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Influence of technological parameters on roughness during coating processing

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Abstract. The authors consider the influence of various processing technological parameters (grinding wheel rotation speed, part rotation speed and longitudinal feed speed) on roughness of the surface restored by induction baking followed by rolling of the marine engine sleeve. These parameters play a key role in ensuring precision processing and achieving minimal roughness, which, in turn, affects the durability and efficiency of the engine. The advantages of impregnated abrasive wheels, which reduce tool wear and improve processing accuracy, were analyzed. The described technologies for restoring parts, such as induction baking and rolling, increase wear resistance and fatigue strength. Importance of precise adherence to processing modes to prevent defects was emphasized. The presented methods improve the quality of the parts, their performance and service life, which is especially important in mechanical engineering. During internal abrasive processing of restored engine sleeves, application of a cutting fluid intensifies the adhesive interaction between nickel- and chromium-based materials and the abrasive grains, resulting in reduced processing efficiency. The impregnated wheels reduce chip sticking, increase self-cleaning, prolong tool life, and lower the temperature in the cutting area. The authors carried out the experiments on processing the internal surfaces of the restored engine sleeves by three processing methods. The proposed improved method for impregnating abrasive wheels ensures an even distribution of the impregnation solution. Reduction of roughness of the treated surface and reduction in wheel loading were experimentally confirmed. It was found that reducing the part rotation speed and the longitudinal feed speed increases the roughness, but the proposed method allows it to be minimized. Influence of rotation speeds of the part and the abrasive wheel on the surface roughness during processing was investigated. Increasing the part speed increases the grain contact length, degrading the surface quality. Increasing the wheel speed, on the contrary, reduces the roughness. The experiments confirmed that impregnated wheels reduce roughness during internal processing of restored sleeves by 1.5 – 1.8 times.

Keywords: grinding wheel rotation speed, part rotation speed, impregnation, abrasive wheels, porosity, impregnators, impregnation

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Влияние технологических параметров на шероховатость при обработке покрытий

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Аннотация. Авторы рассматривают влияние различных технологических параметров обработки (скорости вращения шлифовального круга, скорости вращения детали и скорости продольной подачи) на шероховатость поверхности, восстановленной индукционным напеканием с последующим накатыванием гильзы судового двигателя. Эти параметры играют ключевую роль в обеспечении точности обработки и в достижении минимальной шероховатости, что, в свою очередь, сказывается на долговечности и эффективности работы двигателя. Анализируются преимущества импрегнированных абразивных кругов, снижающих износ инструмента и улучшающих точность обработки. Описанные технологии восстановления деталей, такие как индукционное напекание и накатывание, повышают износостойкость и усталостную прочность. Подчеркивается значение точного соблюдения режимов обработки для предотвращения дефектов. Представленные методы повышают качество деталей, их эксплуатационные характеристики и срок службы. При внутренней абразивной обработке восстановленных гильз двигателей применение смазочно-охлаждающей жидкости приводит к усилению адгезионного взаимодействия никеля и хрома с абразивными зернами, что снижает эффективность процесса обработки. Импрегнированные круги уменьшают прилипание стружки, повышают самоочищение, продлевают срок службы инструмента и снижают температуру в зоне резания. Проведены эксперименты по обработке внутренних поверхностей восстановленных гильз двигателей тремя методами. Предложенный усовершенствованный способ импрегнирования абразивных кругов обеспечивает равномерное распределение пропиточного раствора. Экспериментально подтверждены снижение шероховатости обработанной поверхности и уменьшение засаливания инструмента. Установлено, что повышение скорости вращения детали и продольной подачи увеличивает шероховатость, но предложенный метод позволяет ее минимизировать. Исследуется влияние скорости вращения детали и абразивного круга на шероховатость поверхности при обработке. Увеличение скорости детали повышает длину контакта зерен, но ухудшает качество поверхности. Повышение скорости круга, напротив, снижает шероховатость. Экспериментально подтверждено, что импрегнированные круги уменьшают шероховатость при внутренней обработке восстановленных гильз в 1,5 – 1,8 раза.

