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Accuracy of the geometric shape of the hole in the longitudinal section during honing

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Abstract: The wide application of honing as a finishing treatment of internal cylindrical surfaces for cylinder-piston systems, used in some structures, is caused by high accuracy measured in tenths of a micrometer, and high productivity of the process. The most important indicator of reliable operation of cylinder-piston systems are high requirements for the geometric accuracy of holes. Due to the lack of sufficient theoretical justification for the selection of honing parameters ensuring the accuracy of the geometric shape of the hole in the longitudinal section, the authors proposed a model for the formation of errors in the geometric shape of the hole. The model is built on the kinematic characteristics of the process including the ratio of the honing stone dimensions, the length of the hole, the stroke of the honing head, the ratio of the speeds of translational and rotational movements, and the force action in the processing zone, which changed due to the presence of an overrun of the honing stone. To obtain analytical dependencies ensuring the minimisation of form deviations, the conditions for stock removal for the points of the machined surface were considered, the value of which was taken proportional to the path of movement, and the pressure value. For this purpose, graphs of the distribution functions of displacements and pressure changes were constructed depending on the coordinate of the point location on the generating line of the hole being machined. Using the obtained analytical dependencies, the potential occurrence of a shape error in the form of a saddle shape was found, the dominant factor influencing the value of which is the value of the honing stone overrun. At the same time, it was identified that the ratio of the speeds of translational and rotational movements has an insignificant effect on the violation of the form in the longitudinal section.

Keywords: honing; geometric accuracy of holes; kinematic characteristics of honing; value of overrun; displacement distribution function.

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INTRODUCTION

Honing has been on the rise in recent years due to the need to improve the tribological performance of cylinder-piston systems used in materials-handling machines, hydraulic jacks, engine components, and robotics. In process engineering, abrasive machining methods have always been an important area of research in terms of development and modelling, as they determine the surface quality characteristics of the blank. Honing is an abrasive machining process most often used in roughing, semi-finishing and finishing of cylindrical bores to produce parts with high surface quality and minimal geometric errors [1–3]. A special feature of honing is the transverse scratches made on the surface by two tool strokes. These transverse scratches give the surface special performance characteristics in terms of oil retention and circulation. Therefore, honing is usually used to ensure that the surface of elements that are in contact with others during relative motion, such as in the piston-cylinder system, meets the requirements for geometric and dimensional accuracy and texture [4–6]. One of the key tasks that must be solved in the honing process is to ensure a characteristic surface texture consisting of a network of oil scratches that form cross-hatching, as well as the required values of the roughness profile parameters [1; 2; 7].

During the use of honing processes, many studies have been carried out on both traditional and non-traditional honing. For example, in [8] positive results are noted for the processing with variable kinematic parameters, and it is indicated that honing performed with variable kinematic parameters affects the value of the resulting roughness profile parameters, which is an additional incentive, influencing the further development of CNC machines used for honing.

According to the data given in [9; 10], the honing process is characterised by three overlapping motions of the honing tool: rotation around the tool axis, linear reciprocating motion, and feed motion of the honing stone in the radial direction. The main parameters determining the honing kinematics are: axial linear speed of the honing head during reciprocating motion V_A, m/min, and peripheral speed of the honing head V_P, m/min:

$$V_A = 2l_X n_A \ ; \ V_P = 0.001\pi Dn \ , \qquad (1)$$

where l_X is the stroke length of the honing head during reciprocating motion, m;
n_A is the stroke rate of the honing head during reciprocating motion, 1/min;
n is the rotational frequency of the honing head, rpm;
D is the diameter of the hole being honed, mm.

The specified speeds determine the cutting speed V and the honing angle α:

$$V = \sqrt{V_A^2 + V_P^2} \ ; \ tg\alpha = V_P / V_A \ . \qquad (2)$$

The radial motion of the honing stone can be controlled either by feed or by force. In feed-controlled honing, the honing stone is fed outward in certain stages, and at certain intervals using various mechanisms, for example, a mandrel with conical elements. In force-controlled honing, the height of the feed steps depends on the difference between the required and measured process forces, which leads to different process forces during the honing process [9]. When processing is carried out with a constant honing force, the quality of honed holes can be improved [11].

