

деформації. Якщо ж розмір лунки визначається площею її ортогональної проекції на поверхню зразка, отримуємо **проекційну твердість** з тією самою розмірністю N/mm<sup>2</sup>. Вона характеризує середній тиск, приведений до площі поперечного перерізу зони деформації, і є більш зручною для міжметодичного порівняння результатів інденування.

3. Якщо розмір лунки оцінюється через об'єм матеріалу, витісненого або пластично деформованого під індентором, твердість визначається як відношення сили до цього об'єму і має розмірність N/mm<sup>3</sup>. Така **об'ємна твердість** відображає просторову інтенсивність опору матеріалу пластичному деформуванню та пов'язана з питомою роботою деформації в зоні контакту. Вона враховує тривимірний характер напружено-деформованого стану й забезпечує найбільш повну фізичну інтерпретацію процесу інденування, оскільки описує не лише контактну поверхню, а весь об'єм пластичної течії під індентором.

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### POST-COATING DIFFUSION HARDENING OF DIE-CASTING MOLDS WITH PLASMA- DEPOSITED TIN LAYERS

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In addition to the general requirements [1–7], plasma coatings used to protect copper alloy die-casting molds must meet specific requirements: low thermal conductivity, the ability to withstand thermal changes in an aggressive environment, and high corrosion and scale resistance. Coatings made of refractory compounds, primarily titanium nitride, best meet these requirements [1, 2].

The purpose of this research is to clarify the mechanisms responsible for the significant increase in durability of die-casting molds coated with thin TiN plasma layers and to determine how diffusion processes in the surface layers of tool steels influence the long-term operational performance of molds after coating removal.

The objects of the study were the forming parts of die casting molds for copper alloys made from 4Kh5MFS and 5KhNM steels, as well as specimens cut from them. The specimens were cut from the forming parts of the molds were coated using a Bulat-3T installation at a nitrogen partial pressure of 1 Pa and a substrate temperature of 500 °C with a titanium nitride coating no more than 5 μm thick. The specimens were examined before and after coating application, as well as after use.

Coatings were applied to laboratory test samples and injection mold components using ion bombardment condensation. Coatings produced by this method are characterized by high stability of properties, low porosity, and good adhesion to the substrate.

The coating appears as a light, non-etching coating. A strip coated with nital has a smooth interface with the steel. The coating is followed by a transition zone, which appears as a highly etched layer 5...6 μm thick. X-ray microanalysis, conducted after coating application to determine the titanium distribution, revealed that most of the titanium is contained within the coating itself. Some Ti is present in the transition zone. No titanium is detected in the matrix (Fig. 1).

After the first regrinding, after 3,000 presses, a large number of small, randomly distributed inclusions (Figs. 2, 3) measuring 2...4 μm are observed in the working surface. These inclusions have a pinkish and lilac tint and sharply blackened edges, as illustrated well in Fig. 4. After 12 thousand pressings, a small number of inclusions measuring 8...10 μm, located along the grain boundaries, are observed in the working surface.

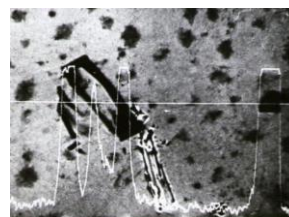
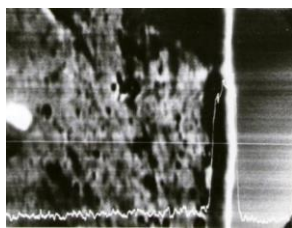


Fig. 1. Microdistribution of titanium in the coating, transition zone and surface layer before operation

Fig. 2. Microdistribution of titanium in inclusions formed during operation (after removal of a surface layer 20 μm thick), ×2000

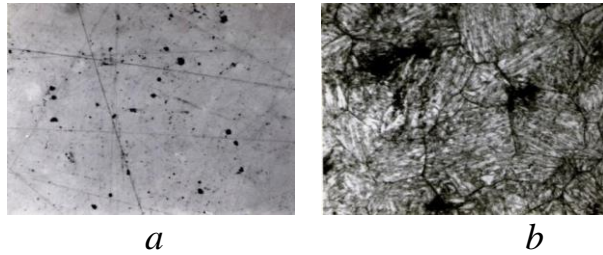


Fig. 3. Microstructure of the working surface after operation for 3 thousand press-ins (20  $\mu\text{m}$  layer removed): a – not etched,  $\times 500$ ; b – etched with nital,  $\times 500$

