion of the mold (displacement, velocity, acceleration and direction of movement), which leads to lower stability and security processes of steel casting on the CCM, lower quality of the billets and reliability of the CCM equipment. Deviations of the vibrational motion parameters of the mold from the set values can be prevented by early detection, identification and troubleshooting of nodes and elements of the swing mechanism by studying the causes and mechanisms of damage. Profile records of the bearing wear grooves were analyzed using interference profilometer Micron Alpha.

3. RESULTS AND DISCUSSION

It is known that machining is a combination of many physical processes occurring under conditions of elastic displacement of the system "machine-tool-billet". Therefore, the occurrence of surface irregularities obtained during machining can be seen as a consequence of adaptation to the technological impact on the billet material [7].

Let us consider circular plots of internal cylindrical surfaces of each of the specimen presented in Figure 1, and average values of surface roughness, which are presented in Table 2.

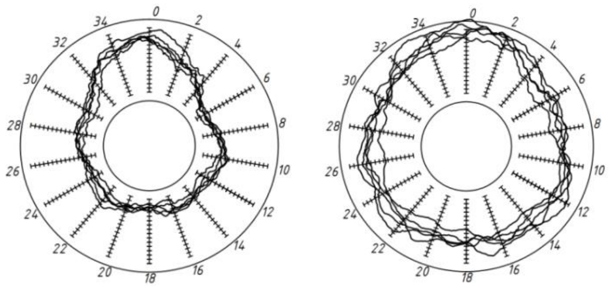
Having found deviations from roundness Δ_i in each of the 36 plots (Figure 2), presented as a difference in distance from the point of the real profile to the circle written in the circular plot, and having approximated the obtained findings by the trigonometric Fourier series (1), we obtained scattering characteristics of roundness deviation for each circular plot; $\overline{\Delta}_{ij}$ – the average value, which is approximately equal to the mathematical expectation given in Table 3, and the range of amplitudes for individual specimens, on which process operations were performed, presented in Table 4.

TABLE 1. Specification of hydraulic cylinder KS-4574.63.900

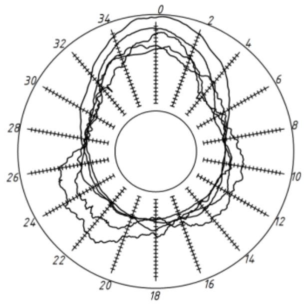
Hydraulic cylinder	Piston diameter (mm)	Rod diameter (mm)	Piston stroke (mm)	Max. pressure in the hydraulic system (MPa)	Weight (kg)
KC-3971.63. 900-02	100	80	6000	25	410

a b

Figure 1. (a) Hydraulic cylinder of the truck crane and (b) bearing of the hinge-lever mould oscillator of the continuous casting machine



a b



c

Figure 2. Circular plots of deviation of cross sections of the inner cylindrical surface after the following process operations: a) – rough boring; b) – semi-finish boring; c) – finish boring using a special head

Having performed calculations, we obtained sample values of mathematical expectation - $M(\Delta)$, deviation from roundness and maximum values of dispersion fields - Δ_{max}, which are presented in Table 5.

TABLE 2. Dimensions and surface roughness during process operations of manufacturing cylinder liners KS-4574.63.900

№ *j*-th operation	Process operation	The resulting diameter (mm)	Average roughness parameters, R_a (μm)
1.	Rough boring	Ø99.5H11	5.0
2.	Semi-finish boring	Ø99.96+0.07	1.25
3.	Finish boring using a special head	Ø100H9	0.32

TABLE 3. Scattering characteristics of deviations from roundness of internal cylindrical surfaces of cross sections of hydraulic cylinders

№ *j*-th operation	Process operation	Average value $\overline{\Delta}_{ij}$, μm				
		Serial number of circular plots				
		№1	№2	№3	№4	№5
1.	Rough boring	11.98	13.68	10.51	12.13	10.38
2.	Semi-finish boring	10.97	13.34	18.17	18.03	17.54
3.	Finish boring using a special head	11.21	7.34	10.82	10.64	9.43

TABLE 4. Amplitudes of harmonics approximated by trigonometric Fourier series, deviations from roundness of internal cylindrical surfaces obtained after the implementation of each process operation

№ *j*-th operation	Values of amplitudes									
	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}
1.	12.36	8.53	6.44	2.96	0.52	2.34	0.58	0.43	0.81	0.65
2.	9.09	8.53	7.14	3.17	1.61	1.23	1.99	1.2	1.32	0.43
3.	3.02	3.81	6.58	0.95	1.48	0.21	2.04	0.98	1.89	0.57

TABLE 5. Sample dispersion characteristics of deviation from roundness of the cross-section of the inner surface of hydraulic cylinders after process operations

№ *j*-th operation	Process operation	Dispersion characteristics	
		$M(\Delta)$, μm	Δ_{max}, μm
1.	Rough boring	14.1	27.0
2.	Semi-finish boring	18.4	39.7
3.	Finish boring using a special head	8.2	17.2

The effect of process operations on $M(\Delta)$ is evaluated by the Student criterion $t_k = -2\left[M(\Delta)_1 - M(\Delta)_2\right] / \sqrt{D(\Delta)_1 - D(\Delta)_2}$. Its essential difference from the tolerance in diameter $\varnothing 100H9\left(^{+0,87}_{0}\right)$, which is stipulated by design documentation, is found.