One of the main goals of the honing process is to reduce the deviation of the shape of honed holes. In [12], based on a comparison of the deviations in the hole shape that can be obtained with certain types of processing, it was concluded that the honing process significantly improves the cylindricality of the processed hole compared to other production methods. The authors of [13] noted that the cylindricality of the cylinder hole is determined primarily by six groups of factors, such as the machine and fixture rigidity, the honing head design, the location of the honing stones, the properties of the material being processed, the honing process parameters and the pre-created initial cylindricality of the honed hole, during previously performed processing.

The work [14] considered the effect of the honing stone speed on obtaining holes with minimal geometric errors. However, the author limits himself to studying the hole accuracy only in the cross-section, without considering its effect on the accuracy in the longitudinal direction. The author of [15] described the effect of changing the reciprocating speed and rotation speed on improving the ovality, and noted that with constant overrun, a decrease in ovality was observed with an increase in the reciprocating speed. Maximum ovality was observed at a higher reciprocating speed, and at a relatively lower rotation speed. At a higher rotation speed of the honing head, ovality decreases for all values of the reciprocating speed [15]. In [16], the effect of axial acceleration of the honing head on cylindrical deviation was confirmed. It was found that with an acceleration of <1 *g* and with an acceleration of >2 *g*, greater deviations in cylindricality of the honed hole were obtained than when processing with an acceleration of 1.5 *g* (*g* is the gravitational value of acceleration).

As follows from the above review, the production of honed holes, with minimal deviations of cylindrical shape, has been studied in sufficient detail in published works. At the same time, as for ensuring the shape of the hole in the longitudinal section, in the few published works, for example [17–19], there are recommendations for the selection of honing parameters, in particular the overrun value, which do not contain sufficient theoretical justifications, and are built only based on some experimental data, the value of which essentially depends on the specific honing conditions.

An analysis of works covering the honing process allowed identifying the main parameters affecting the accuracy of the hole geometric shape: the dimensions of the honing stones, the ratio of the speeds of the rotational and reciprocating motions of the honing head and the rational choice of pressure in the zone of a contact of the stones with the part.

In work [19], it is noted that to obtain the correct geometric shape of the processed hole, the stones must recede out of the hole for a certain length, called the overrun. However, it is emphasised that with an incorrectly selected symmetrical overrun in the hole, a saddle shape or barrel shape can be obtained. It is concluded that if one considers the redistribution of contact radial forces to be the dominant cause, then at any overrun values, an error in the shape in the longitudinal section in the form of a saddle must inevitably form, which increases as the overrun values increase. In this case, the author considers the overrun value l' to be optimal, determined by the relationship

$$l' = (0.33 \ldots 0.25)l = opt \ , \qquad (3)$$

where the length of the stone l is determined by the expressions

$$l = (1.2 \ldots 0.8)L \ \text{ and } \ l = 1.5\pi D tg\alpha / z \ , \qquad (4)$$

where L and D are the length and diameter of the honed hole, respectively;
z is the number of stones:

$$z = (0.25 \ldots 0.35)\frac{\pi D}{b} \ , \qquad (5)$$

where α is the angle of elevation of the trajectory of the cutting tools;
b is the width of the stone.

The range of changes in overrun values specified in [19] fits the values proposed in [18; 20], but without clear justification for their selection.

The purpose of this study is to develop recommendations based on modelling of real honing cycles that will help end users when setting up the machining process.

METHODS

The formation of geometric shape errors during honing can be carried out only on a cutting model, that takes into account local contacts between the blank, and the abrasive tool changing due to the impact of kinematic and force factors.

