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THE EFFECT OF NANOCRYSTALLINE LAYERS ON THE WEAR RESISTANCE OF GREY CAST IRON DURING FRICTION IN AN OIL-ABRASIVE MEDIUM

WPŁYW UTWARDZONYCH WARSTW NANOKRYSTALICZNYCH NA ODPORNOŚĆ NA ZUŻYCIE ŻELIWA PODCZAS TARCIA W ŚRODKU OLEJOWO-ŚCIERNYM

Key words: nanocrystalline layer, friction hardening, wear, oil-abrasive medium.

Abstract Friction hardening is one of the surface hardening methods with the use of highly concentrated energy sources. In the "tool-treated surface" contact area, the surface layer of a metal is heated at a very high rate to phase transition temperatures, and then it is cooled at a high rate, which results in the formation of hardened nanocrystalline layers.

The studies carried out have shown that a hardened nanocrystalline layer is formed in the surface layer in the course of friction hardening of cast-iron (EN-GJL-200) components. The layer thickness is 90–120 µm, and the microhardness is 7–8 GPa. Grain size of the hardened surface layer was equal to 20–40 nm near the treated surface.

It is shown that the hardened layer significantly increases the serviceability of the pair "grey cast iron-grey cast iron" during sliding friction in the lubricated-abrasive medium. When increasing the unit load from 2 to 6 MPa, the wear rate of the hardened pair decreased by 2.6–4.2 times in comparison with an unhardened pair. Only one component of the friction pair was hardened.

Słowa kluczowe: warstwa nanokrystaliczna, utwardzanie tarciowe, tarcie, środek olejowo-ścierny.

Streszczenie Utwardzanie tarciowe stanowi metodę umacniania z użyciem wysoko skoncentrowanych źródeł energii. W strefie styku narzędzia i powierzchni obrabianej warstwa wierzchnia jest podgrzewana z dużą prędkością (10^5–10^6 K/s) do temperatury zmian fazowych, a następnie jest schładzana z dużą prędkością (10^4–10^5 K/s), co wpływa na powstanie utwardzonych warstw nanokrystalicznych.

Przeprowadzane badania doświadczalne wykazały, że w procesie utwardzania tarciowego części żeliwnych w warstwie wierzchniej formowana jest warstwa umocniona o strukturze nanokrystalicznej (warstwa biała). Uzyskana grubość warstwy wynosiła 90–120 µm, a mikrotwardość – 7–8 GPa, natomiast wielkość ziaren utwardzanej warstwy wierzchnej wynosiła 20–40 nm w pobliżu powierzchni obrabianej.

Wykazano, że utwardzona warstwa znacznie zmnięsza intensywność zużycia podczas tarcia ślizgowego pary żeliwo szare–żeliwo szare pracujące w środku olejowo-ściernym. Utwardzona warstwa występowała tylko na jednej części współpracującej pary tarcia. W związku z tym intensywność zużywania pary utwardzonej przy zwiększaniu nacisku powierzchniowego od 2 MPa do 6 MPa zmniejszyła się o 2,6–4,2 razy w porównaniu z parą nieutwardzoną.

INTRODUCTION

Operational properties of machine components depend on the material from which they are made, the accuracy of the resulting dimensions, as well as quality of the resulting surfaces. Damage occurs during the operation of the machine parts formed by tribological, fatigue, corrosion, and erosion processes. The destruction that formed during these processes starts from the surface. Therefore, the increase of the durability of machines

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during friction and wear is determined by the quality of the surface layer of machine components' contact surfaces, which includes both its geometrical parameters, and physical, chemical, and mechanical properties [**L. 1, 2**].

It is possible to change surface layer properties by applying various types of coatings, by alloying it, as well as by modifying the layer structure. When applying coating to the surface of a component, an additional layer is formed, which differs from the base metal of the component in its chemical composition and mechanical properties. When alloying and modifying the surface layer structure, its properties, chemical composition, and structural state (amorphization, creation of metastable nanocrystalline structures) change [**L. 1, 3–10**].

