New technology for restoring Babbitt coatings

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Abstract. The reasons for reducing the durability of sliding bearings and the factors formed both at the stage of their manufacture and during operation are considered. Taking into account the types of destruction of sliding bearing coatings (exfoliation, disintegration of individual sections, field failure) the need for developing technological recommendations for their repair is demonstrated. The analysis of existing technological methods for restoring worn surfaces of parts is shown. The technique for applying the method of electrospark alloying to repair bearing liners is represented. The technologies of applying combined electrospark coatings to increase the adhesion strength of the substrate to the antifriction Babbit layer are described. There have been revealed the correlation dependences of the quality characteristics of the Babbit coatings restored by the method of electrospark alloying versus the technological parameters of the process. This makes it possible to significantly implement the methodology for controlling the surface layer quality while manufacturing and repairing the products with Babbit coatings. A technique has been developed for determining the mass transfer equation constants and for predicting the roughness. The mathematical models have been proposed to specify the quality parameters of the layers being formed in the course of the Babbit coating restoration based on the energy parameters of the electrospark alloying plant.

1. Introduction
The availability of increased speeds, the use of flexible rotors, cantilever and aerodynamic loads, the appearance of self-oscillations and other factors complicated the problem to provide for regulating the characteristics of the system of the “rotor-bearing” type.

Currently it is known three fundamentally different kinds of rotors supports - it rolling bearings, sliding bearings (SB) and active magnetic bearings [1,2].

It is preferable to use various types of SB as high-speed rotor supports in view of their following advantages [3]:
• no wear at the fluid friction mode;
• practically unlimited maximum speed;
• small overall dimensions in the radial direction and weight;
• have the ability to self-center the shaft;
• the lubricating layer of SB has good damping characteristics (104...105 N∙s/m) [4].
The main disadvantage of the SB can be highlighted the high frictional moment during the start-stop period, which leads to rapid wear of the bearing surfaces and deterioration of the support performance up to failure [5].

To minimize the instability and vibration activity of this system, various SB designs are now being developed. Design of thrust SB with increased bearing capacity [6]. Design of radial SB with hydrostatic liners [7].

Problems of improving the SB quality are solved not only by design, but also by technological methods:
- increasing the strength of the bearing journals of the shafts [8-10];
- increasing the adhesion strength of the antifriction Babbitt layer with the substrate [11];
- the formation of a special relief [12];
- applying Babbitt by electrospark alloying (ESA) [13].

For the rotary machines with multiple starts and stops, the actual problem is to ensure not only the increased reliability of the sliding bearings, but also the possibility of their effective repair.

According to statistics, up to 32% of failures of turbocompressor units operating in the gas industry occur due to disruption of the Babbitt sliding bearing (SB) operation, most often this is due to the destruction and wear of the antifriction layer of bearing liners (BL), which leads to dynamic instability of the equipment. Under normal operating conditions, the SB failure is a consequence of various types of wear: cavitation, abrasive wear, wear due to plastic strain, and fatigue wear.

In this regard, the problem of improving the performance and resource of Babbitt SBs not only during their manufacture, but also during their repair is important and relevant.

2. Analysis of main achievements and publications

In the course of manufacturing the SB liners, the antifriction alloys based on tin and lead (Babbitts) are most widely used. The main requirements for the antifriction alloys are determined by the working conditions of the BL.

In [14], the quality of the coating is characterized by the following properties: adhesion strength of the coating to the base, cohesive strength of the sprayed layer, porosity, uniform thickness of the coating, level of residual stresses, uniformity of the coating structure and properties.

In [15], it is stated that the adhesion strength of the iron coatings to the material of the part depends on a lot of factors and conditions of the technological process. The decisive influence on an adhesion strength index is determined by the chemical composition of the part material, its heat treatment, mechanical conditions of the required electrochemical processes, and the initial and subsequent modes of the electrodeposition procedures.

Most processes for restoring surfaces of parts should be considered as alternatives. The same coating material can be applied in several ways. In this case, both the properties of the coating and the costs for its application can vary significantly.