Ключевые слова: скорость вращения шлифовального круга, скорость вращения детали, импрегнирование, абразивные круги, пористость, импрегнатор, пропитка

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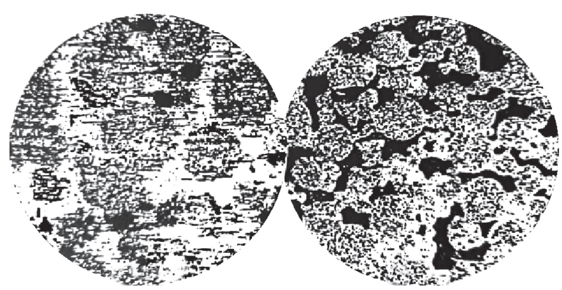
Introduction

Modern processing methods, including electro-pulse treatment and abrasive processing with cooling, significantly enhance the performance of machine parts. These techniques reduce micro-irregularities, decrease friction and wear, and suppress the formation of microcracks. The application of superhard diamond and cubic boron nitride (CBN) grinding further increases hardness and wear resistance, while precision technologies ensure high geometric accuracy. This is particularly critical for parts operating under dynamic loads. Consequently, modern processing methods improve not only part quality but also operational reliability [1 – 3]. At the same time, deviations from prescribed processing modes may cause overheating. Such thermal effects can alter the material structure, promote the formation of quenching cracks, and reduce strength, ultimately leading to warping or even failure of parts during service.

For coating deposition, hardening, and restoration of parts subjected to intensive wear, the use of wear-resistant powder materials such as PG-SR2 and PG-10N-0.2 is considered a promising approach. These materials primarily contain chromium, iron, nickel, and carbide-forming elements (W, Mo, V), which collectively provide high hardness, wear resistance, heat resistance, and corrosion resistance [4 – 6].



a *b*

Fig. 1. Microstructure of powder mixtures PG-SR2 + 30 % NPCh1 (*a*) and PG-SR2 + 75 % NPCh1 (*b*) at heating rate of 5 K/s and heating temperature of 1323 K (150×)

Рис. 1. Микроструктура порошковых смесей ПГ-СР2 + 30 % НПЧ1 (*a*) и ПГ-СР2 + 75 % НПЧ1 (*b*) при скорости нагрева 5 К/с и температуре нагрева 1323 К (150×)

Fig. 1 presents the microstructures of coatings based on PG-SR2 + 30 % NPCh1 and PG-SR2 + 75 % NPCh1. Coatings with a lower filler content (30 % NPCh1) exhibit a more homogeneous microstructure. In this case, the microstructure consists of sintered particles of the base component reinforced by filler particles as a result of liquid-phase sintering.

In contrast, coatings with a higher filler content (PG-SR2 + 75 % NPCh1) show the formation of block-like regions composed of relatively large PG-SR2 particles, with finely dispersed NPCh1 filler particles distributed between them.

The experimental results indicate that adding nickel-based fillers (NPCh1, NPCh2, NPCh3) or iron powder PZh6M to PG-SR2 powder in amounts of up to 35 and 25 %, respectively, makes it possible to obtain high-quality coatings with porosity not exceeding 15 %.

Preliminary experiments on induction baking of powder compositions showed that, for all the two-component powder mixtures considered, both their sinterability and their ability to form a firmly bonded coating on the sleeve substrate during induction baking decrease with increasing filler content. When the content of NPCh1, NPCh2, NPCh3, or PG-10N-04 powders exceeds 35 %, or when iron powder PZh6M exceeds 25 % in mixtures with PG-SR2, coating porosity increases markedly. With further increases in filler content, this porosity develops into macroporosity, with pore sizes ranging from 0.5 to 1.5 mm (Fig. 2, *a*).