EXPERIMENTAL PROCEDURE

One of the methods used for the formation of a hardened nanocrystalline layer on machine components is friction hardening, which is one of the methods of surface hardening with the use of highly concentrated energy sources. A highly concentrated energy source is formed in the "tool-treated surface" contact area during high-speed friction (60–80 m/s). Surface layers of a metal are heated at a high rate (10^5–10^6 K/s) to temperatures that are above the phase transformation point. After removing the energy source, surface layers of the metal are rapidly cooled (10^4–10^5 K/s) due to the transfer of heat to the deeper layers of the component [**L. 11**]. There are also intense shear deformations of the surface layer of the metal in the "tool-part" contact area [**L. 12**]. Friction hardening is based on non-stationary processes of high-speed hardening. Hardened nanocrystal structures (white layers) are formed as a result of such processes in surface layers [**L. 13, 14**].

As for the kinematics of the process, the process of friction hardening is similar to the grinding process. For friction hardening of cylindrical or flat working machine part surfaces, grinding machines with a modernized main drive unit are used, or equipment is developed to provide the required linear velocity on the working part of tool (60–80 m/s) for their use on lathes. A metal disk made from structural or stainless steel is used as a tool during friction hardening. Tool dimensions correspond to the size of the grinding wheel used on this tool-machine.

In the process of frictional hardening, process medium (mineral oil, oils with surface-active polymer-based additives, etc.) is fed to the "tool-part" contact area. During hardening, the process medium is decomposed into chemical elements, which diffuse into a hardened surface layer [**L. 15, 16**].

Metallographic analysis showed that a hardened surface layer with a nanocrystalline structure, the thickness of which is 60–80 µm, is formed after friction hardening of samples (test-pieces) made from grey cast iron (EN-GJL-200) during which mineral oil is used as a process medium (**Fig. 1**). Microhardness of the hardened layer was H_μ = 6.5–6.8 GPa, while the hardness of the base metal was H_μ = 2.1–2.3 GPa. When oil with surface-active polymer-based additives was used as a process medium, the thickness of the hardened layer increased to 90–120 µm. Microhardness also increased to H_μ = 8.6 GPa (**Fig. 2**).

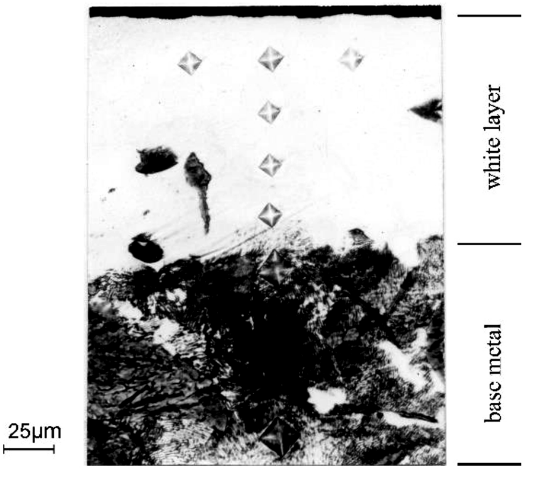

Fig. 1. Microstructure of the hardened layer obtained on grey cast iron EN-GJL-200 (with the use of mineral oil)

Rys. 1. Mikrostruktura warstwy utwarzonej na żeliwie szarym EN-GJL-200 (z użyciem oleiu mineralnego)

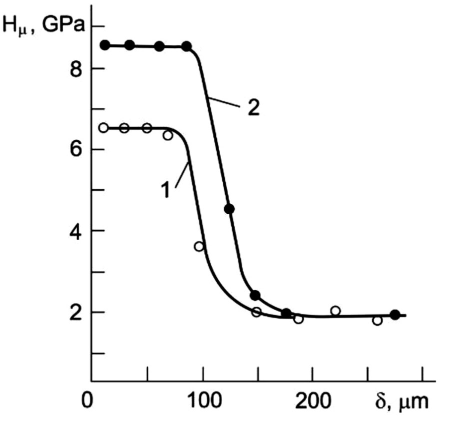

Fig. 2. Microhardness of the hardened layer obtained on grey cast iron EN-GJL-200 after friction hardening: 1 – with the use of mineral oil; 2 – with the use of oil with surface-active polymer-based additives

Rys. 2. Mikrotwardość warstwy utwardzonej na żeliwie szarym EN-GJL-200 po umacnianiu tarciowym: 1 – z użyciem oleju mineralnego; 2 – z użyciem oleju z powierzchniowo aktywnymi dodatkami polimerów

X-ray analysis showed that grain size of the hardened surface layer was 20–40 nm near the surface with a smooth transition to the structure of a source material in deeper layers. The structure of the obtained hardened surface layer after friction hardening is a nanocrystalline one.

