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Technological Support of Wear Resistance in the Repair of Pistons Made of Aluminum Alloys with Nickel–Phosphorus Coating

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Abstract—The article presents the study results of the surface finishing of pistons made of aluminum alloys. It is shown that centerless grinding and polishing before surface coating with a nickel-phosphorus alloy during piston repair provides good adhesive strength of the alloy to the aluminum base, and further chemical nickel plating and polishing with flexible abrasive wheels of the nickel-phosphorus alloy provide an increase in the wear resistance of pistons.

Keywords: finishing, pistons made of aluminum alloys, nickel-phosphorus coating, adhesive strength, increased wear resistance of pistons

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INTRODUCTION

Technological process of nickel plating of pistons of high-pressure compressors made of aluminum alloys (Fig. 1) during their restoration consists of preparatory operations, coating deposition operations and final operations.

Preparatory operations are aimed at ensuring the highest adhesive strength of coatings to the metal of parts. The required properties of coatings are determined by the deposition regimes and the final mechanical treatment [1, 2].

MAIN PART

Route technological process in the repair of pistons, associated with ensuring the wear resistance of the working surfaces of pistons made of cast aluminum

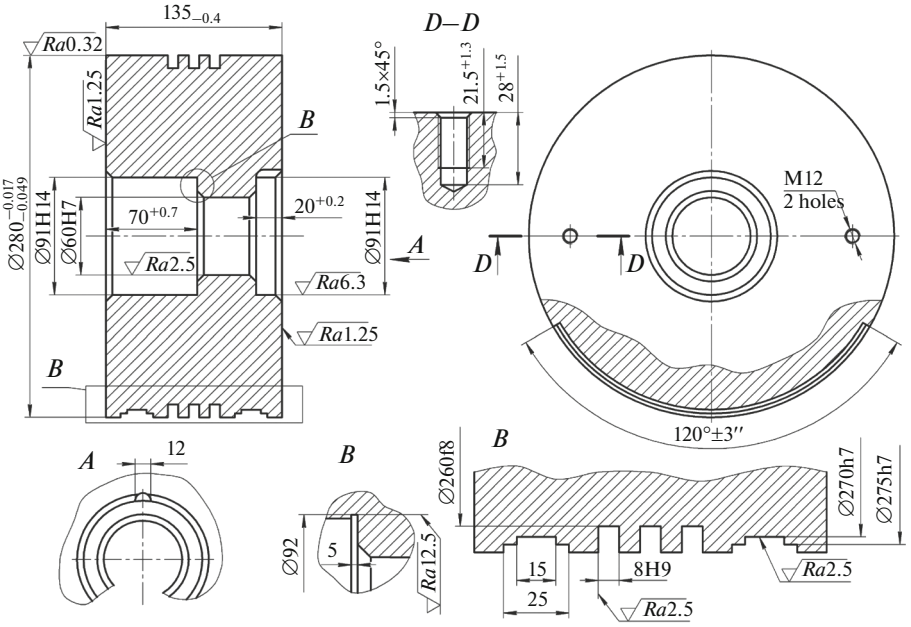

Fig. 1. High pressure compressor piston.

