Selection and design of tools for finishing machining of seal grooves of hydraulic cylinders

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Abstract. The most important operating performance parameters of machine components such as tightness, wear resistance, durability, and corrosion resistance largely depend on the state of their surface layer, determined by the parameters of machine processing during manufacturing. Selection of the technique for final machining of machine components is a rather difficult task, since, despite the large amount of information on technological support of the surface layer parameters, there are practically no recommendations on the quantitative estimates of the parameters of performance properties achieved in this case. Reliable functioning of hydraulic systems, their durability, and, consequently, reliable functioning and durability of the drilling rig, depend on the quality of the surface of the seal grooves. At present, turning is used for grooves machining, which in some cases does not provide the required quality indicators of the machined surface according to the surface roughness parameter. In this regard, an analysis of the possibilities of obtaining the required surface roughness using edge cutting machining techniques was conducted as well as other machining techniques ensuring uniformity of the surface roughness of seal grooves were analyzed. One of the promising processing techniques that can provide the required quality of the machined surface is a surface plastic deformation method. However, in order to use this method effectively, it is necessary to carry out an experimental study of the rolling process and determine processing conditions.

1. Introduction

Friction and wear of the seal assembly largely depend on the roughness of the surfaces of the parts along which the sealing elements slide. An increase in the height of microasperities of the sealing surface is accompanied by an increase in friction forces, and with increasing pressure this dependence appears to become significantly stronger.

In addition, frictional forces depend on the shape and uniformity of the micro-relief. An increase in the radii of the rounded edges of the microasperities significantly reduces friction forces and seal wear.

For O-seals and lip-seals, static friction is of importance; depending on the duration of the seal’s stay at rest in contact with the metal surface it can exceed 3 to 4 times the friction of movement even in the absence of pressure. The O-seal ‘sticks’ to the metal surface, filling microasperities. When the seal is displaced, certain sections of the sealing element can be cut off.

For joints with alternating fluid pressure, agroove surface and, in particular, its bottom must be machined according to the requirements to moving joints with a roughness of $R_a1.25\, \mu m$, which causes certain difficulties in meeting this requirement when applying edge cutting machining of the grooves with a blade tool. As experience indicates, application of abrasive machining for grooves...
surface final finishing is adverse, since the abrasive enters the micropores of the surfaces and subsequently causes seal wear [1, 2].

Application of rolling gives good results with regard to the quality of surfaces; however, to justify its application it is necessary to design a tool and carry out an experimental study.

The article presents the results of the study of the technology and selection of the technique for machining seal grooves for hydraulic systems of drilling rigs as well as the calculation of the selected tool support.

2. Analysis of the process of edge cutting machining of the sleeves for high pressure hydraulic cylinders

As a result of the analysis of the technological process of edge cutting machining of the sleeves for high-pressure hydraulic cylinders (Fig. 1), cutters with interchangeable polyhedral plates were selected as cutting tools [3, 4]. The following cutters are proposed:

– cutters with a boring bar toolholder FSL5—for grooves with a diameter of 38 ... 55 mm;
– cutters with a boring bar toolholder FCDG4—for grooves with a diameter of 55...125 mm.

![Figure 1. Cylinder liner.](image)

There are methods of comparative analysis of the possibilities of different processing methods to ensure the tightness and wear resistance of the joints of the surfaces of rotation. To assess the wear resistance, a relative index of wear rate was obtained based on the well-known equation of wear rate [5] and determined depending on the relative parameters of the surface layer with different methods of machining in comparison with the method taken as the base:

\[
I_n = \left( \frac{R_n W_n H_{max}}{\lambda t_m^{1/2} S_m^{1/2} H_m^{-3/2}} \right)^{1/6}
\]

where \( \lambda \) is the coefficient taking into account the change in a given number of cycles due to surface residual stresses;

\( t_m \) is the relative reference length of the profile at the level of the middle line;

\( H_m \) is the surface microhardness;

\( R_n \) is the arithmetic average roughness;

\( S_m \) is the mean spacing of profile irregularities;

\( W_z \) is the waviness parameter;

\( H_{max} \) is the maximum macro-deviation.

The tightness of joints determines their capability to withstand gas or fluid leakage [5]. According to Darcy’s law for a filtration flow, leakage, characterizing tightness, can be determined by the following formula:

\[
Q_z = \frac{\pi D \Delta p H K_n}{\mu l}
\]
where \( \mu' \) - dynamic viscosity coefficient of the sealing medium; \( l \) and \( D \) are the dimensions of the joint; \( p \) is the differential pressure; \( H \) is the thickness of the porous layer under load; \( k'' \) is the permeability coefficient.

\[
Q_z = \frac{0.0066 D A p U [0.5(H_{\text{max1}} + H_{\text{max2}}) + (W_1 + W_2) + 6(R_1 + R_2)] - y_{\text{ck}} \mu l}{\gamma}
\]

where \( U \) is constant; \( y_{\text{ck}} \) is the contact approach of parts when sliding; \( R_s \) is the arithmetic average roughness; \( W_z \) is the waviness parameter; \( H_{\text{max}} \) is the maximum macro-deviation.

