On the question of improving the finishing operations of processing precise holes in the hulls of ship machinery

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Abstract. The profile of the cut surface is a combination of shape errors, undulations and surface roughness. Plastic deformation allows you to reduce the surface roughness without changing the shape and waviness errors achieved by boring. Combining the operations of fine boring and fine plastic deformation of the surface allows not only to improve the quality of the treated surface, but also under certain conditions provides the opportunity to simultaneously increase the processing performance. The best way to combine these operations in terms of productivity is when both the cutter and the deforming tool are located diametrically opposite in the same hole of the boring bar. Are proposed and described the engineering methods for calculating and selecting the geometry of the deforming tool, the feed and the strain force for combining technological operations of fine boring and fine plastic deformation of the wasted surface of the main holes of the ship's hull mechanisms.

1. Introduction

When machining the main openings of ship’s hulls, the widely used methods for machining precision holes, such as fine boring on diamond boring machines or precision boring on coordinate boring machines, providing high precision machining [1-5, et al.], cannot guarantee high quality machined surfaces and inferior to a number of finishing operations in achievable surface roughness. Therefore, the technological process of processing precise main holes additionally introduces operations: lapping, sizing, honing, rolling or diamond smoothing [6-10, et al.]. Any of these operations can be performed sequentially, which leads to economic problems, but does not create technical problems. These problems arise when combining operations on the same equipment using a combined tool [11-14, et al.]. In this case, as a rule, there are no ready-made technical solutions for both the tool design and the parameters of the combined process.

The purpose of this work is to develop engineering methods for determining the parameters of the technological process of combined processing of the exact main holes of the hull of ship mechanisms by methods of fine boring and plastic deformation. To achieve this goal, the following tasks are set:

- offer the most effective design of a combined tool for combined processing conditions;
- develop and experimentally test engineering methods for calculating and selecting the geometry of the deforming element of a combined tool;
- develop and test a method for determining the optimal feed for combined processing conditions;
- determine the optimal forces for deformation hardening of the surface of the treated holes.
2. Initial position.
Regardless of the method of surface deformation (rolling or diamond smoothing), it arises the problem of calculating and selecting the radius of the sphere of the deforming element. The profile of the cut surface is a combination of shape errors, undulation and surface roughness [15-18, et al.]. The task of plastic deformation is to reduce the surface roughness without changing the shape and undulation errors achieved by boring. You can solve this problem by choosing the radius of the deforming element smaller than the radius of curvature of the wave on the surface of the hole after boring that is under the condition \( R < \rho \).

The main factor determining the surface waviness is the ratio of the frequency of the harmonic relative oscillation of the part and tool \( f_k \) to the rotation frequency of the part or tool \( f_B \). The formation of waviness in the longitudinal section depends on whether the ratio \( f_k/f_B \) is an integer or a fractional number. Longitudinal waves occur only with a fractional ratio of \( f_k/f_B \). Therefore, this ratio in the calculations is expressed as the sum:

\[
\frac{f_k}{f_B} = \psi \pm \psi'.
\]  

(1)

where \( \psi \) – whole part of the relationship; \( \psi' \) – fractional part of the relationship.

The height and length of the waves are determined by the pliability of the technological system and the elements of the cutting mode [15, 18, 19 et al.].

The waviness of the surface in the longitudinal section of the part (figure 1) can be represented as an expression:

\[
Y = a \times \sin(\omega \cdot x),
\]  

(2)

where \( a \) – the amplitude of the waves; \( \omega \) – the frequency of the waves.

![Figure 1. Scheme for calculating a tool for plastic deformation of a surface.](image)

The radius of curvature of the longitudinal wave is determined by the formula:

\[
|\rho| = \left[ \frac{1 + a^2 \omega^2 \cos^2(\omega \cdot x)}{-a \omega^2 \sin(\omega \cdot x)} \right]^{1/2}.
\]  

(3)

The smallest value of the radius of curvature of the wave is obtained when \( \cos(\omega x) = 0 \), therefore

\[
\rho = \frac{1}{a \omega^2},
\]  

(4)

or, considering that \( \omega = \frac{2\pi}{\lambda} \), receive

\[
\rho = \frac{\lambda^2}{4\pi^2a}
\]  

(5)

where \( \lambda \) – length of longitudinal wave.

Thus, by determining the radius of curvature of the longitudinal wave \( \rho \) and maintaining the condition \( R < \rho \), you can choose the optimal radius of the deforming element for crumpling.
irregularities in the longitudinal direction. If this condition is not met, the tool will not be guaranteed to contact the wave troughs and the surface roughness will be reduced only at the wave tops.

If the ratio of the harmonic frequency relative movements (oscillations) of the workpiece and the tool to the spindle rotation frequency is represented by an integer, then the circular wave after one circulation is closed (including offset along the axis for a value of current flow) and the longitudinal wave in this case is absent. The radius of the deforming element for crumpling the irregularities of a circular wave is obtained from the condition

\[ R' < \rho' \]

and is determined by the formula:

\[
R' < R_0 + \frac{a_{\text{max}} - 2R_0 \cos \frac{3f_B}{2f_K}}{2a_{\text{max}} + R_0 \left(1 - \cos \frac{3f_B}{2f_K}\right)},
\]

(6)

where \( R_0 \) – radius of a geometrically regular circle (radius of the hole being machined); \( a_{\text{max}} \) – the maximum amplitude of the circular wave.