It is established that each subsequent process operation is more effective than the previous one in terms of providing surface roughness. However, it is also found that the first and third process operations significantly affect the value of mathematical expectation of deviation from roundness, i.e. they are most efficient in terms of providing the precision of shape. The evaluation of significance of mathematical expectation of deviations from roundness on behalf of internal cylindrical surfaces of hydraulic cylinders formed after the implementation of the second process operation (semi-finish boring) did not confirm a higher precision of the cross-sectional shape of the internal cylindrical surface of the hydraulic cylinders, i.e. the technological heredity is negative.

Bearing. Defects found in bearing 22316 have all signs of “false brinelling”, including regular (ordered) transverse grooves. This is the result of plastic deformation and sliding of the rollers on the bearing cage. As shown in previous papers, relief was found at the bottom of the grooves, which is characteristic not only of wear metal, but its displacement [4]. The formation of grooves is associated with the loading parameters of the bearing and is a manifestation of self-organization of its surface under conditions of force impact [7, 8]. By analyzing the groove front at its peak and across the width of the ring we obtained geometric parameters of its cross-section. The “invasions” of the material characteristic of plastic deformation were absent lengthwise. Given the strength of the ring we can state that the main mechanism is the formation, and considering the hardness of the ring material we can assume that the basic mechanism was abrasive wear, Figure 3.

In our opinion, the main causes of “dents” on bearing raceways are low-amplitude high-frequency oscillations in the contact zone “rollers – raceway” and violations of their lubrication mode. This is confirmed by published data [9, 10], which justify the emergence of congestion and localization of strain, extrusion of lubricants, heat and contact staining due to overheating, and difference in deformation of the surface layer and underlying layers of the substrate. As a result of cyclic loading of the swing mechanism and the imposition of low-amplitude vibrations in the roller surface, mechanical stresses arise periodically.

Microstructure. The surface hardness of bearing 22316 was 64 HRC. Based on metallographic analysis, it was shown that the bearing material had a martensitic structure as Figure 4. Morphological measurements through the thickness of rings did not reveal any wear.

In addition, due to static fracture of the bearing steel, the fracture surface had a silky, porcelain-like look that suggests a good quality of hardening [9].

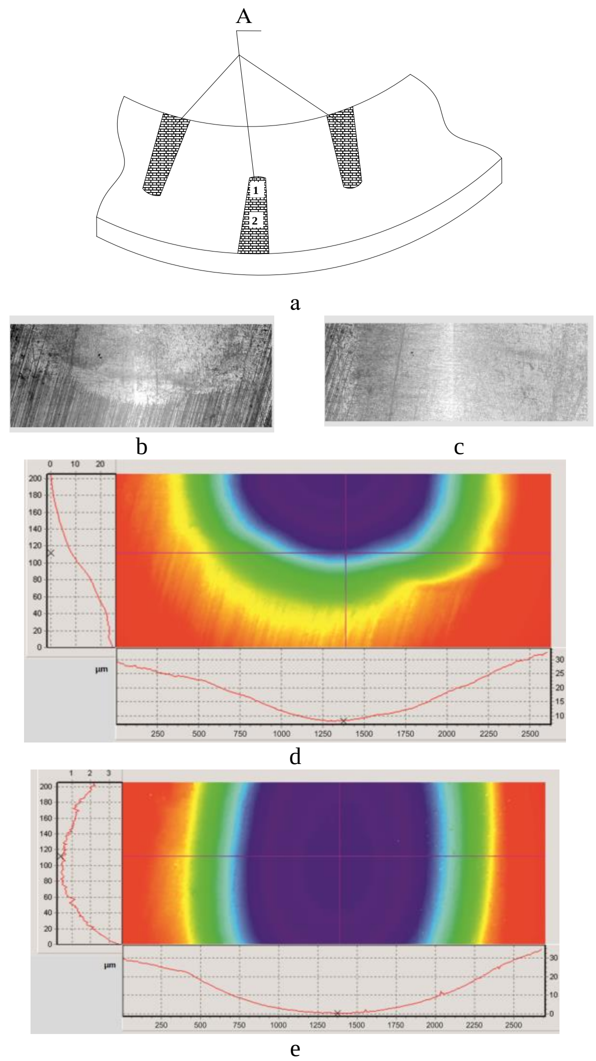


Figure 3. Investigation scheme of the inner surface of the outer bearing ring 22316- a, fragments of wear grooves - b, c and corresponding profile charts - d, e; 1,2 – points of surface analysis; A - false brinelling;