The analysis of the resulting formula shows that the tightness of the joints depend not only on the geometry of the seal, the physical-mechanical properties of its material and external factors but also on the state of the contacting surfaces: roughness parameters \( R_s \), waviness \( W_z \) and macro-deviation \( H_{\text{max}} \). The capabilities of different techniques of edge cutting, diamond-abrasive machining, and finishing and strengthening treatment of external and internal revolution surfaces ensuring the specified parameters of the surface layer are presented in Table 1.

**Table 1.** Possibilities of methods of processing of surfaces of rotation in ensuring quality of the processed surface.

| Machining technique | External surface treatment | Internal surface treatment |
|---------------------|---------------------------|---------------------------|
|                     | Ra, \( \mu m \)          | Wz, \( \mu m \)          | Hmax, \( \mu m \)          | Ra, \( \mu m \)          | Wz, \( \mu m \)          | Hmax, \( \mu m \)          |
| Turning             | 0.8-2.5                   | 1.6-4.0                   | 40-100                     | 0.8-2.0                   | 2.5-6.25                   | 20-80                     |
| Grinding            | 0.2-1.25                  | 0.5-4.0                   | 10-40                      | 0.32-1.60                  | 1.25-6.25                  | 10-40                     |
| Rolling             | 0.05-1.0                  | 0.4-2.5                   | 6-40                       | 0.05-0.32                  | 1.6-5.0                    | 5-40                      |

The calculations carried out in the EXEL application showed that the wear resistance of a joint using the surface plastic deformation method can be increased twice, the tightness – by 1.3 times. Abrasive machining also gives satisfactory results but its use is adverse, since abrasive particles enter the micropores of the surfaces and subsequently cause seal wear.

### 3. Application features and advantages of PPD methods

It should be taken into account that in comparison with turning, grinding, polishing, and finishing, machining based on the plastic deformation of the thin surface layer has a number of advantages and peculiar features, including:

1. Preservation of metal fibers integrity and formation of a fine-grained structure/texture in the surface layer;
2. Absence of embedding of the loose particles of grinding wheels or polishing pastes into the machined/treated surfaces;
3. Absence of thermal defects;
4. Stability of machining processes that ensure consistent surface quality;
5. Possibility to achieve the minimum surface roughness (\( R_a = 0.1 \ldots 0.05\mu m \) or less) both on raw steel, non-ferrous alloys and on high-strength materials, preserving the original shape of the workpieces;
6. Possibility to reduce the surface roughness several times in one working stroke;
7. Creation of a favourable shape of asperities with a larger share of the bearing surface;
8. Possibility to form regular micro-reliefs with a given area of recesses for retaining lubricants;
9. Creation of a favourable compressive residual stresses in the surface layer;
10. Surface microhardness increases smoothly and steadily.
Manufactured roller burnishing tools have complex structures and are rather expensive. Purchasing such equipment without experimental substantiation of the capability of obtaining the required roughness by means of rolling is impractical. It is reasonable to design and make a roller burnishing tool of a simple structure and to carry out experimental studies on rolling out the seal grooves using it. Then, according to the results of the experiment, make the final decision on the application of rolling when processing grooves. Moreover, if the results of rolling with the designed roller burnishing tool are satisfactory, it is reasonable to refuse to purchase industrially manufactured roller burnishing tools.

Based on the analysis, scientific publications, the design of a roller burnishing tool with a spring element was chosen for machining grooves in the sleeves with the diameter of more than 50 mm [6]. The design is quite simple: it provides damping and allows rolling with a constant rolling force. Damping is necessary because in some cases rolling can occur unevenly due to the beating of the roller and the workpiece, their inaccurate installation, poor preliminary machining quality, etc. The uneven rolling force causes the waviness of the machined surface. A damping element is provided in the tool to compensate for this unevenness.

For processing the grooves in the sleeves with the diameter of less than 50 mm, a rigid roller burnishing tool was designed, since it is impossible to provide a damping element on it for design reasons.

4. Selection of rolling parameters for machining grooves
Initial data: the hole diameter is Ø40…110 mm; workpiece material is steel 35; the roller diameter is Ø25 mm.

Requirements to the machined surface: Ra is 0.63 ... 1.25 μm.

Considering the initial data and the requirements for the machined surface, let us assign the following rolling parameters:

1. Longitudinal feed [4] with Ra 0.2 ... 0.4 μm for steel 35 S = 0.20 ... 0.25 mm/rev.; rolling speed is 20 ... 200 m/min.
2. Rolling force. We assign the rolling force according to the nomogram [6, 7], P = 3,150 N for the diameter of Ø 40 mm; P = 1,600 N for the diameter of Ø 110 mm.
3. Machining techniques used for surface grooves rolling:
   to achieve a roughness of Ra = 0.04 ... 0.08 μm – turning to Ra = 1.25 ... 2.5 μm;
   to achieve a roughness of Ra = 0.16 ... 0.32 μm – turning to Ra = 2.5 ... 5.0 μm or grinding to Ra = 2.5 μm.