To obtain analytical dependencies that ensure the minimisation of shape deviations, it is necessary to consider the conditions for metal removal, during rotational and reciprocating motion of the honing head. This problem can be solved by assuming that the amount of metal removal U is proportional to the amount of movement of individual points of the stone relative to the selected point of the machined surface S and the value of pressure p:

$$U = kpS, \tag{6}$$

where k is the coefficient of specific material removal under given honing conditions.

To determine the shape of the machined hole in the longitudinal direction, we denote the metal removal at point x along the length of the hole by $U(x)$ (Fig. 1). The pressure in the contact zone of the stones with the part can depend both on the position of the stones relative to the part, i. e. be a function of the x coordinate on the machined surface (Fig. 1), and on the position of the considered point on the stone contact line, i. e. be a function of the x^* coordinate in the moving coordinates system associated with the honing head:

$$p = p\left(x, x^*\right).$$

In further calculations, we will assume that the pressure $p=p(x, x^*)$ does not depend on the x^* coordinate, but only on the x coordinate on the machined surface, i. e. $p=p(x)$.

The direction of the rotational speed V_P does not change during the machining cycle, and the direction of the translational speed V_A changes at the end of each stroke of the head. In extreme positions, the translational motion velocity decreases to zero, and then increases from zero to V_A in the opposite direction, resulting in a delay in the stroke for some time.

This nature of the head movements leads to an inequality in the path of movement of individual points of the cutting surface of the stones, relative to the machined surface. To take into account what share of the total friction path falls on particular areas of the part surface, and the working surface of the stones, the authors of [20] proposed to introduce a function of the distribution of displacements $\alpha(x)$ in the longitudinal direction, and a function of the distribution of displacements $\beta(x)$ resulting from the head rotation.

Fig. 2, 3 show the distribution functions for two possible conditions of symmetrical honing (under the same conditions for processing the ends of the hole). For the case shown in Fig. 2, when the overrun value l'=0, the stroke length of the head is determined as

$$l_X = L - l.$$

For the extreme sections, the length of which is equal to l, the ordinates of the curve of the longitudinal displacement distribution change according to a linear law, and the ordinates for the middle section of length ($L-2l$) remain constant, and are determined from the normalisation requirement, according to which the area bounded by the distribution curve and the abscissa axis is equal to one:

$$\alpha_{\max} l + \alpha_{\max}\left(L - 2l\right) = 1; \tag{7}$$

$$\alpha_{\max} = 1/\left(L - l\right). \tag{8}$$

For the displacement distribution curve at relative rotation $\beta(x)$, the constancy of the ordinates for each section is characteristic, although their values differ from each other. This difference is determined by the nature of the change in the velocity of the longitudinal displacement of the head at the end of the longitudinal stroke, and the time spent on changing the direction of the head movement. The duration of the stroke delay depends on the inertia of the control system.

Fig. 3 shows a case for which the relation is observed:

$$L - l < l_X < L + l.$$

RESULTS

During head displacement, part of the stone comes out of the hole in both directions, and only part of the cutting surface of the stones passes over the extreme points of the part forming the hole. The longitudinal displacement curve for the extreme sections is a trapezoid. The middle section of length (l_X-l) is characterised by constant ordinates, the values of which are determined from the normalisation requirement:

$$\left(L + 2l' - 2l\right)\alpha_{\max} + 2\frac{\alpha_{\max} + \alpha(0)}{2}\left(l - l'\right) = 1, \tag{9}$$

where $\alpha(0) = \alpha_{\max} l'/l$.