In [16], the processes for applying Babbit to the bases of the SB liners are described, these are: manual babbitting, centrifugal babbitting, babbitting under pressure, thermal spraying. As a rule, in all cases, the basis for spraying is steel of grade 20 (GOST 1050-88). Although the other materials having high adhesion strength to tin can be used. Those are: steel of grade 10, steel of grade 15, bronze, brass. When pouring the liners with a cast iron base, the surfaces whereon the Babbitt layer is applied are nickelized [17].

Over the recent years, several new methods have been used for manufacturing and repairing the sliding bearings: galvanic build-up and stamping in the temperature range [17, 18].

One of the significant reasons for the SB failure is poor-quality Babbitt lining, which is manifested in its peeling (Fig. 1 a, b), chipping of individual sections (Fig. 1, b), and destruction during operation (Fig. 1 b, c).
Figure 1. Destruction of the Babbit layer of SB as a result of poor-quality Babbitt lining.

The quality of the babbit abutment to the body of the liner, as a rule, is checked by the method of (Fig. 2). visible dye penetrant test.

Figure 2. Checking the quality of the antifriction layer adhesion by the method of visible dye penetrant test.

There are other methods: ultrasound testing, visual inspection, by tapping with a light hammer, by providing immersion for of 1.5 to 2 hours in a bath with kerosene followed by dry wiping and squeezing kerosene or air bubbles with human’s fingers, etc.

From the foregoing, it follows that the factors being formed both at the manufacturing stage and during operation are the cause of the decrease in the durability of the sliding bearings (SB).

Acceleration of wear and development of damages and rubbing surfaces after the running-in period depends on the presence of incorrigible micro- and sometimes macro-damages formed on the friction surface in the course of the running-in procedure. Thus, when the Babbit of B83 mark is used in the thin-layer bearings, the microcracks are formed in cubic SnSb crystals, which subsequently become the crack development centers, and now it will occur in the volume of the entire layer [19].

Recently, to improve the quality of the surface layers of machine parts, the method of electrospark alloying (ESA), namely, the process of transferring material to the surface of an item by a spark electric discharge, has become increasingly important [20–23]. In fig. 3 shows the ESA process of the journal of the rotor shaft of a centrifugal compressor (a) and the journal of a gear wheel (b).

Figure 3. ESA of bearing journals of the rotor shaft (a) and gears of a gear wheel (b).
Specific features of ESA that attract technologists are: locality of action, low energy consumption, lack of volumetric heating of the material, strong connection of the applied material with the base, ease of automation, the possibility of combining operations, etc. [24–26]. Using various electrode materials and the environment, applying the ESA method, it is possible to carry out processes that are alternative to the chemical-thermal treatment, but with significantly lower costs [27, 28]. So, using a graphite electrode and saturating the surface of a part with carbon, it is possible to carry out the carburizing process (CESA), with an aluminum electrode - it is possible to carry out the aluminizing, conducting ESA in a nitrogen environment - nitriding, etc. [29]. Moreover, the ESA technology is environmentally and technologically safe.

One of the characteristic features of the ESA method is the limitation in the thickness of the formed surface layer. According to [30], the research by the scientists and specialists in the near and far abroad is mainly aimed at creating new electrode materials for ESA, studying the structures and properties of the coatings [31–34].

The problem of increasing the thickness of the coating and the quality of the coating surface is considered in the papers where the creation of a coating formed by a single electrode material, for example, CuSi3Mn1 bronze, when applying the “hilly” coatings [35,36], the formation of the multilayer combined electrospark coatings (CECA), in which hard wear – resistant materials are combined with soft antifriction metals [37–42], or the ESA technology is combined with other repair technologies, for example, laser process [43–45], surface plastic strain (SPS) [46–51], metal-polymer material application (MPM) [52, 53] and others, have been studied.

The papers [13,54,55] are devoted to the problem of the formation of thick-layer babbit coatings both when manufacturing the bearing liners (BL) and repairing thereof. In [11], there are disclosed the results of the studies of the adhesion strength of an antifriction layer of Babbitt (B83 and B88) with the substrate made of steel 20, which were carried out in the course of the compression tests according to ISO 4386-2-99 by tearing the antifriction Babbitt layer from the substrate.

It has been stated that the use of the copper transition layers deposited by the ESA method in a protective medium (argon) increases the adhesion strength of the steel substrate to the antifriction babbit layer by 35% if compared to the traditional technology (steel 20 + Babbitt).