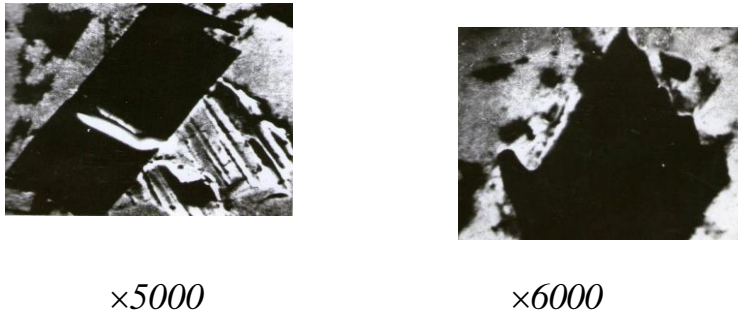


Fig. 4. Inclusions in the surface layers of mold parts formed during operation

When comparing the microstructure of the working surface after operation for 3 and 12 thousand pressings (see Figs. 3, 5), it should be noted that there is a significant increase in the grain size and the size of inclusions, accompanied by a reduction in their number.

Microspectral analysis carried out on the Cambscan installation of one of the typical inclusions on the working surface of a sample cut from a part made of 4Kh5MFS steel after operation, in reflected electrons (Fig. 6,b) and in the characteristic rays  $Ti_{ka}$ ,  $Cr_{ka}$ ,  $Fe_{ka}$ ,  $Si_{ka}$ ,  $Mo_{ka}$ ,  $V_{ka}$ ,  $N_{ka}$  showed the presence of titanium, nitrogen, and vanadium in the composition (see Fig. 6).

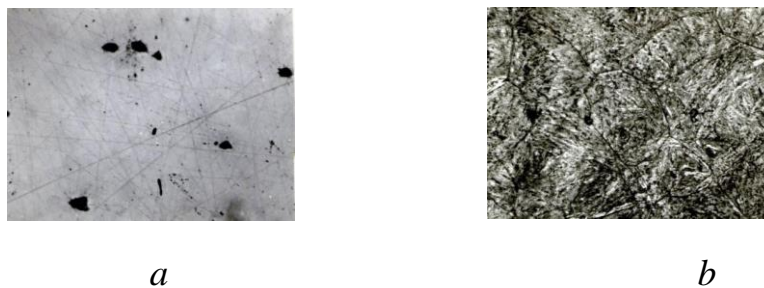


Fig. 5. Microstructure of the working surface after operation for 12 thousand press-ins ( $\sim 80 \mu\text{m}$  layer removed): a – not etched,  $\times 500$ ; b – etched with nital,  $\times 500$