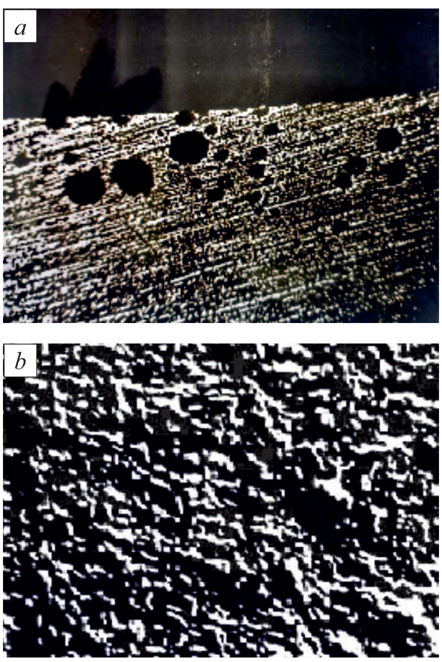


Fig. 2. Microstructure of PG-SR2 coating before processing:
a – macroporosity of the coating obtained by induction baking a powder mixture of PG-SR2 + 50% PG-10N-04 (24$^\times$);
b – fractographs of the local fracture zone of PG-SR2 coating surface and the pin surface (48$^\times$)

Рис. 2. Микроструктура покрытия ПГ-СР2 до обработки:
а – макропористость покрытия, полученного напеканием смеси порошков ПГ-СР2 + 50 % ПГ-10Н-04 (24$^\times$); *b* – фрактограммы локальной зоны разрушения поверхности покрытия ПГ-СР2 и поверхности штифта (48$^\times$)

Fracture surfaces formed after pin detachment from the baked coating were examined using a scanning microscope. The fractograph of the local fracture zone of the PG-SR2 coating surface is shown in Fig. 2, *b*. The examined region exhibits a mixed fracture mechanism combining ductile and brittle features. Sharp transition boundaries correspond to brittle fracture, whereas smoother regions indicate ductile deformation. Detachment of the pin along the transition zone (Fig. 2, *b*) occurs predominantly through ductile fracture, indicating good contact between the coating and the sleeve substrate.

To further improve the properties of baked layers, a surface rolling technology applied after induction centrifugal baking (ICB) was developed. In this approach, restoration is achieved by forming a metallic layer that is then processed by rolling. As a result, surface roughness decreases, the structure becomes more compact, porosity is reduced, and residual compressive stresses are generated. These effects collectively enhance fatigue strength and reduce wear of the working surfaces.

Restoration of the inner surface of a cylinder sleeve by induction baking involves the application of a powder material followed by heating. This technique provides strong adhesion, minimizes thermal impact on the base

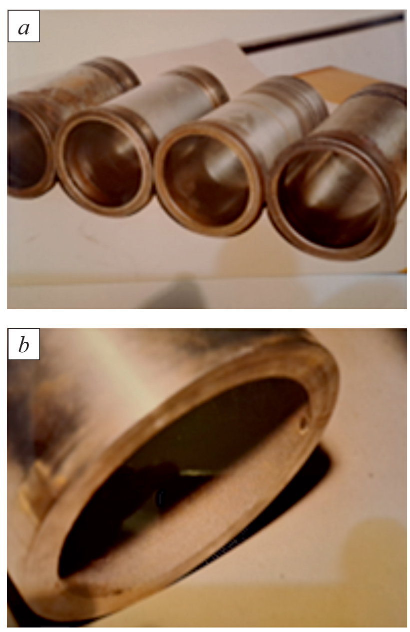


Fig. 3. Worn, restorable (*a*) and restored by induction centrifugal baking (*b*) marine engine sleeves 6Ch17/14

Рис. 3. Изношенные, подлежащие восстановлению (*a*) и восстановленные индукционным центробежным напеканием (*b*) гильзы судового двигателя 6Ч17/14 material, and increases wear resistance (Fig. 3). Nevertheless, subsequent processing of the restored layer remains challenging due to its high hardness, structural heterogeneity, and microstructural changes caused by rapid heating and cooling [5; 6].

