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Evaluation of Wear Mechanisms of Graphites Used for Crystallisers for Continuous Casting

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Abstract

This paper presents the results of research concerning the evaluation of tribological properties of graphite materials used, among others, for crystallisers for continuous casting of non-ferrous metals and their alloys. Graphite materials differing not only in their physical properties but also in the technology of their production were selected from a wide range of commercially available products. Wear resistance investigations of the tested graphite materials were carried out on a pin-on-disc tribometer under technically dry friction conditions on a sliding distance of 1000 m. A constant load but variable speed was used in the tests. The mean value of the coefficient of friction and the wear of the material were determined based on the tribological tests carried out. It was observed that as the speed increases, the average value of the coefficient of friction decreases, while the wear increases. A microstructural analysis of the wear track showed that the friction mechanism depends mainly on the graphite formation technology, which is related to the microstructure of the tested materials, and to a lesser extent to their physical and mechanical properties. Varying the speed values made it possible to trace changes in the wear mechanism, on the basis of which it is possible to predict the durability and reliability of graphite crystalliser operation.

Keywords: Innovative foundry technologies and materials, Wear resistance, Graphite, Crystalliser, Tribology

1. Introduction

Continuous casting of metals and their alloys is one of the basic processes for the manufacturing of semi-finished products and products with different cross-sectional geometries for further plastic processing. With the proper selection of casting parameters, this process can be carried out continuously and products with high surface quality can be obtained [1-2]. The most used material for crystallisers for continuous casting of non-ferrous metals and their alloys is isostatically or pressure-formed graphite [3]. The division differentiating graphite depending on the densification process results from the lack of differences accompanying the remaining stages of the forming technology, which include fragmentation of carbon materials, preparation of compositions with a specific composition, impregnation of compressed graphite with pitch, pressing and annealing at elevated temperatures of the densified material in the carbonisation process (around 1000°C) and graphitization (around 3000°C).

Graphite materials used for continuous casting products should be characterized by an appropriate set of functional features, mainly high hardness, bending and compressive strength, abrasive wear resistance, heat resistance, thermal conductivity, and low electrical resistivity [4-6]. Wear of crystallizers as a result of abrasion of the internal part by friction of metal against graphite, as well as burning due to high temperature and the presence of oxygen, leads to deterioration of the surface quality of the cast products and the formation of structural defects.

An important factor influencing the quality of the cast product, especially the quality of its surface, is the possibility of creating a lubricant layer between the internal surface of the crystalliser and the surface of the cast [7]. This eliminates the need to use additional lubricants in the form of e.g., mineral oils, synthetic oils, or powders. The formation of a self-lubricating layer in graphite crystallizers is possible due to the specific structure of the graphite crystallographic cell [8]. Low value of graphite shear strength causes destruction of bonds in the {100} plane, separation of hexagonal carbon (graphene) layers and formation of a layer of wear products (tribofilm – solid lubricant) separating the surfaces of interacting materials [9-10].

This paper presents the results of a study of the tribological properties of different types of graphite materials used to produce crystallisers for continuous casting of non-ferrous metals and their alloys. The wear mechanism was characterised as a function of load and speed.

2. Materials and research methodology

Graphites offered by various companies were used in the research. Three types of isostatically pressed graphites were used for the tests: CGT Carbon GmbH CGI-185 (C iso), SGL Carbon SIGRAFINE® R4550 (R iso), Sinograf SA HG 22 (H iso) and isostatic pressed graphite Sinograf SA IEG 45 (I pres). The general characteristics of the materials tested are shown in Table 1. This table also includes the results of Brinell hardness measurements. The hardness measurement was carried out on an HK 467 machine with a load of 365 N and a ball diameter of 5 mm.

Table 1.
Properties of tested graphite materials

Material	Density, g/cm^3	Grain size, μm	Porosity, %	Thermal conductivity, W/mK	Coefficient of thermal expansion, $x10^{-6}K$	Hardness Shore'a, D	Brinell Hardness, HB
C iso	1.77	-	15	100	4.0	52	139
H iso	1.82	7	17	105	5.1	64	140
R iso	1.83	10	10	105	4.2	68	159
I pres	1.80	<45	15	110	3.8	75	91

Observations of the microstructure and macroscopic traces of the wear surface were carried out using an Olympus 148 microscope and a KeyenceVHX-7000 digital microscope. A HitachiS-3400N scanning microscope was used for the analysis of the wear mechanisms. Tribological properties (coefficient of friction, wear) were evaluated according to ASTM G99-05 norm based on tribological tests carried out on a pin-on-disc high-temperature tribometer from CSM Instruments. The tests were carried out at ambient temperature with a constant load of 10N and variable speeds of 10, 25 and 50 cm/s, over a sliding distance of 1000 m. The average value of the coefficient of friction was determined on the basis of the course of the friction coefficient for the distance covered and distance. The counter-sample was a ball made of 100Cr6 steel with a diameter of 6 mm. The samples and counter-samples were weighed on laboratory scales with a resolution of 0.1 mg before and after the test and the mass loss was determined from the differences in weight. The change in speed was used to determine how quickly a layer of wear products would be formed during friction with the formation of a lubricating tribofilm.