It should be noted that all methods for monitoring the filling of Babbitt cannot give a full guarantee of its quality. A significant drawback of Babbitt is their low fatigue resistance, especially at temperatures above 100 °C. With a decrease in the thickness of the bearing, the fatigue resistance increases, while it is allowed the minimum thickness of 0.25 to 0.4 mm for the Babbitt lining layer.

Thus, the thinner the coating formed by the ESA method, the greater the load it perceives within the boundaries of the allowable working gap between the BL and the shaft. In addition, a thin coating reduces the cost of manufacturing a Babbitt BL.

Earlier, in [13], the authors described their process using the ESA method which was developed to form the Babbitt coatings on steel 20 comprising intermediate coatings with a sublayer of copper, tin bronze and tin. In [20], it was established that the most durable bond between steel 20 and Babbitt was provided by an intermediate layer of copper.

The obtained combined ESA coating has a minimum thickness of 250 microns and a maximum thickness of 1.0 mm. A further increase in the thickness of the layer is possible, but not advisable due to the increase in processing time and decrease in mechanical strength of Babbitt. The liners of the sliding bearings processed by the proposed method are characterized by their high reliability and durability.

Taking into account the different types of SB damages, there is a need to develop the technological recommendations for their repair. Such technologies are relevant for the floating rings of the compressor equipment sealing units, as well as for the thrust and journal sliding bearings, and also for the support pins of the planetary multipliers gears, etc.

Thus, the aim of the work is to improve the technology for restoring Babbitt coatings by identifying the dependence of the qualitative characteristics of the restored layers obtained by the ESA
method on the technological parameters of the process, which would significantly allow implementing the methodology for controlling the quality of surface layers when manufacturing and repairing of the items covered with Babbitt coatings.

3. Research methodology
For research, the samples made of steel 20 and sized 10×10×6 mm were used as the cathodes (parts) for the studies of the cathode weight gain (ΔPc), the deposited layer thickness (Δh), and the surface roughness (Rz) (Fig. 4). The material of steel 20 complies with GOST 1050-88 requirements.

![Figure 4. Flat sample sized 10×10×6 mm (a) and the Elitron-52A plant designed for performing fine and rough ESA (b).](image)

The surfaces of the samples were ground to $Ra = 0.5$ microns. Initially, copper was applied to the surfaces of the samples by the ESA method at the Elitron-52A plant (Fig. 4, b). In order to form a coating with maximum continuity and minimum roughness, the alloying process was carried out in stages, first at the discharge energy of $W_p = 0.27$ J, then at $W_p = 0.05$ J. The layer thickness decreased from 0.08 mm to 0.05 mm. The continuity of the layer was 100% (Fig. 5, a).

It should be noted that when applying copper at the 2nd stage with the use of a lower alloying mode, the electric discharges occur along the protrusions of the roughness of the previously deposited layer, as a result of which those protrusions are partially collapsed and deformed, which results in decreasing the surface roughness and increasing its continuity.

The copper electrodes are periodically oxidized, which significantly affects the quality of the formed coatings. With a prolonged process of alloying, there appear burns, the electrodes are mechanically destroyed and individual particles of up to 0.2 mm in size are welded to the alloyed surface. Subsequent treatment with a metal brush eliminates possible disadvantages and thus significantly improves the quality of the formed surface.

Further, the Babbitt of B88 mark was applied in various modes on the copper coatings of the separate samples. The Babbitt was checked for the compliance with GOST 1320 – 74 by the basic elements.

Taking into consideration the specific features of alloying with Babbitt and in order to form layers with maximum continuity, the formation of the Babbitt layer proceeded in stages. First, to obtain 100% coating continuity and subsequently apply the Babbitt with a lower surface roughness, there was used a mode with $W_p = 0.05$ J, and then some other samples were processed at different discharge energies, namely: $W_p = 0.31; 0.53; 0.9; 2.6; 4.6,$ and $6.8$ J.