A critical stage of final processing that ensures geometric accuracy, minimal surface roughness, and the required mating characteristics with the piston is the grinding of restored sleeves. Rough grinding removes the primary material allowance, whereas finish grinding achieves precise dimensions and refines surface microgeometry. Strict compliance with processing requirements is essential, as this stage directly affects engine service life, wear of the piston assembly, and oil consumption. High-quality grinding is therefore particularly important for engines operating under high load conditions [7 – 9].

In mechanical engineering practice, various approaches are employed to enhance the performance characteristics of abrasive tools. Optimization of tool structure, composition, and operating modes contributes to increased tool durability and improved processing efficiency. Key development directions include the use of advanced abrasives such as diamond and cubic boron nitride, composite, ceramic, and hybrid bonding systems, as well as self-sharpening and porous wheels that promote effective chip removal and heat dissipation. In addition, auxiliary technologies, including electro-pulse and ultrasonic treatments, together with the application of cutting fluid, reduce tool wear and energy consumption [10 – 13].

Internal grinding of engine cylinder sleeves represents a crucial operation for achieving high dimensional accuracy and minimal surface roughness. However, when conventional abrasive wheels (e.g., 25A20PSM18K8B3) are employed, chip adhesion, clogging, and accelerated tool wear often occur, leading to a deterioration in processing accuracy. Previous studies have shown that, during the machining of baked surfaces produced from powder materials such as PG-SR2 containing chromium, iron, and nickel, the issue of wheel loading becomes especially pronounced.

One promising approach to addressing this problem is the use of impregnated abrasive wheels. These wheels are treated with specialized compositions – such as oils, polymers, or metallic compounds – that enhance their functional characteristics. Their main advantages include stable grinding performance, reduced thermal load, diminished clogging, and improved dimensional accuracy, making them particularly suitable for hard and difficult-to-machine materials.

The effectiveness of impregnated wheels is largely attributed to the presence of solid lubricants within their composition. This results in lower contact pressure and cutting forces, reduced processing temperature, and slower wheel wear. Consequently, the use of impregnated abrasive wheels improves both productivity and processing quality long tool life are required.

Materials and methods

Experimental results show that, during internal processing of restored engine sleeves, the use of cutting fluid causes rapid cooling of the chip formation zone. This effect promotes adhesive sticking of nickel and chromium to the abrasive grains, which reduces the cutting ability of the wheel and impairs heat dissipation [14 – 16]. As a consequence, tool wear increases and the temperature in the cutting area rises, potentially leading to the formation of microcracks and defects on the processed surface.

To minimize adhesive sticking, appropriate selection of the abrasive tool, optimization of processing modes, and the use of effective cutting fluids are required. In addition, regular dressing of the grinding wheel is essential [17 – 19].

The use of impregnated abrasive wheels reduces chip adhesion, enhances grain self-cleaning, extends tool life, and lowers the temperature in the contact zone. Impregnators actively participate in the chip formation process by improving friction conditions and reducing cutting forces during the processing of powder materials [20; 21].

The effectiveness of impregnation is determined by the uniformity of impregnator distribution, wheel porosity, and the impregnation technology employed. Impregnated wheels acquire hydrophobic properties that protect them from moisture and extend their storage life [18; 19].

In the present study, three methods were used to process the internal surfaces of restored engine sleeves:

– processing with cutting fluid (3 % emulsion);

– processing using abrasive wheels impregnated by the standard method [18; 19];

– processing using abrasive wheels impregnated by the proposed method.

In the proposed impregnation method, the abrasive wheel is mounted on spindle *7* of the impregnation device (Fig. 4) and immersed in bath *6* containing the impregnation solution, allowing free filling of the wheel pores. After removal, the wheel is rotated at 1000 rpm to eliminate excess solution. This procedure ensures uniform distribution of the impregnator and reduces the likelihood of wheel loading by chips [18; 22].