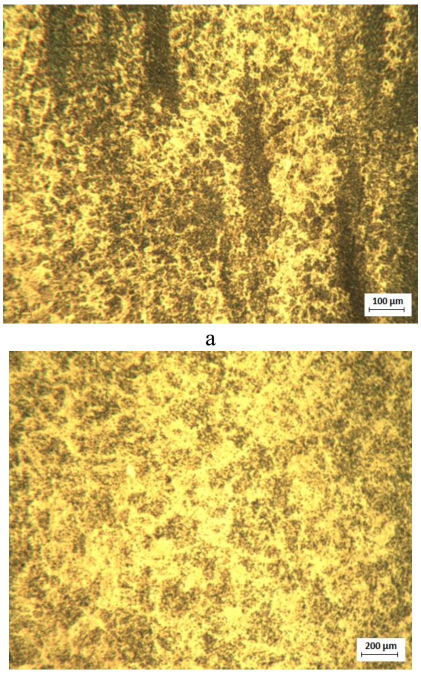


Figure 4. Steel microstructure of bearing 22316

4. DISCUSSION AND GENERALIZATION

Studies show that the self-organization of the cylinder liner and bearing steel is primarily due to the evolution of deformation and fracture processes in the field of force (Table 6). The nonlinearity of the process is associated with the properties of the surface layers of the material and mode of exposure [11, 12].

The above mechanisms of cutting and wear are confirmed by good engineering practice in the factory. The analysis of the geometry and shape of the hydraulic cylinder surface indicates the need to consider the cumulative impact of process operations on molding and surface relief formation [12]. The analysis of the contact point geometry and tribogram data for bearing 22316 suggests an uneven development of localization of friction zones [13] that allows considering the process, which takes place in the grooves obtained on the surface of the ring, as a sequence of localization stages of deformation and wear.

In a number of previous works, mathematical modeling of the relief formation processes under different types of temperature- force action on the material surface has been developed based on a tiered approach [1]. The results obtained in this work are a prerequisite for the creation of data processing algorithms in the zone of wear based on the proposed mathematical model [14]. This will allow for statistical analysis of the relief parameters of local spatial domains (contact points), taking into account cyclic nature, stochasticity and the presence of the spatial self-organization of relief formations.

TABLE 6. Self-organization of the cylinder liner and bearing steel

Object	Deviation from shape	Deviation from roughness	Proposed technical solutions
Hydraulic cylinder liner	Increasing deviation from roundness on behalf of cross-sections of internal cylindrical surface	-	Process optimization by excluding the process operation of “semi-finish boring”
Bearing	The occurrence of “grooves” because of high amplitude loadings	Damage to the track surface by wear of metal ring	Changing lubrication, vibration control measures

The practical value of this work is that the methods of physical mesomechanics for the technical diagnostics of the surface condition under contact influences during friction have found practical application. In addition, based on the experimental data obtained and the theoretical approaches of physical mesomechanics, new technological solutions for the machining of parts by cutting are proposed. The results obtained can be used to optimize the manufacture of parts of this type in machine building and aircraft construction, while designing structures with increased anti-erosion and antifriction properties.

5. CONCLUSIONS

Processes of deformation and formation of cylindrical internal bearing surfaces (in operation) of the hydraulic cylinder (in production) are described. They illustrate that both mechanical surface machining and wear are complex self-organized processes, containing a variety of interrelated mechanisms of friction and deformation. In this case, the result of the microscopic interaction (the cutting tool and roller/the surface) is determined by the nature of the elastic-plastic deformation, friction and wear of local areas of their working surfaces. The morphological features of the surfaces resulting from different manufacturing operations (hydraulic cylinder) are described quantitatively. The recommendations on process optimization with regard to the shape and roughness of the component are given. There have been established the basic morphological characteristics of the bearing rings damaged by “false brinelling” due to the impact of elastic-plastic deformations on the bearing raceways surface and the formation of slip and wear areas.

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چکیده

این مقاله بر پایه مفهوم مزومکانیک فیزیکی است که به هر برش پلاستیک در بدن استرسی اجازه می دهد که به عنوان از دست دادن پایداری برشی مواد در مناطق تمرکز استرس محلی در نظر گرفته شود. این رویکرد، که به لحاظ جسمی بسیار محکم است، به ما اجازه داد پردازش ماشینکاری با برش و سایش فولادها را از یک نقطه در نظر بگیریم. تعاریف فیزیکی و مکانیکی در اثر عملیات پردازش خاص بر شکل و زبری سطح سیلندر هیدرولیکی یافت می شود. مکانیزم های سازماندهی فضایی امداد و سطح بلبرینگ در شرایط برآورد نادرست، خلاصه و تحلیل می شود. داده های به دست آمده می تواند برای تعمیم یا پیش بینی و تشخیص علمی وضعیت سطح حمل بار و حمایت از سیستم های مکانیکی مورد مطالعه، مورد استفاده قرار گیرد.

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