5. Calculation of the damping capacity of the tool
Let us carry out the calculation of stiffness of the damping element [8] of the roller burnishing tool structure, which is separated in the drawing by the plane (Fig. 1).

Assuming the width is constant, let us calculate the thickness h of the damping element of the roller burnishing tool (Fig. 2, a).

![Figure 2. Roller burnishing tool damping head(a) and design diagram(b).](image)

This structural element is a flat curved bar. The loading force is in its axial plane. The design diagrams shown in Fig.2, b.

Based on the design diagram, the bending moment in a given direction in the arbitrary cross section of the bar is determined by the expression:

$$M_p = P(R_0 \sin \varphi + l),$$

(4)
where \( P \) is the rolling force; \( l \) is the force arm; \( \varphi \) is the angle defining the position of the cross section; \( R_0 \) is the radius of curvature of the neutral layer.

For a rectangular section, the radius of curvature is determined by the formula:

\[
R_0 = \frac{R}{\ln(R/R_n)},
\]

where \( R \) is the radius of curvature of the bar axis; \( R_n \) is the outer bar radius; \( R_i \) is the inner bar radius.

To find the horizontal displacement of point \( A \), let us exert a unit force on the bar at point \( A \).

Bending moments from a unit force we denote \( M \):

\[
M = R_0 \sin \varphi + l.
\]

Displacement \( \Delta \) is found using the Mohr’s formula:

\[
\Delta = \int_0^l \frac{M_p M ds}{E J},
\]

where \( E \) is the modulus of elasticity; \( J \) is the moment of inertia for rectangular section.

Moment of inertia for rectangular section:

\[
J = \frac{bh^3}{12}.
\]

Transforming formula (7), we get:

\[
\Delta = \int_0^l \frac{M_p M ds}{E J} = \int_0^\pi \frac{PR_0 \sin \varphi + Pl(R_0 \sin \varphi + l)}{E J} R \sin \varphi + PlR_0 \sin \varphi + P l l^2 d \varphi =
\]

\[
= \frac{PR_0^2 \pi + 8R_0 l + 2l^2 \pi}{2EJ}
\]

We obtained the dependence of the displacement of the damping part of the roller burnishing tool on the normal force and its geometrical parameters.

The geometric parameters of the section of the damping part will be obtained by applying numerical calculation methods [9-11].

6. Mathematical model of designing a tool by a graphoanalytical method. Synthesis of tool design

A roller burnishing tool is an assembly unit. We present the design taking into account the relationships between the coordinate systems of the parts: cutter head \((X_B Y_B Z_B)\), roller \((X_A Y_A Z_A)\), axis \((X_D Y_D Z_D)\), holder \((X_C Y_C Z_C)\), pin \((X_E Y_E Z_E)\), bolt \((X_F Y_F Z_F)\). The graph of the elements of the roller burnishing tool structure was created (Fig.3). An automated design and structure synthesis (Fig. 4) were performed [12-15].

![Figure 3. Graph of the roller burnishing tool structure.](image-url)
7. Industrial testing of grooves machining applying rolling

Industrial grooves machining was carried out on a 16K20F3 machine in the sleeve with one groove of Ø90 for sealing and two grooves of Ø85 for guide rings (Fig. 1). Boring of the grooves was carried out with a CDG4132R4 MDGM40 CTNx2525 cutter, which allows machining with both transverse and longitudinal feeds.

Machining was carried out according to the program by three changeovers. At the third changeover, the bottom of the groove was rolled in the following modes: the rotational speed of the workpiece – 80 min⁻¹; the pressure of the roller burnishing tool – 1700 N due to the additional transverse movement of the sliding member by 1.5 mm relative to the nominal dimensions of the bottom of the grooves of Ø90 and Ø85 mm; longitudinal roller feed – 0.1 mm/rev, processing speed – 18 ... 22 m/min. The machining was carried out in two strokes of the roller burnishing tool according to the diagram shown in Fig. 5.

Workpiece inspection after machining: Ra 0.99 ... 2.93 μm. The parameter Ra 2.93 μm is only in certain places, i.e. there are risks. The roughness of the bottom of the grooves meets the requirements of the drawing.

8. Conclusions

1. The results of industrial application of the cutters showed that it was not possible to achieve a stable surface roughness of the bottom of the seal grooves using cutting. Dispersion of this indicator was Ra 0.68 ... 2.8 μm due to the influence of a large number of factors such as cutting conditions, geometry of the cutting tool, vibrations, and, mainly, the instability of the structure of the material being processed.

2. The method of surface plastic deformation for machining grooves with a new tool with a damping element makes it possible to stably obtain a roughness of the bottom of the grooves of Ra 0.99 ... 2.50, which meets the requirements of the drawing.

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