It should be noted that when tin-based Babbitt is applied onto a copper substrate with the pulse energy of more than 0.05 J, the quality of the coating sharply decreases (the continuity decreases and the roughness increases). Babbitt is transferred in the form of individual droplets, and the larger the discharge energy, the larger are the droplet sizes and the smaller is the continuity of the coating. The initially applied layer of Babbitt at $W_p = 0.05$ J accumulates heat and increases the droplet spreading time when the subsequent layer of Babbitt is deposited under the high alloying conditions (Fig. 5, b).
Further, in order to reduce the surface roughness, the coating was treated with the use of the EEA (ESA) process by the graphite electrode of EG-4 grade (OST 229-83) at \( W_p = 0.39 \) J, and then at \( W_p = 0.13 \) J. Before each treatment with graphite, the coating surface was brushed.

To rehearse the technology for the restoration of Babbitt coatings, the treatment procedures with a graphite electrode were carried out each to obtaining the specific thickness of the deposited layer of 0.3; 0.5; 0.8; 1.2; 1.5 and 1.6 mm formed, respectively, at \( W_p = 0.31; 0.53; 0.9; 2.6; 4.6 \) and 6.8 J.

While the ESA process with a graphite electrode, electric discharges flow along the protrusions of the microroughnesses of the surface of the previously deposited coating. In this case, there occurs their melting, reducing the height of the microroughness, and spreading the coating material over a large area, thereby increasing the continuity of the Babbitt coating.

To improve the quality of the formed coatings, after each stage of the ESA process, the surface obtained was treated with a wire brush. The formed coating was carefully inspected using a magnifier of 6–time magnification. In the case of identifying untreated areas, the ESA process was repeated.

The thickness of the coating layer was measured with a micrometer, and the surface roughness was determined with the use of the Profilograph - Profilometer device of 250 model of the «Kalibr» factory production by reading and processing profilograms. The continuity of the coating was evaluated visually.

### 4. Research results

In Table 1, there are shown the results of measuring cathode gain \((\Delta P_c)\), deposited layer thickness \((\Delta h)\), and surface roughness \((R_z)\) after applying B88 Babbitt onto the sample of steel 20 precoated with copper before and after the ESA process by graphite.

Based on the data of Table 1, it can be noted that between average values of the cathode gain \((\Delta P_c)\) and discharge energy \((W_p)\) in the first approximation, there is an exponential dependence (Fig. 6, a). In addition, the analysis of the Tables data shows that with increasing the discharge energy there increases cathode gain. In this case, the cathode gain increases the stronger, the greater the activation energy of mass transfer \(E\) becomes.

Based on the experimental dependence of \(\Delta P_c\) on \(W_p^{-1}\) (decreasing exponent) (Fig. 6, b,) it can be concluded that \(\ln \Delta P_c\) is proportional to \((-W_p)^{-1}\) and the value of \(E\) (Fig. 6, c), i.e.

\[
\ln \Delta P_c \sim (-W_p)^{-1}, E
\]

Passing from the approximate equality to exact one, we have:

\[
\Delta P_c = c \cdot e^{\frac{-E}{W_p}}
\]

where \(C = \Delta P_{cs}\) (\(\Delta P_{cs}\) - gain of saturation).
Table 1. Quality indices (average values) of the coating formed with the use of the ESA process on steel 20 by sequentially applying copper and Babbitt at different ESA discharge energies and productivities before and after processing with graphite.

| Discharge energy, (Wp), J | Productivity, Φ, sm²/min | Deposited coating thickness, Δh, mm | Cathode gain, ΔРc, g·10⁴/sm² | Roughness, Rz, μm | Coating thickness, Δh, mm | Cathode gain, ΔРc, g·10⁴/sm² | Roughness, Rz, μm |
|--------------------------|---------------------------|------------------------------------|-------------------------------|-----------------|---------------------------|-------------------------------|-----------------|
| 0.31                     | 1.5                       | 0.37                               | 2.4255                        | 64.3            | 0.3                       | 2.205                        | 9.1             |
| 0.53                     | 2.0                       | 0.68                               | 4.8425                        | 74.7            | 0.5                       | 3.675                        | 8.7             |
| 0.90                     | 2.5                       | 0.89                               | 6.468                         | 85.3            | 0.8                       | 5.880                        | 8.9             |
| 2.60                     | 3.0                       | 1.34                               | 9.902                         | 112.4           | 1.2                       | 8.820                        | 8.6             |
| 4.60                     | 3.5                       | 1.61                               | 12.1275                       | 125.7           | 1.5                       | 11.025                       | 8.5             |
| 6.80                     | 4.0                       | 1.75                               | 12.936                        | 131.2           | 1.6                       | 11.760                       | 8.1             |