Results and discussion

Surface roughness of the processed surfaces was evaluated as a function of the processing modes. The results show that the dominant factor influencing surface roughness is the rotation speed of the part. Curve *3* in Fig. 5

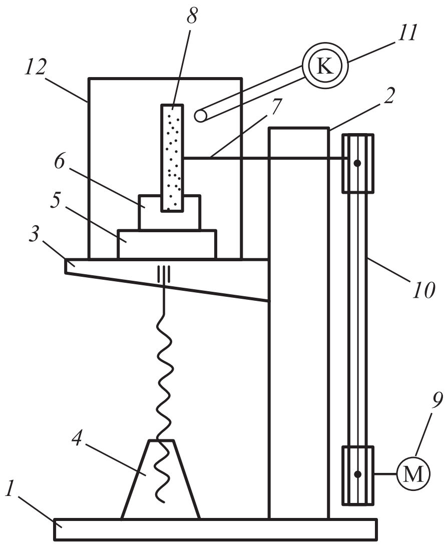


Fig. 4. Device for impregnating an abrasive tool:
1 – base; *2* – rack; *3* – table; *4* – screw; *5* – heater; *6* – bath;
7 – spindle; *8* – abrasive tool; *9* – electric engine; *10* – belt drive;
11 – heater; *12* – chamber cover

Рис. 4. Устройство для пропитки абразивного инструмента:
1 – основание; *2* – стойка; *3* – стол; *4* – винт; *5* – нагреватель;
6 – ванна; *7* – шпиндель; *8* – абразивный инструмент;
9 – электродвигатель; *10* – ременная передача; *11* – калорифер;
12 – крышка камеры

corresponds to processing with a conventional abrasive wheel using cutting fluid, whereas curve *2* represents processing with an abrasive wheel impregnated by the standard method. Curve *1* demonstrates a pronounced reduction in surface roughness when the proposed impregnation method is applied, yielding the best overall performance.

Abrasive wheels impregnated by the proposed method reduce cutting forces and plastic deformation, which contributes to lower surface roughness. In addition, these wheels are less susceptible to wheel loading, and grinding chips are efficiently removed from the contact zone.

Experiments investigating the influence of processing modes – namely, the part rotation speed V_p, the grinding wheel speed V_s, and the longitudinal feed S_f – showed that increasing V_p and S_f leads to an increase in surface roughness for all processing methods. As V_p increases, the R_a value rises for all investigated modes (Fig. 5). The minimum roughness values are characteristic of mode *1*, corresponding to the abrasive wheel impregnated by the proposed method, whereas mode *3* (a conventional abrasive wheel used with cutting fluid) produces the highest R_a values over the entire range of part rotation speeds.

An increase in the grinding wheel rotation speed V_s results in an overall decrease in R_a for all investigated modes (Fig. 6). The minimum roughness values are again achieved under mode *1*, while mode *3* is characterized by the highest R_a values throughout the studied range of wheel rotation speeds.

As shown in Fig. 7, increasing the longitudinal feed S_f leads to a rise in R_a for all processing modes. The lowest surface roughness is observed for mode *1*, whereas mode *3* yields the highest R_a values over the entire range of longitudinal feed rates.

The differences between the curves presented in Figs. 5 – 7 clearly indicate the significant influence of processing conditions on the formation of surface microrelief.