3. Analysis of the research results

The change of graphite properties is mainly determined by their density. Increasing the density increases thermal properties, hardness and reduces porosity. The most homogeneous structure is characteristic for the R iso and H iso material types (Fig. 1). The grain size is close to the value given by the producers [11], the grains are evenly distributed, well connected with each other with a small number of pores. In the Ciso isostatically pressed and pressure-pressed material, greater porosity can be noticed, and above all the presence of very large grains (over 50 μm), unevenly distributed in the structure.

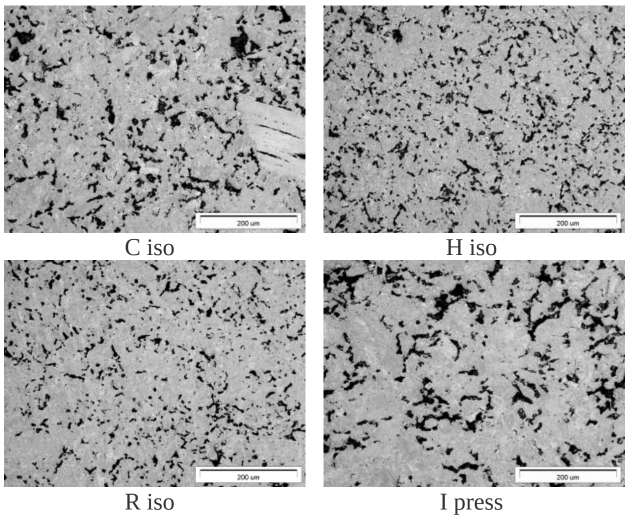
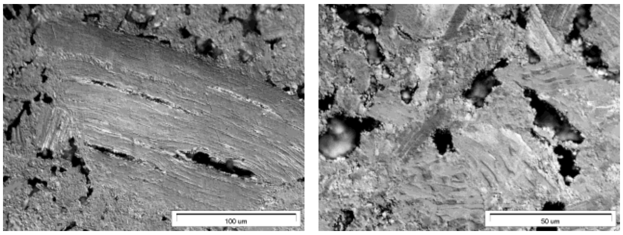


Fig. 1. Microstructure of tested materials manufactured by isostatic pressing (C iso, H iso, R iso) and unidirectional pressing (I press), LM

It is probably related to improper fragmentation of carbon components prior to the densification process. The grains are polygonal in shape, and their structure is layered (Fig. 2). Microstructure observations in this case differ from the data presented in the technical characteristics of the materials. The grain size in graphite also influenced its hardness.

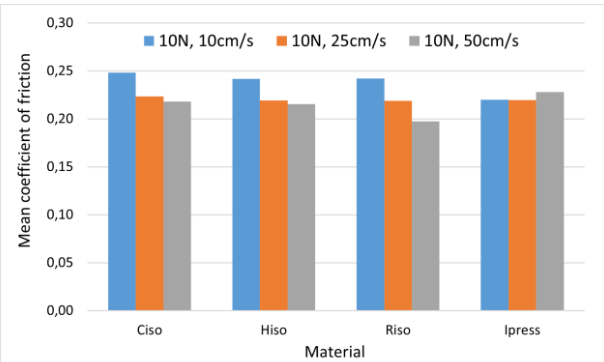


C iso I press

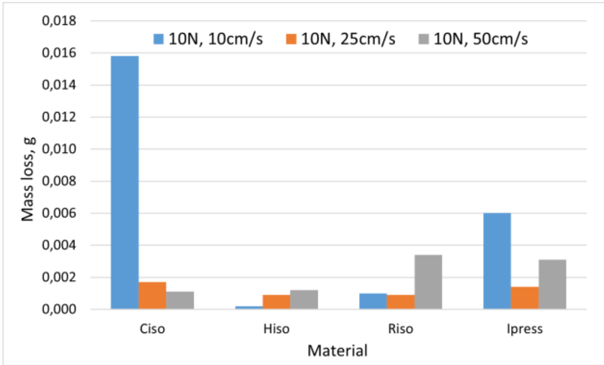
Fig.2. Form and microstructure of the precipitates in graphite material C iso and I press, LM

This type of precipitates structure may indicate a properly performed graphitisation process, during which an amorphous carbon phase forms a graphite crystalline phase [12-13].