Figure 6. Dependence of cathode gain (ΔPc) on: a - (Wp); b - (Wp)⁻¹; c - lnΔPc from (-Wp)⁻¹.
Then
\[ \Delta P_{cs} = \Delta P_{cs} \cdot e^{\frac{-E}{W_p}} \]  
(3)

Dependence (3) will be called the babbit mass transfer equation.

Taking in (3)
\[ E = W_p, \]  
(4)

we have:
\[ \frac{\Delta P_{cs}}{\Delta P_{cs}} = e^{-1} \]  
(5)

Hence \( E \) is a physical quantity equal to such a discharge energy at which \( \Delta P_{cs} \) is \( e \) times less than \( \Delta P_{cs} \).

Here we call it as the ESA constant. Dimension \([E] = \text{J} \).

In order to pass from the cathode gain to the growth (growth means layer thickness (linear dimension \( \Delta h_l \)) by which the item changed as a result of the ESA process), it is necessary to write the mass transfer equation (3) in the form of
\[ \Delta h_l \cdot S \cdot r_l = \Delta h_{ls} \cdot S \cdot r_{ls} \cdot e^{\frac{-E}{W_p}} \]  
(6)

where \( S \) is the ESA area,
\( r_l, r_{ls} \), respectively, is the density of the alloyed layer and the saturation layer,
\( \Delta h_{ls} \) (i.e., the layer of the maximum thickness achieved for a specified pair of electrode materials - anode and cathode).

After the necessary transformations, we have
\[ \Delta h_f = \Delta h_{ls} \cdot \frac{r_{ls}}{r_l} \cdot e^{\frac{-E}{W_p}} \]  
(7)

Thus, when determining the thickness of the ESA layer, it is necessary to correct for a change in the density of the alloyed layer.

Substituting relation (4) into (7), we have:
\[ \Delta h_f = \Delta h_{ls} \cdot \frac{r_{ls}}{r_l} \cdot e^{-1} \]  
(8)

From here
\[ \frac{\Delta h_f}{\Delta h_{ls}} \cdot \frac{r_l}{r_{ls}} = e^{-1} \]  
(9)

Therefore, \( E \) is a physical quantity equal to the discharge energy at which \( \Delta h_f r_l \) is \( e \) times less than \( \Delta h_{ls} r_{ls} \).

Here we note that at \( r_{ls} = r_l \), \( \Delta h_f / \Delta h_{ls} = e^{-1} \).

Based on the data of Table 1, it can be noted that between the cathode (growth) gain (\( \Delta h_l \)) and the discharge energy (\( W_p \)), to the first approximation, there is an exponential dependence (Fig. 7, a). In addition, the analysis of the Table shows that with increasing \( W_p \), the cathode gain increases the stronger, the greater the activation energy of mass transfer \( E \) becomes.

Based on the experimental dependence of \( \Delta h_l \) on \( W_p^{-1} \) (decreasing exponent) (Fig. 7, b), it can be concluded that \( \ln \Delta h_l \) is proportional to \((-W_p)^{-1} \) and the value of \( E \) (Fig. 7, c).

The mass transfer affects not only the amount of material transferred from the anode to the cathode and the cathode growth, but also the roughness of the surface layer formed. For the specified pair of anode and cathode electrodes, the surface roughness is formed when the discharge energy (\( W_{p_{th}} \)) is different from the activation energy of the mass transfer process.
There is an exponentially decreasing dependence between the roughness of the surface layer $R_z$ and the reciprocal of the discharge energy $W_p^{-1}$ till the saturation period exists, when $\Delta R_z = \Delta R_z_s = \Delta R_{z_{\text{max}}}$.

With an increase in the discharge energy, the surface roughness increases the stronger, the greater is the discharge energy spent on the formation of the surface roughness $E_{\Delta R_z}$.