RESULTS AND DISCUSSION

Abrasion wear is one of the most common types of wear. As for the production, friction in pure oil is a rare thing, since abrasives from the environment, including products of wear, get into the oil while in service.

Wear resistance during sliding friction in an oil-abrasive medium was studied on a friction test rig according to the "ring-insert" scheme (**Fig. 3**) at the sliding velocity of $V = 0.9$ m/s and the change in the unit load P from 2 MPa to 6 MPa. Testing time of the friction pair was $t = 6$ h. Abrasive (0.1% by weight) with a dispersion of 10–20 microns was added to mineral oil. Oil with an abrasive was intensively fed into a friction zone using a special autonomous system.

Before the beginning of testing, all friction pairs were worked until the frictional moment stabilized and the contact of mating surfaces was established, which was evaluated by the presence of friction traces in an area of not less than 90% of the working sliding surface of each sample.

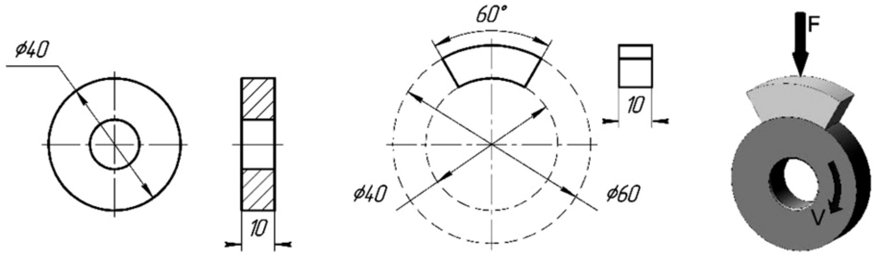

Fig. 3. Drawing of sample (a), insert (b) and diagram of the study the wear-resistance of friction pairs (c)
Rys. 3. Rysunek pierścienia (a), wkładki (b) i schemat badania zużycia pary tarcia (c)

The samples' mass loss after a certain sliding distance, which was determined by weighing them on analytical balances with ±0.2 mg accuracy, was the wear criterion. After that, the wear rate of each sample of the friction pair was determined.

The studied samples (rings and inserts) were made from grey cast iron EN-GJL-200. For comparison, inserts were made from bronze CuSn5Zn5Pb5-C and Sn-Pb composite (antifriction alloy, 6% Sn, 6% Sb). Only working surfaces of rings were hardened. The working surfaces of inserts were not hardened, they were only ground using an aluminium oxide wheel. Working surfaces of the rings underwent friction hardening with the use of special equipment mounted on a universal screw-cutting lathe. Mineral oil and oil with surface-active polymer-based additives were used as a process medium. The roughness of the samples' working surfaces after friction hardening was $Ra = 0.25$–0.58 µm, after grinding, it was $Ra = 0.50$–0.63 µm.

Different methods of surface hardening are used in order to improve the wear resistance of machine components. Hardening using high-frequency currents, as well as ultrasonic machining of samples' working surfaces, were also used in order to evaluate the effectiveness of the friction hardening method during the wear of friction pairs made from cast iron.

Studies have shown that each of the surface hardening methods increases wear resistance of the pair "cast iron EN-GJL-200 – cast iron EN-GJL-200" during friction in an oil-abrasive medium (**Fig. 4**).

Thus, in the case of friction at a sliding velocity of $V = 0.9$ m/s and a unit load of $P = 4.5$ MPa, hardening of rings using high-frequency currents increases their wear resistance by only 40%, whereas it increases the wear resistance of inserts that worked with them as a pair by about 50% in comparison with the unhardened pair. When hardening working surfaces of ring samples using ultrasonic machining, a white layer similar to that typical of friction hardening is formed in their surface layers. Ultrasonic machining of rings' working surfaces was performed without a process medium.