Analysing the change in the mean value of the coefficient of friction (Fig. 3A), it can be seen that the value of the coefficient of friction decreases with increasing speed. This relationship applies to isostatically pressed materials. However, the effect of speed on mass loss is difficult to determine (Fig. 3B). For graphite types C and I, it decreases with increasing speed, while for graphite types H and R it increases. Such changes may be dependent on the microstructure present in the graphites. The microstructure of C and I materials (Fig. 1) is more heterogeneous. It contains precipitates that can degrade and chip very quickly in the friction process. Additionally, due to the type of tested material, which is characterised by high hygroscopicity, and due to environmental conditions of the tests conducted – difference in humidity level, results of mass loss of the samples are difficult to interpret. This applies particularly to the mass loss of the counter-sample, which was a ball made of 100Cr6 steel.



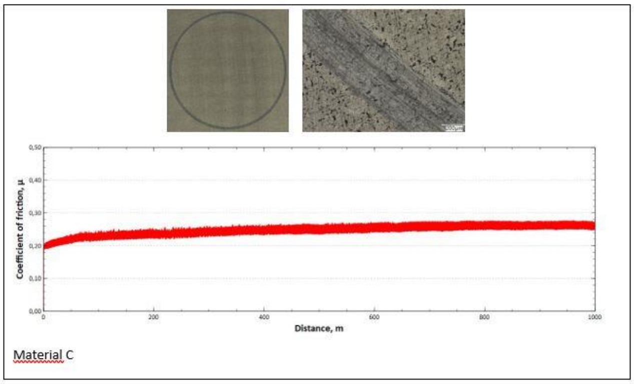
a)

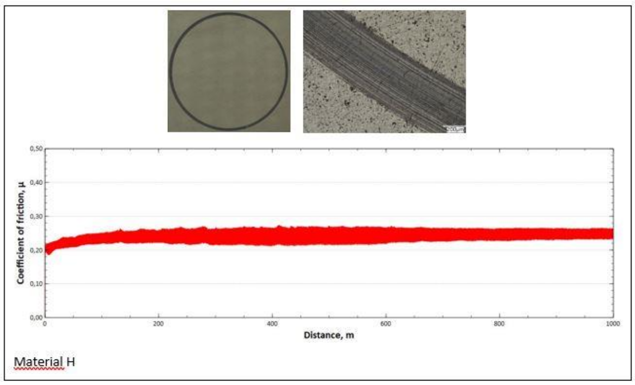


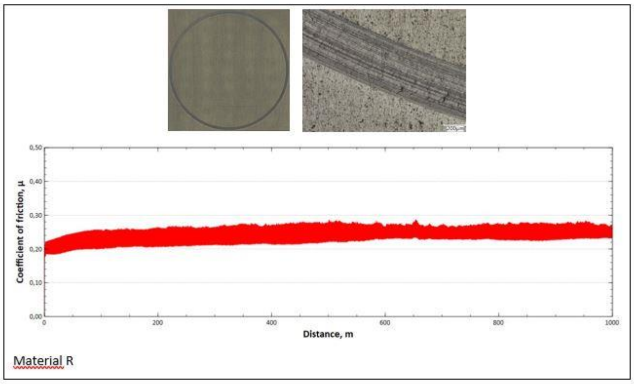
b)

Fig. 3. Change of the mean coefficient of friction (a) and wear (b) of graphites as a function of speed

This behaviour is confirmed by changes in the coefficient of friction as a function of the sliding distance and macroscopic wear tracks. Sample courses of the coefficient of friction as a function of the sliding distance for the tested materials are shown in Figs. 4 and 5. A comparison of values of the coefficient of friction as a function of the sliding distance and microphotographic images of wear tracks was made for the speed of 10 cm/s (Fig. 4) and 50 cm/s (Fig. 5).