As a result, are obtained two values of the radius of the deforming element \( R \) and \( R' \) for squeezing the irregularities of the longitudinal and circular waves. The smaller of these two radii is guaranteed to provide crushing of irregularities in both circular and longitudinal waves.

3. Materials and methods of research.

The correctness of this theory of calculation and selection of the geometry of the deforming tool was checked by the example of preliminary thin boring of holes and their subsequent rolling out on the finishing and boring machine model 2705B. For finishing boring when \( V=100 \) m/min; \( S=0.08 \) mm/rev; \( D=60 \) mm, \( f_k=395 \) 1/s, \( f_B=55 \) 1/s, receive \( R<3.4 \) mm.

B The effect of the radius of the deforming element on the surface roughness was determined when processing cast iron EN-GJL-200. The initial surface roughness corresponded to \( Ra=2.5 \) µm. Increasing the radius of the deforming element to 3 mm leads to a significant reduction in surface roughness. The ball rolls along the wave, crushing the crests of irregularities, both at the tops and in the depressions of the wave. A further increase in the radius to 5 mm leads to a deterioration of the surface roughness, because the ball crushes the scallops of irregularities only at the tops of the waves. The described mechanism of crumpling of irregularities was also confirmed by a set of profilogram of the treated surface. The use of a tool with a radius less than optimal (1÷2 mm) also provides effective crumpling of irregularities, but at significantly lower feed rates, that is, with lower processing performance.

The combination of the operations of thin boring and thin plastic deformation of the surface allows not only to improve the quality of the treated surface, but also, under certain conditions, provides the opportunity to simultaneously increase the processing productivity [20-22, et al.]. The best option for combining these operations in terms of productivity is when both the cutter and the deforming tool are diametrically opposed in the same hole of the boring bar. In this case, it is necessary that the tip of the cutter be shifted forward due to the grinding by the template by the value \( L \) to prevent contact of the sphere of the deforming tool with the untreated surface (figure 2).

The value of the offset \( L \) can be determined by the dependence:

\[
L = R \sin \varphi - \left(R(1 - \cos \varphi) - t_v\right) \cdot \text{tg} \varphi + \frac{S}{2},
\]

(7)

where \( R \) – radius of the deforming element; \( \varphi \) – main angle of the cutter in the plan; \( t_v \) – depth of embedding of the deforming element in the processed material.

In case of thin plastic deformation of the surface of holes on diamond-boring machines, only the ridges of irregularities are subject to processing, so we can assume that:

\[
t_v = Rz, \quad t_v = \frac{S^2}{8r}
\]

(8)
Since the feed value $S$ is the same for boring and plastic deformation, the roughness of the rolled (smoothed) surface is determined by the formula:

$$R_{z_d} = \frac{L}{R} R_{z_p}$$

(9)

where $r$ – radius of rounded tip of the cutter; $R_{z_p}$ – the roughness of the surface after thin boring; $R_{z_d}$ - the roughness of the surface after plastic deformation.

On the other hand, during pressure treatment, the feed rate should be less than the diameter of the imprint of the deforming element on the surface to be treated, since there may be untreated areas on it. In addition, it must be taken into account that the most smooth pressure treatment will take place when at least three protrusions of irregularities are in contact with the deforming element. The number of protrusions of irregularities of the bored surface that are in contact with the deforming element is determined from the expression:

$$z = \frac{d_{\text{print}}}{S}$$

(10)

where $d_{\text{print}}$ – the diameter of the impression of the deforming element on the treated surface at an optimal indentation force equal to the plastic deformation force.

![Figure 2. The design of the tool combined hole boring and thin plastic deformation: 1– workpiece; 2– boring tool; 3– cutter; 4– ball deforming tool; 5– adjusting screw; 6-clamping screw.](image)

Substituting in the obtained expression (10) the number of protrusions of the irregularities $z = 3$ and the experimentally obtained indentation diameter for the accepted values of the diameter of the deforming element and the clamping force, it is possible to determine the feed that is optimal for these conditions.