Experiments have shown that surface hardening of ring samples using ultrasonic machining increases their durability by 3 times, and it increases durability of unhardened inserts which worked with them as a pair by 3.1 times in comparison with the unhardened pair. Friction hardening increases wear resistance during friction in an oil-abrasive medium even more significantly. Wear processes are affected by the quality of the hardened layer, which is formed due to the use of different process media (mineral oil, oil with surface-active polymer-based additives) during hardening. Thus, during friction hardening of ring samples where mineral oil is used as a process medium, their wear resistance increased by 3.4 times, and the wear resistance of unhardened inserts that worked as a pair increased by 3.3 times in comparison with the unhardened pair. The highest wear resistance was obtained in a pair where ring samples underwent friction hardening during which oil with surface-active polymer-based additives was used as a process medium. Thus, the wear resistance of ring

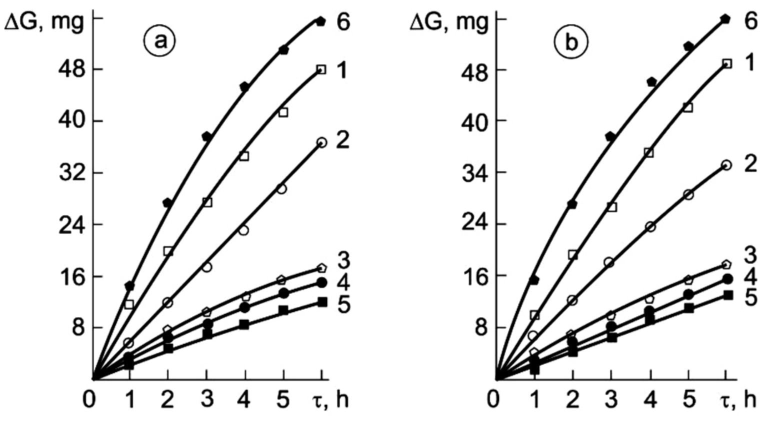

Fig. 4. Wear kinetics of the pair "cast iron EN-GJL-200 – cast iron EN-GJL-200" during friction of a ring (a) and an insert (b) in an oil-abrasive medium (*P* = 4.5 MPa; *V* = 0.9 m/s): 1 – grinding; 2 – hardening using high-frequency currents; 3 – ultrasonic machining; 4 – friction hardening, mineral oil; 5 – friction hardening, oil with surface-active polymer-based additives; 6 – intermittent white layer

Rys. 4. Kinetyka zużycia pary żeliwo szare EN-GJL-200–żeliwo szare EN-GJL-200 przy tarciu w środowisku olejowo-ściernym pierścienia (a) i wkładki (b) (*P* = 4.5 MPa; *V* = 0.9 m/s): 1 – szlifowanie; 2 – hartowanie prądem z wysoką częstotliwością; 3 – utwardzanie ultradźwiękiem; 4 – utwardzanie tarciowe, olej mineralny; 5 – utwardzanie tarciowe, olej z powierzchniowo aktywnymi dodatkami polimerów; 6 – warstwa biała przerwana

samples increased by 4.1 times, and the wear resistance of inserts increased by 3.8 times in comparison with the unhardened pair.

A hardened layer (white layer) during high values of machining and cutting modes (turning, milling, grinding) and during the operation of heavy-loaded friction pairs can be formed. During grinding, burn zones can be formed, which are similar in structure to white layers, and they are a cast-off of the processed surface. This burn zones have higher hardness than the base material of the surface and look like spots [**L. 3, 8, 9, 10**].

However, the main task of friction hardening is to form a uniform (solid) hardened layer on the surfaces of machine parts. In all cases, a qualitative uniform white layer was studied. To evaluate the effect of the quality of hardened layers on their wear resistance, ring samples were hardened in such a way as to obtain an intermittent (non-continuous) white layer. Studies have shown that, during friction in an oil-abrasive medium, the friction pair where a ring sample had an intermittent white layer had lower wear resistance than the unhardened pair. Thus, the wear resistance of both rings and inserts decreased by almost 20% in comparison to the unhardened pair. Therefore, for the normal performance of a friction pair during wear in an oil-abrasive medium and in order to obtain positive effects from surface hardening, it is necessary that a hardened layer is of high quality and uniform (solid) throughout the entire contact surface. If a hardened layer is intermittent, abrasive grains, including products of wear, are pressed into places that have lower hardness, and the durability of such a friction pair sharply decreases. This can explain why some authors obtained negative results with regard to the impact of hardened layers on the wear resistance of friction pairs.