Hence

$$\alpha_{\max} = \frac{l}{Ll - \left(l - l'\right)^2}. \tag{10}$$

The equation of the $\alpha(x)$ straight line for the section $0 \le x \le l-l'$:

$$\alpha(x) = \frac{\left(x + l'\right)}{Ll - \left(l - l'\right)^2}. \tag{11}$$

Therefore, the magnitude of the relative displacement of particular points of the stone for a point of the machined surface with coordinate x can be determined in the longitudinal direction as

$$S_A = V_A \alpha\left(x\right)\tau,$$

and in the direction of the head rotation as

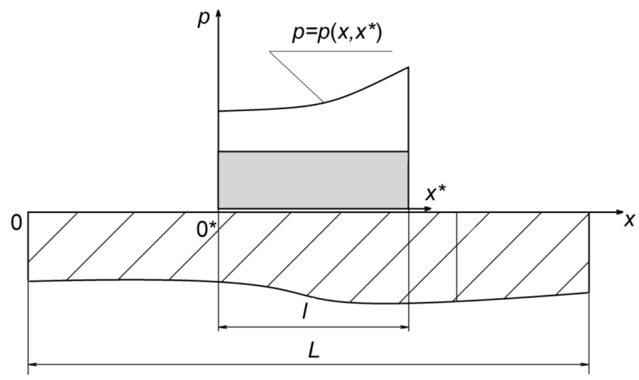

Fig. 1. *Computational scheme for determining metal removal during honing*
Рис. 1. *Расчетная схема для определения съема металла при хонинговании*

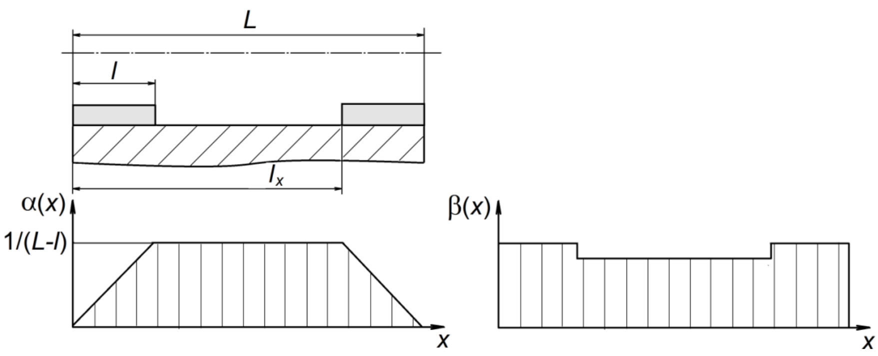

Fig. 2. *Distribution curves of displacements α(x) and β(x) during honing without overrun (l'=0)*
Рис. 2. *Кривые распределения перемещений α(x) и β(x) при хонинговании при отсутствии перебега (l'=0)*

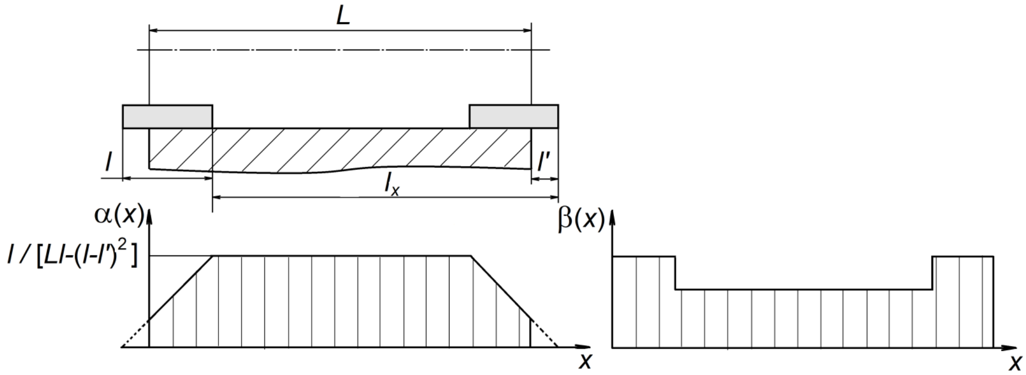

Fig. 3. *Distribution curves of displacements α(x) and β(x) during honing in the presence of overrun (l'≠0)*
Рис. 3. *Кривые распределения перемещений α(x) и β(x) при хонинговании при наличии перебега (l'≠0)*

$$S_P = V_P \beta(x) \tau ,$$

where τ is the honing duration.