Table 1. The route of the piston surface treatment for coating

Operation no.	Operation and equipment	Contents of operation
1	2	3
0.05	Flushing. Washing machine NO-3753	Rinse and clean the piston
010	Troubleshooting	Detection of deviations in the shape and location of surfaces, geometric dimensions, inspection for cavities, cracks, fractures, dents on the piston
015	Centerless grinding machine. Centerless circular grinding semiautomatic machine model 3E183A	Finish the piston surface to a roughness of $Ra = 0.8$ μm to apply a nickel-phosphorus coating
020	Polishing. Polishing and grinding machine model 3B854	Polish the piston surface to roughness $Ra = 0.32$ μm for nickel-phosphorus plating
025	Control	Control the resulting dimensions
030	Zincate processing	For a strong adhesion of the chemical nickel to aluminum, it is necessary to pre-treat the piston surface with zinc
035	Etching	Remove the zinc layer of zinc in a nitric acid solution
040	Zincate processing	Re-zinc treatment of piston surface
045	Etching	Remove the zinc layer of zinc in a nitric acid solution
050	Isolation	Apply zapon varnish to areas not to be coated
055	Chemical nickel plating. Installation for nickel plating	Nickel plating of worn piston skirt surface with 150 μm coating thickness
060	Stripping (Removing the insulation)	Removing insulation materials
065	Thermal processing	Internal stress relief after nickel plating
070	Polishing. Polishing and grinding machine model 3B854	Polish piston skirt surfaces with flexible wheels until roughness $Ra = 0.32$ μm
075	Flushing. Washing machine NO-3753	Washing and cleaning the piston from insulation
080	Control	Control of coating thickness and obtained dimensions

alloy grade AL1 (GOST 2685–75) with a hardness of 85–90 HB, is shown in Table 1.

Centerless grinding by the method of transverse feed (plunging method) is carried out by the transverse feed of the driving circle towards the grinding wheel. Before this, the part is placed on a support from above or from the side. At the end of the grinding of part, when the required size is reached, the leading wheel is retracted, the part is removed and a new one is laid (Fig. 2).

For centerless grinding of the outer surface of piston, the following operating parameters were chosen: depth of cut $t = 0.015$ mm, grinding wheel feed $s_1 = 0.001$ mm per one revolution of part, and the driving wheel feed $s_2 = 0.003$ mm per one revolution of part. Rotational speeds of the grinding and driving wheels are taken to be $n_1 = 2886$ min^{-1}, and $n_2 = 200$ min^{-1}, respectively. Cutting speed $V = 10$ m/s. Centerless grinding provides $Ra = 0.8$ μm. Grinding wheel brand: grinding wheel 1300 × 32 × 127 GOST R 52781–2007, and the leading wheel—grinding wheel 1300 × 32 × 127 GOST R 52781-2007. Grinding wheel parameters: grade 64C (green silicon carbide), grit size 25–16 (F60-F90), hardness CM1, ceramic bond (K). Cutting fluid used for centerless grinding is Akvol 6 (2–10% aqueous solution). After the centerless grinding operation, the piston is polished on a semi-automatic polishing and grinding machine (Fig. 3).

Polishing is the process of processing materials to obtain a mirror-like surface finish. The purpose of the polishing process is to remove traces of previous processing and various surface irregularities (strokes, scratches, shallow shells and other defects) in order to obtain a smooth surface with a high ability to reflect a light. Various explanations of mechanism of the polishing process can be summarized in the following three directions:

• mechanical polishing—when the mechanism of the process is explained by the removal of microroughnesses from the surface layer, and the course of process is explained by such mechanical material properties as hardness and plasticity;

• physical polishing—when the main factors determining the polishing process are the melting point and thermal conductivity of the polished material;

• chemical polishing—when the polishing process is explained mainly by the removal of oxide films that