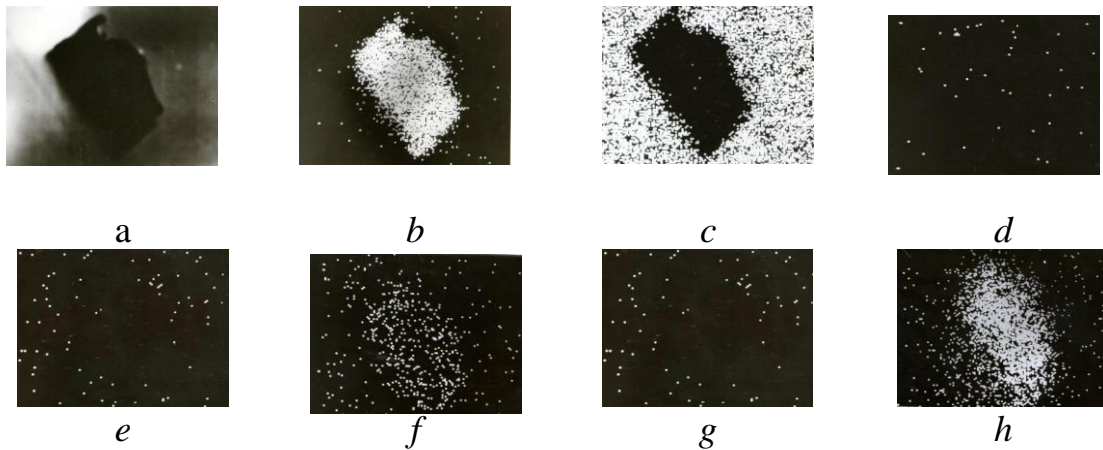


Fig. 6. Inclusion at the working surface of the sample: a – in reflected electrons; in characteristic rays: b –  $Ti_{ka}$ ; c –  $Cr_{ka}$ ; d –  $Fe_{ka}$ ; e –  $Si_{ka}$ ; f –  $Mo_{ka}$ ; g –  $V_{ka}$ ; h –  $N_{ka}$

Studies of inclusions formed during operation in the working surfaces of 5KhNM steel revealed the presence of titanium and nitrogen. No other elements were detected. Fig. 8 shows the distribution of elements contained in a 10  $\mu m$  inclusion (5KhNM steel).

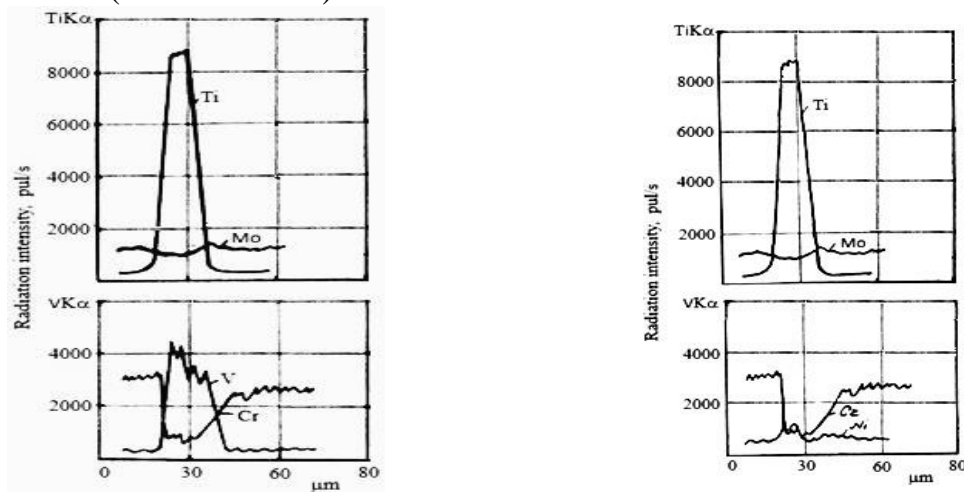


Fig. 7. Distribution of elements along a line intersecting a typical inclusion. Steel 4Kh5MFS

Fig. 8. Distribution of elements along a line intersecting a typical inclusion. Steel 5KhNM

Thin TiN plasma coatings with a thickness of up to 5  $\mu m$  provide effective initial protection of die-casting molds due to their low thermal conductivity, high resistance to temperature fluctuations and reduced adhesion to molten copper alloys. This results in a 1.5–2.5-fold increase in durability before the first regrinding.

Even after the coating layer is removed during maintenance grinding, the operational lifetime of the molds remains significantly higher than that of uncoated tools, reaching an increase of up to six times.

During repeated thermal cycles, titanium atoms migrate from the transition layer into the steel matrix to depths exceeding 100  $\mu\text{m}$ , forming finely dispersed Ti-N and Ti-V-N particles.

These inclusions act as strengthening elements that limit dislocation mobility and increase the microhardness of the surface layers to 750–800 MPa.

When the inclusions grow to critical dimensions of approximately 8–10  $\mu\text{m}$  and accumulate along grain boundaries, microcracks begin to develop, which eventually leads to mold failure.

The discovered diffusion-controlled strengthening effect represents an additional mechanism for improving the durability of die-casting molds and can be used as a technological approach for increasing the reliability of tooling operating under severe thermal loads.

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