To find the function $U(x)$ that determines the metal removal in the hole section with coordinate x, it is necessary to take into account the pressure of the honing stone $p=p(x)$ on this section of the hole:

$$U(x) = U_A(x) + U_P(x) = k_A S_A p(x) + k_P S_P p(x), \qquad (12)$$

where $U_A(x)$, $U_P(x)$ are the metal removal at the point with coordinate x due to the stone movement in the longitudinal direction and in the direction of rotation of the honing head, respectively;

k_A, k_P are coefficients of specific material removal under the given honing conditions caused only by the translational or rotational movement of the honing head, respectively.

Let us consider in more detail the case of honing in the presence of overrun ($l'\neq0$) (Fig. 3), if the pressure diagram within the length of the contact of the stone with the part is a rectangle, i. e. there is a uniform pressure distribution in the contact zone. Taking into account the symmetrical nature of the processing (the overruns at the ends of the hole are the same), we will consider only one side of the hole (Fig. 4) for the case when $2l<L$. The graph $p=p(x)$ displayed in Fig. 4 shows a gradual decrease in pressure due to an increase in the contact area of the stone with the part. Therefore, three areas can be distinguished along the x coordinate, differing in processing conditions: 1) $0\leq x\leq l-l'$; 2) $l-l'<x<l$; 3) $l<x<L-l$. Consequently, within sections 1 and 3, the pressure $p=p(x)$ does not change and is:

– for section 1: $p(x) = p_1 = \dfrac{P_y}{(l-l')b}$;

– for section 3: $p(x) = p_3 = \dfrac{P_y}{lb}$.

Then for section 2

$$p(x) = p_2 = \frac{P_y}{l(l-l')b}(2l - l' - x),$$

where P_y is the force of pressing the stone to the processed surface;

b is the stone width.

Thus, in accordance with formula (12), assuming that $k_A=k_P=k$, we obtain:

$$U_1(x) = U_{1A}(x) + U_{1P}(x) = k\tau[V_A\alpha_1(x) + V_P\beta(x)]p_1 ; \qquad (13)$$

$$U_2(x) = U_{2A}(x) + U_{2P}(x) = k\tau[V_A\alpha_2(x) + V_P\beta(x)]p_2 ; \qquad (14)$$

$$U_3(x) = U_{3A}(x) + U_{3P}(x) = k\tau[V_A\alpha_3(x) + V_P\beta(x)]p_3 , \qquad (15)$$

where, taking into account the absence of delays in the extreme positions $\beta(x)=1/L$.

If we assume that $V_A=\xi V_P$, then for comparison of stock removal by sections, the obtained dependencies (13)–(15) can be presented in the following way:

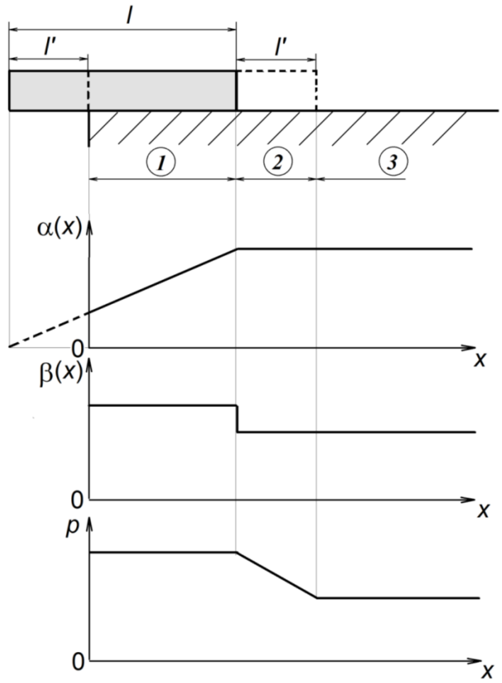

Fig. 4. *Distribution functions of displacements α(x), β(x) and pressures p(x)*
Рис. 4. *Функции распределения перемещений α(x), β(x) и давлений p(x)*