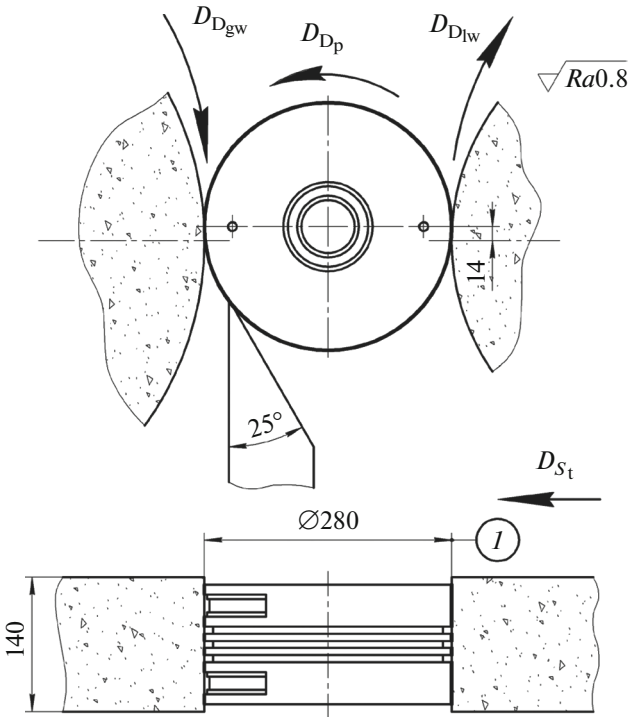

Fig. 2. Schematic diagram of centerless grinding of a piston by the plunge cut method.

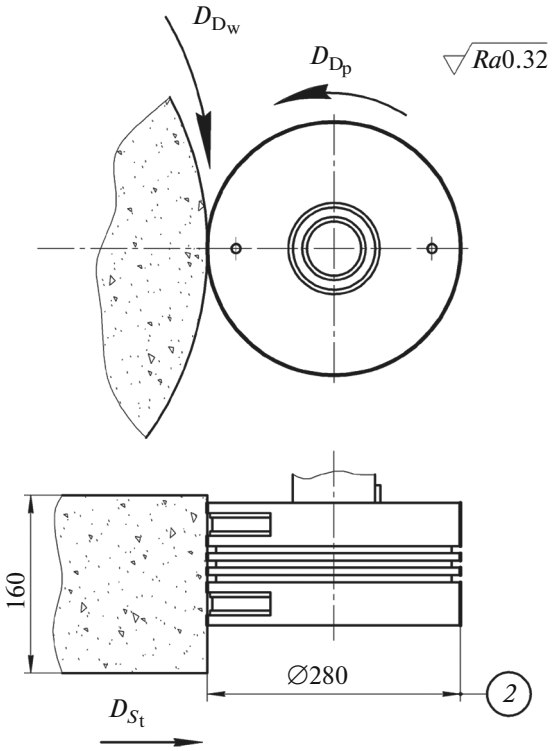

Fig. 3. Piston polishing scheme.

are constantly formed under the influence of environment.

Based on practical observations, we can conclude that the polishing process is a complex of mechanical, physical, electrical and chemical phenomena that are closely related and interrelated, and separately change up or down depending on the type of material being polished, polishing tool, processing modes and external environment. Polishing is most widely used in the preparation of surfaces for electroplating and chemical coatings, as well as to impart shine to parts after coating. This can be achieved by other processing methods, such as honing, lapping, super-finishing, but these processes require special rather complex equipment, properly selected tools and modes and justify themselves only in case when besides the quality of machined surface the specified accuracy is required. Therefore, to improve the appearance of the treated surfaces, polishing has become widespread, since it is carried out on very simple machines, and the polishing tools can be easily made in any conditions from felt, leather, fabric and other materials. Linear removal of metal during polishing is, as a rule, 0.01–0.03 mm. Any metals and alloys of different hardness, from aluminum alloys to hardened and stainless steels and cast irons, can be polished.

There are two types of polishing: rough (preliminary) and finishing (final). Rough polishing is used for mechanical removal of surface irregularities using free (loose) or adhesive-fixed abrasive grains on the working surface of flexible abrasive wheels and strips. Finishing polishing is carried out with free fine-grained abrasive powders or soft flexible wheels and strips coated with fine polishing pastes. Depending on the shape of the surface to be treated, the polishing wheels have to be sharpened and profiled. In single production, profiling is usually done by hand. Since this operation requires a highly skilled worker and is unsafe, it is not recommended to use it. It is expedient to carry out profiling with a grinding wheel having a profile opposite to that of the polishing wheel being machined. During polishing, 50–25 grit wheels with an open structure rotate towards each other, and when approaching, the grinding wheel removes all irregularities from the polishing wheel, giving it the desired shape.

