Correction of form errors during centerless grinding of balls

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Abstract. This article describes the problem of ensuring effective correction of errors in the form of the spherical surface of the ball during its centerless grinding. The process of embedding ball roughness in the surface of the driving wheel is nonlinear due to the complex form of the roughness and abrasive grains. The mechanism of interaction of the ball with the driving wheel as a process of contacting elastic bodies is analyzed. The value of embedding the abrasive grain size of the driving wheel into the workpiece surface is mathematically determined. It is shown that an increase in the grain of the driving wheel leads to correction of the ball form error during its centerless grinding. At the same time, with increasing wheel abrasive grain, the number of grains per unit surface area of the driving wheel decreases. Based on this, it is concluded that the influence of the characteristic of the driving wheel on the process of correcting errors in the form of the sphere is prevailing.

1. Introduction

Spherical parts are widely used in industry [1, 2-5]. The greatest difficulty in production are balls for bearings, as their manufacture is associated with the use of complex technologies [3, 4, 5] and expensive equipment. Requirements for the accuracy of parts are constantly increasing, therefore, manufacture requires ensuring high accuracy of the spherical surfaces of the balls, which requires a special approach to the finishing methods for their processing [1, 2, 4, 5, 6, 7]. Today, the manufacture of ceramic balls for bearings is widespread [3, 8, 9, 10, 11]. However, the published works do not provide data on the possibility of using these technologies for steel billets. The main methods for final processing of balls are the following: processing the special section with cast-iron discs with V-shaped grooves [2, 12, 13, 14] and methods of centerless grinding of balls [4, 6, 15, 16]. Methods of processing with magnetic fluid [17] and using ultrasound [3, 8, 9] are less common. However, the processing cycle is rather long and unfavorable for the environment [8, 9].

In mass production, the most acceptable methods for processing balls are centerless grinding methods [4, 6, 15, 16, 20], because it does not require the use of complex special technological equipment and it is possible to quickly reconfigure and automate it.

Research on creating spherical form models and theoretical analysis has been conducted by many scientists [15, 16, 18, 19, 21]. Creating and analyzing a mathematical model that predicts obtaining a spherical surface of a given accuracy is the main task of various studies of finishing balls, it is the basis and prerequisite for further study.

In the work [20] (as shown in figure 1), the process of correcting errors in the form of spherical parts processed by centerless grinding is researched. It is shown that if the values of errors in the form of the sphere have the same order as the grain size of the abrasive wheels, then the protrusions
(notches) of the abrasive grains in contact with the processed surface begin to play the same role as the protrusions (roughness) on the surface of the workpiece. Interacting with each other randomly, they control the behavior of the workpiece in the cutting zone [20].

Figure 1. Schema of the ball location in the processing zone [20].

However, the results of this research are only the first approach to the solution of the problem of ensuring the accuracy of the spherical rolling bodies forms, since the author has adopted ideal restrictions. So, if the support knife can really be considered absolutely rigid, and its surface is absolutely smooth, then the working surfaces of the abrasive wheels have a finite stiffness, which is not taken into account by the dependencies obtained by the author. Meanwhile, the malleability of the driving wheel surface can be so significant, depending on the type of ligament and structure of the wheel, that calculation by the mentioned method [20] will lead to an unacceptably large error, which will not allow choosing the parameters of the technological operation of centerless grinding of spheres correctly.

The author [20] rightly believes that the form of a spherical workpiece can be described as a harmonic function:

\[
f(x) = \frac{a_0}{2} + \sum_{k=2}^{\infty} A_k \sin(kx + \varphi_k)
\]

(1)

where \(a_0\) is the diameter of the sphere;
\(A_k\) is the amplitude of the \(k\)-th harmonic;
\(k\) is the ordinal number of harmonics;
\(\varphi_k\) is the angle of the initial phase of the \(k\)-th harmonic.

The author's creative finding is the statement that the surface roughness of the harmonic sphere \(k = 2\), which are the cut and have the largest value, randomly contact the driving wheel at points \(K_1, K_2\) (as in figure 1), as well as with a grinding wheel and a support knife. At the same time, the interaction at these points (as in figure 2) provides an indirect "feed" of the material to the cutting zone and the removal of the additional asymmetric allowance that is formed in this case, which, in fact, leads to correction of form errors [20].
Figure 2. Scheme of interaction of sphere roughness with abrasive grains [20]: 1 – grinding wheel; 2 – the ball to be processed; 3 – driving wheel; 4 – support knife.