A change in the unit load during friction in an oil-abrasive medium of the pair "cast iron EN-GJL-200 – cast iron EN-GJL-200" effects the wear rate of hardened and unhardened friction pairs in different ways. Thus, an increase in the unit load to *P* = 2 MPa leads to a sharp increase in the wear rate of an unhardened pair (**Fig. 5**). A further increase in the unit load to *P* = 4.5 MPa has a small effect on the wear rate value. A load increase to *P* = 6 MPa again leads to a sharp increase in the wear rate of an unhardened pair. During the wear of hardened pairs, the wear rate gradually increases with an increase in the unit load. Throughout the entire range of the studied unit loads, the highest wear resistance was obtained in the friction pair with ring samples after friction hardening where oil with surface-active polymer-based additives was used as a process medium. The nature of wear curves of inserts is similar to the wear curves of rings that worked with them as a pair. Hence, in order to increase wear resistance of a cast iron friction pair during sliding friction in an oil-abrasive medium, it is enough to harden only one component of the pair, usually the more technologically complex one.

During sliding of a friction pair in which rings had an intermittent white layer with an increase in the unit load, the wear rate of both rings and inserts was higher than that of an unhardened pair.

In practice, high-strength cast iron (ultimate tensile strength – 500 MPa, elongation at rupture, short – 2%) and bronze or Sn-Pb composite are used for heavy-loaded and critical friction units. The choice of materials

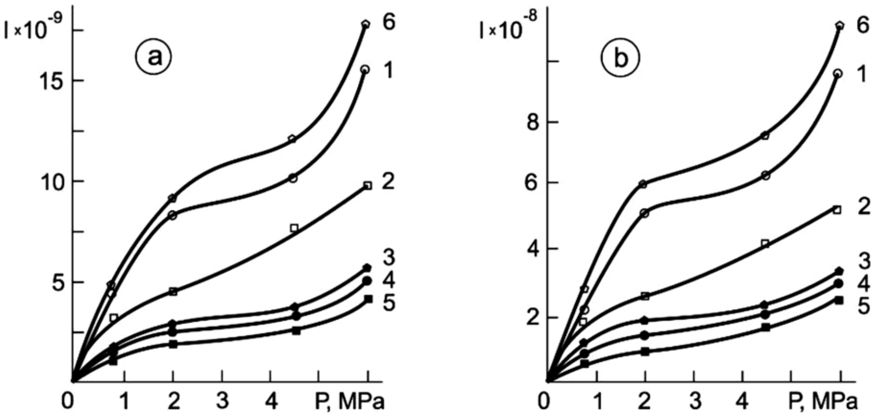

Fig. 5. The effect of the unit load on the wear of the pair "cast iron EN-GJL-200 – cast iron EN-GJL-200" during sliding of a ring (a) and an insert (b) in an oil-abrasive medium (*V* = 0.9 m/s): 1 – grinding; 2 – hardening using high-frequency currents; 3 – ultrasonic machining; 4 – friction hardening, mineral oil; 5 – friction hardening, oil with surface-active polymer-based additives; 6 – intermittent white layer

Rys. 5. Zależność zużycia pary żeliwo szare EN-GJL-200–żeliwo szare EN-GJL-200 od nacisku powierzchniowego przy tarciu w środowisku olejowo-ściernym pierścienia (a) i wkładki (b) (*V* = 0.9 m/s): 1 – szlifowanie; 2 – hartowanie prądem z wysoką częstotliwością; 3 – utwardzanie ultradźwiękiem; 4 – utwardzanie tarciowe, olej mineralny; 5 – utwardzanie tarciowe, olej z powierzchniowo aktywnymi dodatkami polimerów; 6 – warstwa biała przerwana

for friction pairs, as well as the use of surface hardening technologies, significantly affects the durability of friction pairs during wear. Experiments have shown that friction hardening significantly increases wear resistance during friction in an oil-abrasive medium (mineral oil +0.1% abrasive) of high-strength cast iron, which works as a pair with bronze CuSn5Zn5Pb5-C and Sn-Pb composite at the unit load of *P* = 4 MPa and sliding velocity of *V* = 1.2 m/s (**Fig. 6**). Friction hardening increases wear resistance of a "cast iron-bronze" friction pair by 3.5 times, and it increases wear resistance of inserts by 3 times.