After turning and profiling, abrasive grains are applied to the working surface of polishing wheel and fixed them by knurling in the following order. New wheels that have not yet been in work are primed several times with an adhesive solution, allowing each layer of glue to dry. Then the glued surface is lubricated with another layer of solution and immediately abrasive grains heated to a temperature of 40–45°C are rolled manually or on special machines. Rolling can be single-layer and multi-layer. With multi-layer rolling, each subsequent layer is applied after the previous one has dried. On felt wheels, the first layer is rolled using skin glue, and the subsequent ones are

rolled with liquid glass. On cotton circles, the first layer of grain can also be fixed with liquid glass, since the fabric adheres well to it. On paper wheels, the abrasive grain is fixed with silicate glue. The knurled circles are dried in natural or artificial conditions.

Polishing of parts made of non-ferrous alloys with an initial surface roughness of $Ra = 2.5$ microns at the required $Ra = 0.08$ microns is carried out in three operations. Rough polishing to $Ra = 0.63–1.25$ microns—with cotton wheels rolled with green silicon carbide grit 8–12 and black grit 16–25 (F60-F90) for copper and 10–12 (F100-F120) for brass. Pre—polishing to $Ra = 0.63–0.32$ microns with felt or cotton wheels rolled with electrocorundum, grit 6–4 (F180–F220) for aluminum alloys, black silicon carbide, grit 8–12 (F100–F150) for copper and 5–6 (F180–F220). Final polishing to $Ra = 0.32– 0.08$ microns is carried out with wheels with a paste based on chromium oxide for aluminum alloys and based on iron oxide and alumina for copper and brass. In practice, the polishing allowance ranges from 0.12 to 0.3 mm. The most common tool for grinding are wheels of various hardness made of felt or other material, on which an abrasive is applied with an adhesive bond. The lower the hardness of the material, the more flexible the abrasive wheel used for its processing should be. Highly profiled parts, regardless of the hardness of material, are recommended to be processed with soft (flexible) wheels. When polishing with an elastic wheel coated with a paste or suspension, the contact pressure of polishing pad on the surface to be treated has a significant effect. With an increase in pressure, the intensity of the polishing process rises to certain limits, and in the future, exceeding the optimal pressure value not only reduces the processing quality, but also productivity, the polishing pad wears out prematurely, and there is a noticeable heating of the processed parts.

When choosing the contact pressure value, the material properties to be polished are taken into account. Polishing of hard materials is carried out with high specific pressures of polishing wheel on the surface to be treated, in comparison with soft material. In the practice of material polishing, the softer the material, the easier it is to remove the metal layer, but the more difficult it is to achieve a uniform stroke. In some cases, this processing mode is subjectively evaluated by those who perform polishing. Thus, for example, when it is required to remove a large layer, the polished part is pressed against the polishing pad with great effort. In this case, the polishing process proceeds more intensively, but the product heats up strongly and the surface quality decreases. When polishing, a distinction is made between the total cutting force with a polishing wheel P_z and the cutting force—scratching with a single grain. As a result of the conducted one-factor experiments, we obtain the following empirical dependence for determining the cutting force P_z(N) during polishing [1, 2]:

$$P_z = C_{P_z} V_p^{0.9} S_t t^{0.5}, \quad (1)$$

where C_{P_z} is a coefficient that characterizes the cutting conditions for a specific material grade of polished part, V_p is the speed of the workpiece, S_t is the transverse feed of polishing wheel to the part, t is the polishing depth.

For example, we calculate the cutting force when polishing an aluminum alloy piston with a felt wheel at $C_{P_z} = 15$, $V_p = 15$ m/min, $S_t = 0.001$ mm/rev, and $t = 0.01$ mm.

$$P_z = 15 \times 15^{0.9} \times 0.01 \times 0.01^{0.5} \approx 0.225 \text{ N}.$$

Contact pressure when polishing is defined as follows:

$$p = \frac{P_z}{F}. \quad (2)$$

where P_z is the tangential component of the cutting force, F is the average instantaneous section of layer removed by all abrasive grains.