The solution to the problem of ensuring effective correction of form errors is to determine the value of the additional allowance removed by the grinding wheel and formed when the roughness of the workpiece with an amplitude $A_k$ on the verge of the driving wheel grooves at the points $K_1$ and $K_2$ as well as on the knife surface. The author [20] believes that the roughness is completely embedded in the surface of the driving wheel and the protrusion of the profile in contact with the grinding wheel is removed accordingly.

However, "immersion" of the roughness is not only due to the notches on the surface of the abrasive wheel, but also by embedding abrasive grains into the surface of the spherical workpiece, and due to the ligament’s pliability.

In addition, the process of the notches embedding in the surface of both the driving wheel and the grinding wheel, due to the complex form of notches and abrasive grains, is nonlinear, which is not taken into account by the author.

2. Research methods

Let's consider the process of interaction with the customer.

The surface roughness of the workpiece having the form of a curvilinear cone, interact with the surface roughness of the grooves verge of the driving wheel $\Delta_B$ and with the surface roughness of the support knife $\Delta_H$ embedded in the surface of the driving wheel that has a specific, but finite stiffness. It should be noted that roughness of the highest harmonics having a size the same order of the grain size of the driving wheel and less, are mainly located between the grains of the driving wheel, not involved in the formation of additional allowance and therefore cannot be corrected, forming as a result of processing of the form error in the form of waviness. Roughness only of the lower harmonics, mainly of the second harmonic, form an additional allowance. Therefore, when running roughness $A_2$ (roughness equal in magnitude to the second harmonic amplitude) on the roughness of the groove surface of the drive wheel, the displacement of the center of mass of the workpiece in the direction of the point of contact with the surface of the grinding wheel.
\[ \Delta = \sqrt{A_{2}^{2} - \Delta_{a3}^{2}} \]  
(2)

where \( \Delta_{a3} \) is the value of the driving wheel abrasive grains embedding in the surface of the workpiece.

First approximation the value \( \Delta_{a3} \) can be defined as the value of convergence of a spherical surface with a cylindrical surface under the action of some force:

\[ \Delta_{a3} = 1,231 \cdot \frac{3}{\sqrt{\left( \frac{F}{E_{np}} \right)^{2}} \cdot \frac{1}{\rho_{np}}} \]  
(3)

where \( F \) is the value of contact area; \( E_{np} \) is the reduced elastic modulus of contacting bodies:

\[ E_{np} = \frac{2 \cdot E_{1} \cdot E_{2}}{E_{1} + E_{2}} \]  
(4)

where \( E_{1} \) is the modulus of ball elasticity; \( E_{2} \) is modulus of driving wheel elasticity; \( \rho_{np} \) is the reduced radius of contacting bodies curvature.

\[ \frac{1}{\rho_{np}} = \frac{1}{R_{1}} + \frac{1}{R_{2}} \]  
(5)

where \( R_{1} \) is the radius of curvature of the ball workpiece sphere; \( R_{2} \) is the radius of the driving wheel curvature.

Let’s determine the total value of the contact areas of a spherical workpiece with active abrasive grains on the surface of the driving wheel at a depth of \( \Delta_{a3} \):

\[ F = F_{i} \cdot n_{Z} \]  
(6)

where \( F_{i} \) is the contact area of the \( i \)-th grain with the workpiece; \( n_{Z} \) is the number of active abrasive grains that come into contact with the surface of a spherical workpiece at a depth \( \Delta_{a3} \).

The value \( F_{i} \) in contact of different grains varies from zero to \( 2 \cdot \pi \cdot \rho \cdot \delta \), where \( \delta \) is the maximum depth of abrasive grains embedding in the workpiece surface at this value of the external force; \( \rho \) is the radius of rounding the abrasive grain top.