The experimental results further demonstrate that, during internal processing of engine sleeves restored using powder materials, the application of impregnated

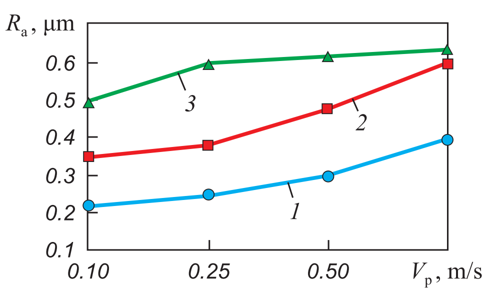


Fig. 5. Influence of the part rotation speed V_p on surface roughness during internal processing (V_s = 35 m/s; t = 0.003 mm; S_f = 0.2 m/s):
1 – abrasive wheel impregnated with the proposed method;
2 – abrasive wheel impregnated in the usual way;
3 – conventional abrasive wheel with cutting fluid

Рис. 5. Влияние скорости вращения детали V_p на шероховатость поверхности при внутренней обработке (V_s = 35 м/с; t = 0,003 мм; S_f = 0,2 м/с):
1 – абразивный круг, импрегнированный предложенным способом;
2 – абразивный круг, импрегнированный обычным способом;
3 – обычный абразивный круг со смазочно-охлаждающей жидкостью

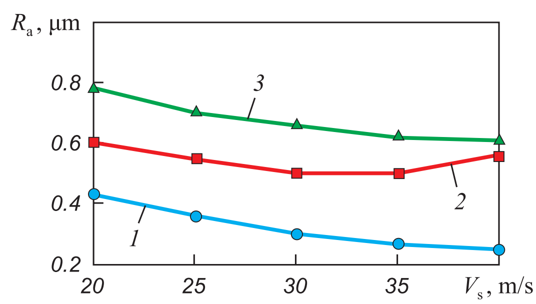


Fig. 6. Influence of the grinding wheel rotation speed V_s on surface roughness during internal processing (V_p = 0.5 m/s; t = 0.003 mm; S_f = 0.2 m/s):
1 – abrasive wheel impregnated with the proposed method;
2 – abrasive wheel impregnated in the usual way;
3 – conventional abrasive wheel with cutting fluid

Рис. 6. Влияние скорости вращения шлифовального круга V_s на шероховатость поверхности при внутренней обработке (V_p = 0,5 м/с; t = 0,003 мм; S_f = 0,2 м/с):
1 – абразивный круг, импрегнированный предложенным способом;
2 – абразивный круг, импрегнированный обычным способом;
3 – обычный абразивный круг со смазочно-охлаждающей жидкостью

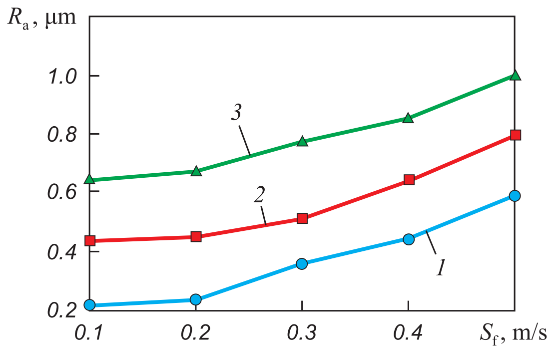


Fig. 7. Influence of longitudinal feed S_f on surface roughness during internal processing (V_s = 35 m/s; V_p = 0.5 m/s; t = 0.003 mm):
1 – abrasive wheel impregnated with the proposed method;
2 – abrasive wheel impregnated in the usual way;
3 – conventional abrasive wheel with cutting fluid

Рис. 7. Влияние продольной подачи S_f на шероховатость поверхности при внутренней обработке (V_s = 35 м/с; V_p = 0,5 м/с; t = 0,003 мм):
1 – абразивный круг, импрегнированный предложенным способом;
2 – абразивный круг, импрегнированный обычным способом;
3 – обычный абразивный круг со смазочно-охлаждающей жидкостью

abrasive wheels reduces surface roughness by a factor of 1.5 – 1.8. Thus, the proposed impregnation method provides a substantial improvement in the processing quality of restored engine sleeves.