In accordance with [1, 2] F is determined by the following relationship:

$$F = \frac{V_p}{60 V_w} t S_t, \quad (3)$$

where V_p is the rotation speed of part, m/min; V_w is the wheel rotation speed, m/s. Taking in accordance with the reference data $V_w = 20$ m/s, $V_p = 15$ m/min, $t = 0.01$ mm and $S_t = 0.001$ mm/rev, we obtain $F = 1.25 \times 10^{-3}$ m^2. Let's calculate the contact pressure of polishing wheel on the part:

$$p = \frac{0.225}{1.25 \times 10^{-3}} = 180 \text{ N/m}^2 = 0.018 \text{ MPa}.$$

Comparison of the obtained data with the results of [3–5] experimental studies of contact pressure during polishing of parts made of aluminum alloys showed that they vary in the range of 0.01–0.04 MPa, which indicates sufficient accuracy of the proposed calculation method. After applying the nickel–phosphorus coating, it was polished on a polishing machine with similar operating parameters. In this case, the polishing depth is $t = 0.05$ mm. A wear test showed that the nickel-plated sample wore out almost 20 times less than the uncoated sample. The total mass loss of the AL1–Ni–P-coating friction pair is almost 24 times less than that of the AL1–AL1 pair. The study of the wear resistance of coating was carried out by the gravimetric method at various contact loads on the setup shown in Fig. 4. The rubbing pair is an aluminum alloy cylinder with a diameter of 0.8 mm and a coated sample. The coated sample performs a reciprocating motion; under the action of the tip, the coating under study is abraded. Friction force was determined using

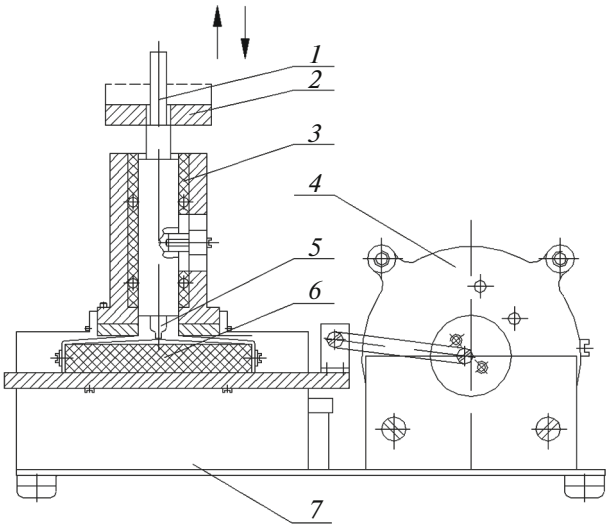

Fig. 4. Installation scheme for testing the coating for wear resistance: (*1*) rod, (*2*) weights, (*3*) separator, (*4*) RD-09 electric motor, (*5*) tip, (6) coated sample, (*7*) device base.

a G10-5 gramometer, the friction coefficient was calculated by the formula:

$$f = F/p, \quad (4)$$

where F is the friction force, N; p is load, N.

First, a sample with an untreated coating was tested. With a contact load of 0.98 N and a friction force of 0.137 N, the friction coefficient was 0.14, and the wear was 2.3 mg. When testing a sample with a coating after processing, the friction coefficient was equal to 0.12 ($F = 0.115$ N), and the wear amounted to 1.9 mg.

CONCLUSIONS

Thus, after mechanical treatment of nickel-phosphorus coatings, the wear resistance in process of applying the repair technology increases by an average of 12–15%. This phenomenon is explained by a decrease in the friction force after machining, which is associated with an increase in the contact area of the rubbing surfaces. After nickel plating, heat treatment was carried out for 2–2.5 h at a temperature of 200–220°C to relieve internal stresses.

To impart the initial roughness to the restored surface, polishing with flexible wheels is used as the final operation.

CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interest.

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