Verification of the described methodology was carried out while thinly boring and ball rolling holes with a diameter of 60 mm in castings of cast iron EN-GJL-200. The pressing force of the deforming element to the surface to be treated was 100 N. The diameter of the imprint was checked on workpieces with the initial roughness obtained after fine boring with a cutter with $r=0,7$ mm. For the diameter of the deforming element $R=3$ mm, the estimated number of protrusions of irregularities that are in contact with it at different feeds are shown in table 1.

| $R=3$ mm | $S=0,04$ mm/rev | $S=0,08$ mm/rev | $S=0,12$ mm/rev | $S=0,16$ mm/rev |
|-----------|-----------------|-----------------|-----------------|-----------------|
| $P_f=100$ N | $R_{z_{\text{orig}}}$ | $d_{\text{print}}$ | $z$ | $R_{z_{\text{orig}}}$ | $d_{\text{print}}$ | $z$ | $R_{z_{\text{orig}}}$ | $d_{\text{print}}$ | $z$ | $R_{z_{\text{orig}}}$ | $d_{\text{print}}$ | $z$ |
| 1,12 | 0,22 | 5,5 | 1,25 | 0,245 | 3,06 | 1,87 | 0,274 | 2,28 | 2,41 | 0,283 | 1,7 |

According to the accepted method, optimal for the given initial conditions, the feed should be $S=0,08$ mm/rev. This conclusion is confirmed by the results of an experiment with the combination of boring and rolling holes. When changing the overall feed for boring and plastic deformation, both the initial (table1) and the final surface roughness are changed (figure 1). The relationship between them
agrees with the calculation by formula (9) with a sufficient degree of accuracy. The taper of the holes at a length of 60 mm when feeding $S=0.04$ mm/rev was 34 microns, and when feeding $S=0.08$ mm/rev did not exceed 2 microns. Thus, with a slight deterioration in surface roughness at the optimal feed, the accuracy and productivity of processing increased.

When processing holes with thin plastic deformation with a longitudinal feed, the resultant of all forces is decomposed into three components, as in the case of cutting: normal $P_y$, tangent $P_z$ and axial $P_x$. The main component that creates the necessary pressure in the contact zone of the deforming element and the workpiece is the normal force $P_y$.

In accordance with the task of the operation, the optimal will be the force $P_y$, which is achieved by crumpling only the surface roughness without changing the parameters of the accuracy of the shape and surface undulation achieved by the previous processing.

The value of the $P_y$ force, required to crumple the roughness of the previous processing can be determined by the following dependencies:

- when diamond smoothing
  \[ P_y = 2\pi R\sigma_T k_\mu R_z^{\text{orig}} , \]  
  (11)

- when rolling out
  \[ P_y = 5.14\pi R \cdot \sigma_T R_z^{\text{orig}} , \]  
  (12)

where $R$ – radius of the deforming element, mm; $\sigma_T$ – yield strength of the processed material, MPa; $R_z^{\text{orig}}$ – the height of the roughness of the original surface, $\mu$m; $k_\mu$ – parameter taking into account the nature of the friction of the deforming element and the workpiece.

\[ k_\mu = \frac{3\pi}{4} \frac{\arccos 2\mu}{2} + \frac{\sqrt{1 - 4\mu^2}}{2} + \frac{1}{2} \]  
(13)

where $\mu$ – coefficient of friction.

When machining on diamond-boring machines, when the deforming element rotates together with the boring bar, it is also necessary to take into account the value of the centrifugal force that acts on the deforming element. In this case, the total normal force acting on the surface to be treated is determined by the expression

\[ P_y = P_N + P_{cw} \]  
(14)

where $P_N$ – the force developed by the spring of the deforming element (setting force); $P_{cw}$ – centrifugal force acting on the deforming element.

Then:

\[ P_{cw} = \frac{mV^2}{r_{cw}} \]  
(15) \quad and \quad \[ P_y = P_N + \frac{mV^2}{r_{cw}} \]  
(16)

where $m$ – mass of the deforming element, kg; $V$ – processing speed, m/s; $r_{cw}$ – radius of the center of gravity of the deforming element, m.

Since the centrifugal force $P_{cw}$ occurs when the rod rotates during processing, regardless of the presetting force of the elastic element (spring) of the deforming tool, the setting of this element must be performed not on the calculated value of the $P_y$, but on the setting force

\[ P_N = P_y - P_{cw} = P_y - \frac{mV^2}{r_{cw}} \]  
(17)

Experimental verification of the calculation of the normal component of the deformation force was performed when processing holes with a diameter of $D=60$ mm in workpieces made of cast iron EN-GJL-200. The processing speed $V=100$ m/min, the mass of the rolling part of the roller $m=0.02$ kg, the radius of the center of gravity of the deforming element $r_{cw}=25$ mm, the initial height of the surface microns $R_z^{\text{orig}}=10$ $\mu$m, radius of the deforming element $R=3$ mm. As a result, are obtained the following force values: $P_y=97$ N; $P_{cw}=22$ N; $P_N=75$ N.

The results of rolling out the hole surfaces confirmed that as the $P_y$ force increases to 100 N, the
surface roughness decreases noticeably. Further increase in the clamping force within the range studied practically does not affect the surface roughness. Thus, the force $P_y = 100$ N for the initial conditions of the experiment can be considered optimal, which fully corresponds to the results of the calculation.

4. Conclusion
As a result of theoretical and experimental studies, the paper offers methods for calculating and selecting the geometry of the deforming tool, the feed and strain forces for combining technological operations of fine boring and fine plastic deformation of precise holes of the bored surface contribute to the simultaneous achievement of the following results:
- improving processing accuracy by balancing the forces from the cutting and deforming tools;
- significantly increase productivity and cost-effectiveness of processing;
- reducing the height of micro-roughness on the treated surface and its hardening.

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