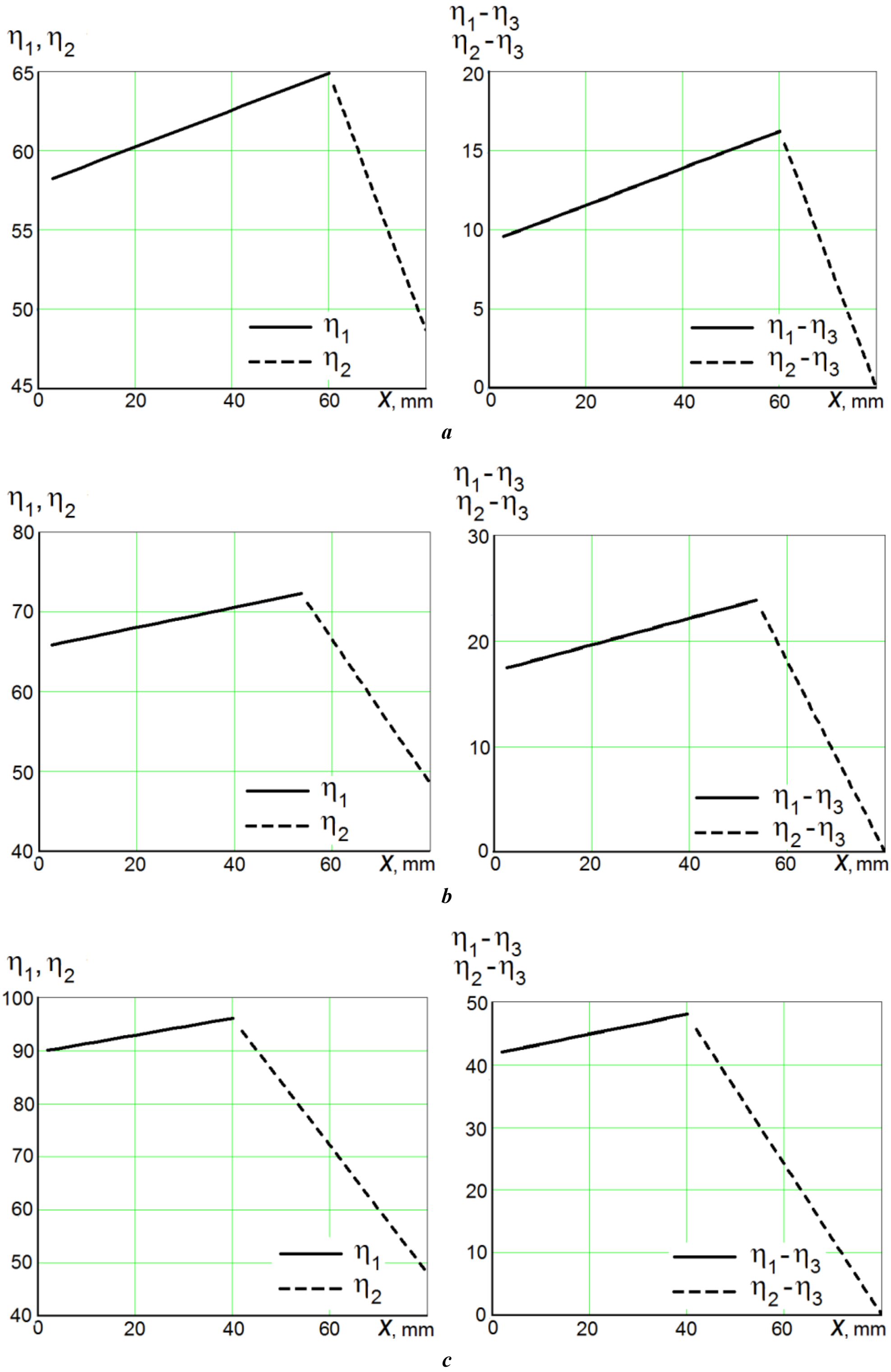

Fig. 5. *Values of η_1, η_2, η_3 for L=300 mm; l=80 mm and ξ=1/7:* ***a*** *– ε=0.25;* ***b*** *– ε=0.33;* ***c*** *– ε=0.5*
Рис. 5. *Значения η_1, η_2, η_3 для L=300 мм; l=80 мм и ξ=1/7:* ***a*** *– ε=0,25;* ***b*** *– ε=0,33;* ***c*** *– ε=0,5*