Sn-Pb composite provides significantly higher wear resistance than bronze. The wear of unhardened rings, which were only ground, during friction with inserts made from Sn-Pb composite decreased by 2.3 times,

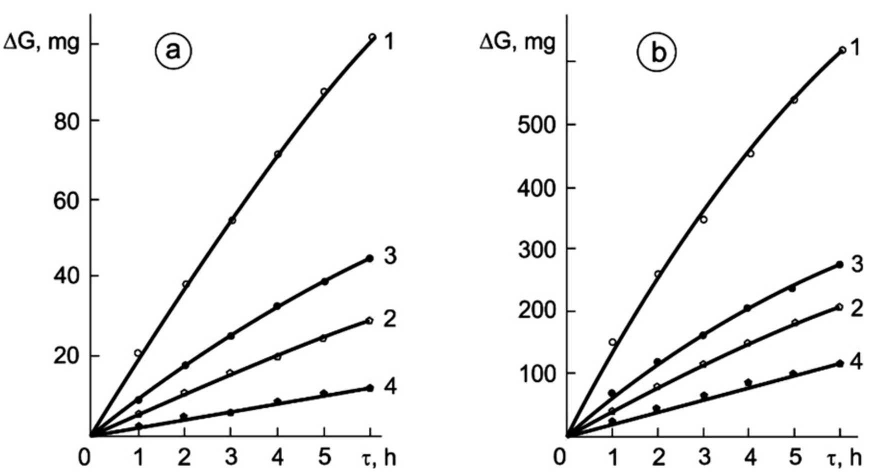

Fig. 6. Wear kinetics of the pair "high-strength cast iron (EN-GJS-500-7) – bearing alloy" during sliding of a ring (a) made from high-strength cast iron EN-GJS-500-7 and an insert (b) made from bronze CuSn5Zn5Pb5-C (1, 2) and Sn-Pb composite (3 , 4) in an oil-abrasive medium (*P* = 4 MPa; *V* = 1.2 m/s): 1, 3 – grinding; 2, 4 – friction hardening

Rys. 6. Kinetyka zyżycia pary żeliwo sferoidalne (EN-GJS-500-7)–stop łożyskowy przy tarciu w środowisku olejowo-ściernym pierścienia (a) z żeliwa sferoidalnego EN-GJS-500-7 i wkładki (b) z brązu CuSn5Zn5Pb5-C (1, 2) i Sn-Pb babbitu (3, 4) (*P* = 4 MPa; *V* = 1.2 m/s): 1, 3 – szlifowanie; 2, 4 – utwardzanie tarciowe whereas the wear of inserts decreased by more than 2 times in comparison with the wear of a similar pair with a bronze insert. In the case of the friction of rings that underwent friction hardening and work as a pair with an insert made from Sn-Pb composite, wear decreased by 3.8 times; whereas, in the case of the friction of inserts, wear decreased by 2.3 times in comparison with the unhardened pair. It should be noted that the wear of rings which underwent friction hardening decreased by almost 9 times during friction with an insert made from Sn-Pb composite, whereas the wear of inserts decreased by more than 5 times in comparison with the wear of unhardened rings that worked as a pair with a bronze insert. You can effectively increase wear resistance of friction pairs by applying new methods of shaft surface hardening, as well as by choosing the right antifriction materials for inserts.

CONCLUSION

A hardened nanocrystalline layer is formed in a surface layer in the course of friction hardening of cast-iron components, and the layer thickness is 90–120 µm, and the microhardness is 7–8 GPa. Grain size of the hardened surface layer was 20–40 nm near the treated surface.

The hardened layer significantly increases the performance of the pair "grey cast iron-grey cast iron" during sliding friction in the lubricated-abrasive medium. When increasing the unit load from 2 to 6 MPa, the wear rate of the hardened pair decreased by 2.6–4.2 times in comparison with an unhardened pair.

Only one component of the friction pair was hardened. After the hardening of both friction pairs, the effect of the increase in wear resistance is levelled off.

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