Therefore, with sufficient accuracy for the analysis, it can be recorded that the average contact area of a single abrasive grain is:

\[ F_{cp} = \pi \cdot \rho \cdot \delta \]  
(7)
The number of active grains can be determined using the expression obtained in the research [22]:

\[ Z = 0.24 \cdot Z_0 \cdot \left( \frac{\delta}{d_0} \right)^{2.75} \]  

(8)

where \( Z_0 \) is the total number of grains per unit surface area of the driving wheel; 
\( d_0 \) is the value of abrasive grains (graininess of the wheel).

It is logical to assume that the embedding depth \( \delta \) of driving wheel abrasive grains in the surface of the spherical workpiece at the value of convergence \( \Delta_{a3} \):

\[ \delta = \frac{P_y}{G} \]  

(9)

where \( P_y \) is the radial component of the cutting force; 
\( G \) is the stiffness of the material of the spherical workpiece.

However, since the contact area is extremely small, it can be shown that its value is equal to:

\[ F_K = \pi \cdot \delta \cdot d_{III} \]  

(10)

where \( d_{III} \) is the diameter of the spherical workpiece.

Then:

\[ n_Z = F_K \cdot Z_0 \]  

(11)

\[ F = F_{iwp} \cdot n_Z = 0.24 \cdot \frac{\pi^2 \cdot \delta^{4.75} \cdot \rho \cdot d_{III} \cdot Z_0}{d_0^{2.75}} \]  

(12)

Then:

\[ \Delta_{a3} = 1.231 \cdot \left( \frac{0.24 \cdot \pi^2 \cdot \delta^{4.75} \cdot \rho \cdot d_{III} \cdot Z_0}{E_{np}^2 \cdot \rho_{np} \cdot d_0^{4.75}} \right)^{\frac{1}{3}} \]  

(13)

Extracting the value \( \delta \) from under the root and substituting (9), we get:

\[ \Delta_{a3} = 0.48 \left( \frac{P_y}{G} \right)^{3.17} \cdot \left( \frac{\pi^2 \cdot \rho \cdot d_{III} \cdot Z_0}{E_{np}^2 \cdot d_0^{4.75} \cdot \rho_{np}} \right)^{\frac{1}{3}} \]  

(14)

The largest value of additional allowance that occurs due to the form error of a spherical workpiece and fed to the cutting zone, and, consequently, the greatest correcting ability occurs when \( \Delta_{a3} = 0 \). Let's analyze this situation.
Expression (14) can be zero if one of the cofactors on the right side of the equality is zero. Force $P_y$ and stiffness $G$ cannot be zero. Therefore, the expression (14) can be equal to zero if the numerator in the second factor is equal to zero. This is possible only if $\rho = 0$, and namely, the radius of rounding the abrasive grains tops of the of the driving wheel is equal to zero. Of course, this cannot be achieved. However, it is possible to reduce $\rho$ to values close to zero by using special correcting methods for the driving wheel.

In addition, the expression (14) will be zero if the denominator of the fraction in the second factor tends to infinity:

$$E_{np}^2 \cdot d_0^{4.75} \cdot \rho_{np} \rightarrow \infty$$

(15)

All cofactors in (15) are finite and have a fixed value. However, the parameter $d_0$ can be used as a control factor for correcting form errors. Namely, if you increase the graininess of the driving wheel, the correcting ability of the centerless grinding process of the sphere will improve.

It should be noted that with increasing grain value $d_0$, the number of grains per unit surface area of the driving wheel decreases simultaneously. Therefore, the influence of the characteristic of the driving wheel on the process of correcting form errors of the sphere is prevailing.

3. Conclusion

The value of driving wheel abrasive grains embedding in the surface of a spherical workpiece during centerless grinding of balls is mathematically determined.

It is presented that the greatest correcting ability occurs when the value of driving wheel abrasive grains embedding in the surface of a spherical workpiece tends to zero.

The use of special correcting methods that reduce the radius of rounding the top of the abrasive grain has a positive effect on the accuracy of the resulting spherical surface of the ball.

Increasing the grain of the driving wheel increases the correcting ability of the process.

It is mathematically proved that the influence of the driving wheel characteristic on the process of correcting form errors of the sphere is prevailing.

Acknowledgments

The article was prepared with the financial support of the grant of the President of the Russian Federation for governmental support of young Russian scientists (PhD) Grant No. MK-2395.2020.8.

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