$$\eta_1=\frac{U_1(x)b}{k\tau V_P P_y}=\left[\xi\alpha_1(x)+\frac{1}{L}\right]\frac{1}{(l-l')}=\left[\xi\frac{(x+l')}{Ll-(l-l')^2}+\frac{1}{L}\right]\frac{1}{(l-l')}; \qquad (16)$$

$$\eta_2=\frac{U_2(x)b}{k\tau V_P P_y}=\left[\xi\alpha_2(x)+\frac{1}{L}\right]\frac{1}{l(l-l')}(2l-l'-x)=\left[\xi\frac{l}{Ll-(l-l')^2}+\frac{1}{L}\right]\frac{1}{l(l-l')}(2l-l'-x); \qquad (17)$$

$$\eta_3=\frac{U_3(x)b}{k\tau V_P P_y}=\left[\xi\alpha_3(x)+\frac{1}{L}\right]\frac{1}{l}=\left[\xi\frac{l}{Ll-(l-l')^2}+\frac{1}{L}\right]\frac{1}{l}. \qquad (18)$$

Fig. 5 shows the values of η_1, η_2, $(\eta_1-\eta_3)$ and $(\eta_2-\eta_3)$ for sections 1 and 2 at different values of overrun, where $\varepsilon=l'/l$.

The graph in Fig. 6 shows the influence of the overrun value on the maximum values of $(\eta_1-\eta_3)$ when changing the length of the stone (80; 100; 120 mm).

DISCUSSION

From the graphs in Fig. 5 and 6, it follows that the maximum values $(\eta_1-\eta_3)$ located on the boundary of sections 1 and 2, and determining the maximum deviations from the straightness of the generating line of the machined hole will increase non-linearly as the overhang increases. The obtained result coincides with the conclusions of work [19] that in the presence of overrun, a shape error in the longitudinal section in the form of a saddle is inevitably formed, which increases as the overrun value increases.

The influence of the overrun value on the maximum values $(\eta_1-\eta_3)$ with a change in the length of the stone shown in Fig. 6, indicates that the processing accuracy will increase with an increase in the length of the stone.

The developed model allows estimating the effect of the ratio of translational and rotational speeds, i. e. the coefficient ξ ($V_A=\xi V_P$). Fig. 7 shows the dependence $\max(\eta_1-\eta_3)=f(\xi)$ for L=300 mm, l=100 mm and $l'=0.3l$ indicating that the maximum deviation of the hole generating line from straightness depends linearly on the coefficient ξ. However, when comparing the results shown in Fig. 6 and 7, one can note that the influence of pressure due to a change in overrun is much more significant than the choice of the ratio of the translational and rotational speeds of the stone.

Taking into account specific honing conditions (k, τ, V_P, P_y, and b parameters) allows finding the $U_1(x)$, $U_2(x)$, $U_3(x)$ values using dependencies (12)...(18) and determining the linear dimensions of the deviations of the hole generating line. The obtained analytical dependencies allow estimating the accuracy of the hole geometric shape in the longitudinal section, during honing both with symmetrical and asymmetrical processing, when the overruns at the ends of the hole are not the same. This circumstance is especially relevant when honing blind holes.

CONCLUSIONS

Based on the developed honing model, taking into account the influence of the kinematic factor, dependencies are obtained that allow estimating the errors in the geometric shape of the hole in the longitudinal section. It is shown that the dominant factor is the presence of overrun. It is found that due to the presence of overrun, the machined surface has a tendency to saddle-shaped appearance. To improve the accuracy of the geometric shape of the hole in the longitudinal section during honing, well-founded recommendations can be used to increase the length of the honing stone and ensure constant pressure in the contact zone of the hone, and the machined surface during tool overrun.