Based on the experimental dependence of $\Delta R_z$ on $W_p^{-1}$ (decreasing exponent), it can be concluded that $\Delta R_z$ is proportional to $(-W_p)^{-1}$ and the value of $E_{\Delta R_z}$, i.e.

$$\ln \Delta R_z = (-W_p)^{-1}, E_{\Delta R_z}$$

(10)

Passing from approximate equality to the exact one, we have:

$$\Delta R_z = c \cdot e^{-\frac{E_{\Delta R_z}}{W_p}}$$

(11)

![Figure 7](image)

**Figure 7.** Dependence of the cathode gain ($\Delta h$) on: a - $(W_p)$; b - $(W_p)^{-1}$; and $\ln \Delta h$ on $(W_p)^{-1}$.
where \( C = \Delta R_z \) (\( \Delta R_z \) is the saturation roughness, i.e., the largest one for the specified pair of electrodes).

Then

\[
\Delta R_z = \Delta R_z s \cdot e^{-\frac{E_{\Delta R_z}}{W_p}}
\]

(12)

Dependence (12) will be called the surface roughness prediction equation for the ESA process.

Taking in (12)

\[ E_{\Delta R_z} = W_p, \]

(13)

we have:

\[
\Delta R_z / \Delta R_{zs} = e^\frac{-E_{\Delta R_z}}{W_p}
\]

(14)

Hence, \( E_{\Delta R_z} \) is a critical quantity equal to such a discharge energy at which \( \Delta R_z \) is \( e \) times less than \( \Delta R_{zs} \).

Here we call it the ESA constant. Dimension \([E \Delta R_z] = J\).

Using the above dependencies (1-14) and the data in Table 1, it can be determined the coefficients of the equations of gain (3), growth (7), and roughness (12) for the coating as functions of the discharge energy (Table 2).

**Table 2. Coefficients of the equations of the dependences of gain (3), growth (7) and roughness (12) of the coating on the discharge energy.**

| \( \Delta P_c \) | \( \Delta P_c \) after ESA with graphite | \( \Delta h_l \) | \( \Delta h_l \) after ESA with graphite | Roughness, \( R_z \) |
|----------------|----------------------------------------|----------------|----------------------------------------|------------------|
| 12.9372        | 11.6301                                | 1.7150         | 1.5760                                  | 125.0858         |
| 0.5281         | E                                      | E, J           | E, J                                    | E_{\Delta R_z}, J|

When restoring a layer of Babbitt, destroyed up to the substrate itself as a result of peeling, chipping, or for any other reason (Fig. 1, a, b), it is necessary to brush off the damaged area, measure the thickness of the Babbitt lining, degrease the surface of the substrate to be restored, and using the ESA method, apply the coating with copper electrode instrument in stages first at the discharge energy of \( W_p = 0.27 \) J, then at \( W_p = 0.05 \) J.

Having known the final thickness of the layer to be restored \( \Delta h_l \) (after the ESA process by graphite) and the coefficients: \( \Delta h_{ls} = 1.5760 \) mm and \( E = 0.5438 \) J (Table 2), it is possible to determine the discharge energy \( W_p \) from (7).

And with \( r_{ls} = r_l \),

\[
W_p = E / \ln(\Delta h_l / \Delta h_{ls})
\]

(15)

Having known the discharge energy \( W_p \) and the coefficients: \( \Delta h_{ls} = 1.7150 \) mm and \( E = 0.4882 \) J (Table 2), using (7), we can determine the thickness of the Babbitt coating \( \Delta h_l \) applied before the ESA process performed with graphite (Fig. 8).

In addition, by using the known discharge energy and coefficients: \( \Delta R_z = 125.0858 \) \( \mu \)m and \( E_{\Delta R_z} = 0.2321 \) J (Table 2), it is possible to determine the roughness of the Babbitt coating before the ESA process with graphite.

It should be noted that the density of Babbitt, according to GOST 1320-74, is 7.35 g / cm\(^3\). Taking into account the obtained dependences of \( \Delta P_c \) on \( W_p \) (Fig. 9), it is possible to determine the cathode gain at any discharge energy by dependence (3), and thus, the density of the restored coating layer can be found.
The following is a specific example of restoring a Babbitt coating of a sliding bearing liner destroyed by peeling up to a steel substrate. The measurements showed that the thickness of the deposited Babbitt layer is \( \Delta h = 1.2 \text{ mm} \).