Fig. 8 presents micrographs of polished sections obtained from worn cylinder sleeves of the 6Ch17/14 marine diesel engine that had reached their inter-repair service life. In terms of graphite distribution within the metallic matrix, the microstructure of the worn sleeve corresponds to grade Gd-6. The graphite morphology in the cylinder sleeves is predominantly dendritic–rosette, with the presence of rounded graphite inclusions. The metallic matrix of the cylinder sleeves (Fig. 8, *a*) corresponds to pearlite of grade P–P95, with the ferrite content not exceeding 1.0 – 1.5 % of the polished section area.

Figs. 8, *e* and *f* show the microstructure of the cylinder sleeves after induction baking of the powder coating. In the coating zone, graphite inclusions in the cast iron correspond to grade Gd-5. The graphite morphology remains dendritic–rosette, with a slight increase in the fraction of rounded graphite.

After subsequent mechanical processing, the microstructure of the coated sleeves closely resembles that of the worn sleeve. Analysis confirmed that the structure of the metallic matrix of the sleeves remains within the requirements specified by GOST.

Conclusions

Increasing the part rotation speed during grinding extends the contact length between the abrasive grains and the processed surface. This results in higher residual roughness heights, enhanced thermal effects, and modifications of the mechanical properties of the surface layer.

By contrast, increasing the grinding wheel rotation speed raises the frequency of contacts between the wheel and the part, thereby involving a larger number of abrasive grains in the material removal process. This leads to a more uniform material removal and, consequently, to a reduction in surface roughness.

Kinematic analysis of the grinding process confirms that higher workpiece rotation speeds increase the contact length of abrasive grains, which in turn causes an increase in residual roughness heights. At the same time, higher grinding wheel rotation speeds are associated with an overall decrease in the roughness of the inner surface of the sleeve.

Experimental investigations further demonstrate that, during internal processing of engine sleeves restored using powder materials, the use of impregnated abrasive wheels reduces surface roughness by a factor of 1.5 – 1.8.

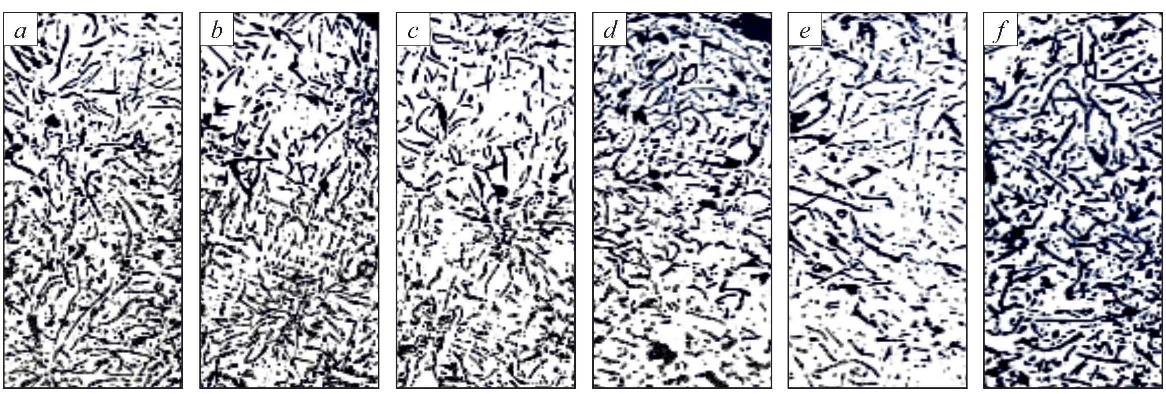


Fig. 8. Microstructure (100×) of the worn sleeve in the coating baking area (*a*, *b*) and outside it (*c*, *d*), as well as the baked sleeve in the coating baking area (*e*, *f*)

Рис. 8. Микроструктура (100×) изношенной гильзы в зоне напекания покрытия (*a*, *b*) и вне зоны напекания покрытия (*c*, *d*), а также напеченной гильзы в зоне напекания покрытия (*e*, *f*)

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