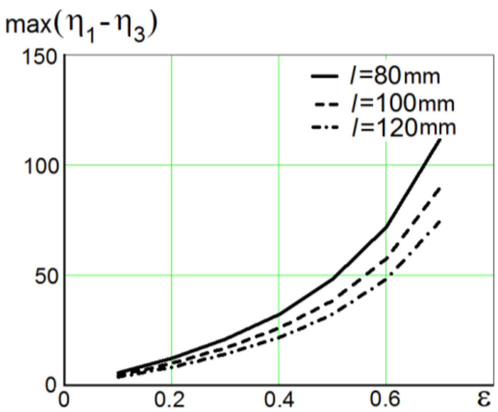

Fig. 6. *The influence of the overrun value on the maximum values of $\eta_1-\eta_3$ when changing the length of the stone for L=300 mm and ξ=1/7*
Рис. 6. *Влияние величины перебега на максимальные значения $\eta_1-\eta_3$ при изменении длины бруска для L=300 мм и ξ=1/7*

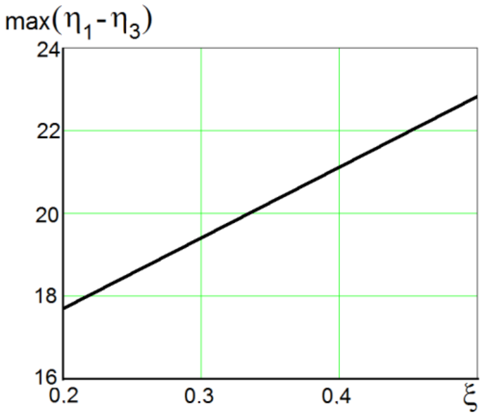

Fig. 7. *Dependence of maximum η_1–η_3 values on the ξ coefficient for L=300 mm; l=100 mm and ε=0.3*
Рис. 7. *Зависимость максимальных значений η_1–η_3 от коэффициента ξ для L=300 мм; l=100 мм и ε=0,3*

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Точность геометрической формы отверстия в продольном сечении при хонинговании

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Аннотация: Широкое применение хонингования в качестве финишной обработки внутренних цилиндрических поверхностей для цилиндропоршневых систем, используемых в ряде конструкций, обусловлено высокой точностью, измеряемой десятыми долями микрометра, и высокой производительностью процесса. Важнейшим показателем надежной работы цилиндропоршневых систем являются высокие требования к геометрической точности отверстий. В связи с отсутствием достаточных теоретических обоснований выбора параметров хонингования, обеспечивающих точность геометрической формы отверстия в продольном сечении, была предложена модель образования погрешностей геометрической формы отверстия, построенная на учете кинематических характеристик процесса, включающих соотношение размеров хонинговального бруска, длины отверстия, хода хонинговальной головки, соотношения скоростей поступательного и вращательного движений и силового воздействия в зоне обработки, которое изменялось за счет наличия перебега хонинговального бруска. Для получения аналитических зависимостей, обеспечивающих минимизацию отклонений формы, были рассмотрены условия съема припуска для точек обрабатываемой поверхности, величина которого принималась пропорциональной пути перемещения и величине давления. С этой целью были построены графики функций распределения перемещений и изменения давлений в зависимости от координаты расположения точки на образующей обрабатываемого отверстия. В результате использования полученных аналитических зависимостей установлено потенциальное появление погрешности формы в виде седлообразности, доминирующим фактором влияния на значение которой является величина перебега хонинговального бруска. Вместе с тем показано, что соотношение скоростей поступательного и вращательного движений несущественно влияет на нарушение формы в продольном сечении.

Ключевые слова: хонингование; геометрическая точность отверстий; кинематические характеристики хонингования; величина перебега; функция распределения перемещений.

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