Having known the final thickness of the layer to be restored, namely, \( \Delta h_f = 1.2 \text{ mm} \) (after the ESA process by graphite) and the coefficients: \( \Delta h_{ls} = 1.5760 \text{ mm} \) and \( E = 0.5438 \text{ J} \) (Table 2), it is possible to determine the discharge energy \( W_p \) by (15).

\[
W_p = \frac{E}{\ln(\Delta h_{ls}/\Delta h_{ls})} = \frac{0.5438}{\ln (1.576 / 1.2)} \approx 2 \text{ J}.
\] (16)

Knowing the discharge energy \( W_p \) and the coefficients: \( \Delta h_{ls} = 1.7150 \text{ mm} \) and \( E = 0.4882 \text{ J} \) (Table 2), using (7), we can determine the thickness of the Babbitt coating of \( \Delta h_1 \) applied before the ESA process performed with graphite.

At \( r_l = r_s \),

\[
\Delta h_1 = \Delta h_{ls} \cdot \left( \frac{r_l}{r_s} \right) \cdot e^{(E/W_p)} = 1.715 \cdot 2.718^{(0.4882/2)} \approx 1.34 \text{ mm}
\]

According to (12) and the coefficients: \( \Delta R_{z_s} = 125.0858 \mu\text{m} \) and \( E_{\Delta R_{z_s}} = 0.2321 \text{ J} \) (Table 2), it is possible to determine the roughness of the Babbitt coating before the ESA process with graphite.

\[
\Delta R_e = \Delta R_{z_s} \cdot e^{(E_{\Delta R_{z_s}}/W_p)} = 125.0858 \cdot 2.718^{-0.2321/2} \approx 0.89 \mu\text{m}.
\]

The peeling area of the Babbitt coating (Fig. 10, a) was treated with copper and graphite, and then there was deposited Babbitt with \( W_p = 2.0 \text{ J} \) (Fig. 10, b).
Figure 10. Various stages of restoring the bearing liner (BL) coating: a – ESA processing of the peeling section of the copper coating; b – ESA processing of the most damaged areas of the coating covered with B88 Babbitt; c – ESA processing of the entire surface of the bearing liner (BL) with B88 Babbit; d - polishing the entire surface of the bearing liner (BL).

Separate places with crumbled areas (Fig. 10, b) were treated with Babbitt at \( W_p = 0.31 \) J. After staggered processing by graphite, first at the discharge energy of \( W_p = 0.27 \) J, and then at \( W_p = 0.05 \) J, the entire surface the coating was treated with Babbitt at \( W_p = 0.05 \) J (Fig. 10, c) and polished (Fig. 10, d).

5. Conclusions
1. The analysis of existing technological methods for the restoration of worn surfaces of parts is carried out.
2. The correlation dependences of the qualitative characteristics of the restored Babbitt coatings (the weight of transferred Babbitt onto the item being restored, the thickness and roughness of the formed layer) by the ESA method on the technological parameters of the process (discharge energy) have been found out, which fact allows significantly implementing the methodology for controlling the quality of surface layers when manufacturing and repairing the items with Babbitt coatings.
3. The coefficients of the equations for predicting mass transfer (3), the thickness of the cathode gain (layer increment) (7) and the surface roughness (12) have been stated.
4. Based on the experimental studies, the mathematical models are proposed (mass transfer equations (3,7) and surface roughness prediction (12)), which allow determining the main technological parameters of the formed layer quality by the energy parameters of the ESA plant: amount of transferred material \( \Delta P_{cs} \), increase in layer thickness \( \Delta h_l \) and surface roughness \( \Delta R_z \).
5. A methodology has been developed for determining the constants for: mass transfer equations (activation energy for mass transfer process \( E \); gain and saturation gain, respectively, \( \Delta P_{cs} \) and \( \Delta h_l \)); roughness prediction equations (saturation roughness \( \Delta R_a \) and critical power \( E_{\Delta R_z} \)).
6. The new technology for restoring Babbitt coatings can be used for floating rings of compressor equipment sealing assembly units, thrust and journal bearings, gear support pins for planetary multipliers, etc.

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