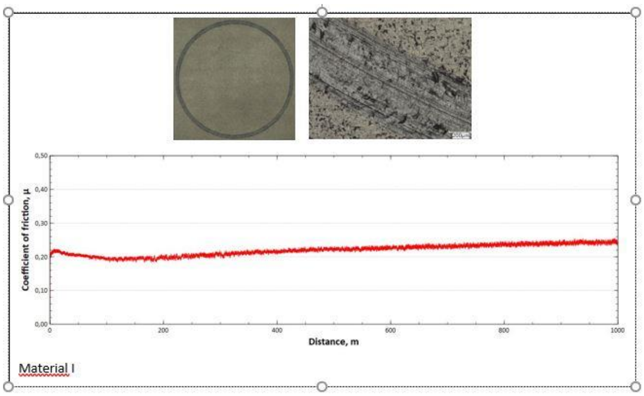
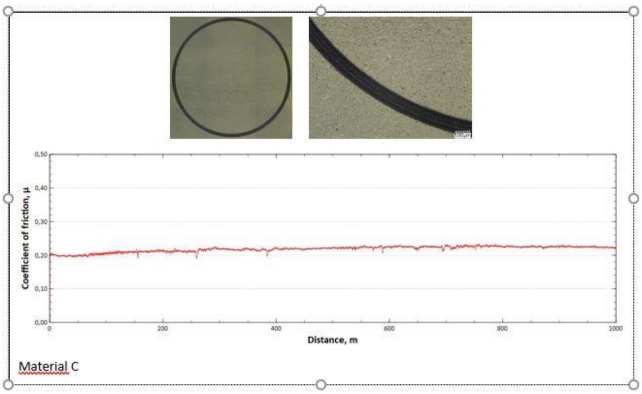
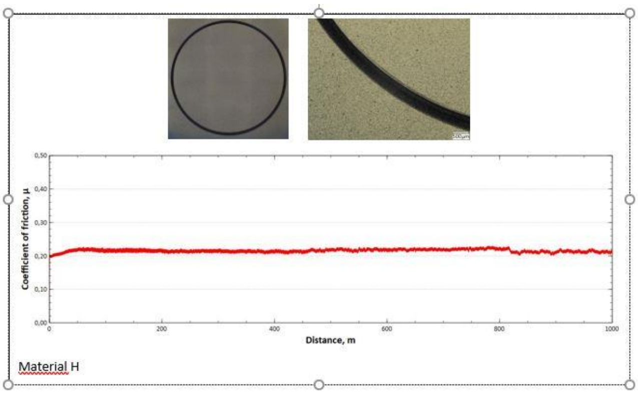
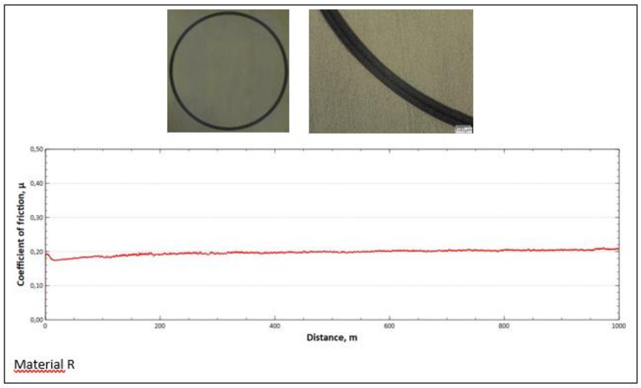


Fig. 4. Course of coefficient of friction changes and wear tracks with the load of 10 N and speed of 10 cm/s







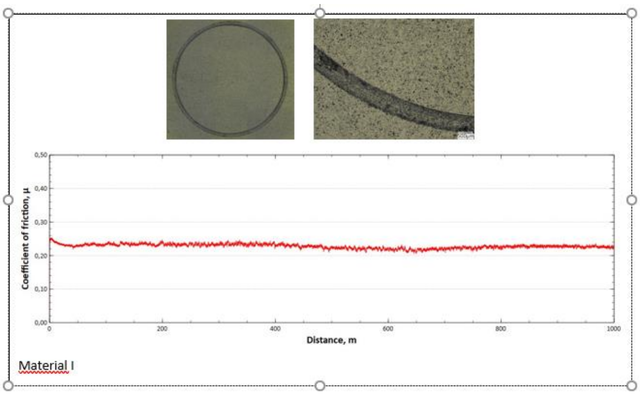


Fig. 5. Course of coefficient of friction changes and wear tracks with the load of 10 N and speed of 50 cm/s

The main difference between the two compared series of samples is the smaller width of the wear track for the samples after tests conducted at the speed of 10 cm/s. In the case of lower speed (10 cm/s) the dominant wear mechanism is micro-cutting, causing large differences in instantaneous values of friction forces, which makes the COF course very unstable. At the speed of 50 cm/s for isostatically pressed materials, changes in instantaneous coefficient of friction values are more stable. Scratches caused by micro-cutting are still visible in the wear track. Plastic deformation, destruction of graphite grains on the friction pair contact surface and deposition of the resulting wear products on the graphite surface are also observed.

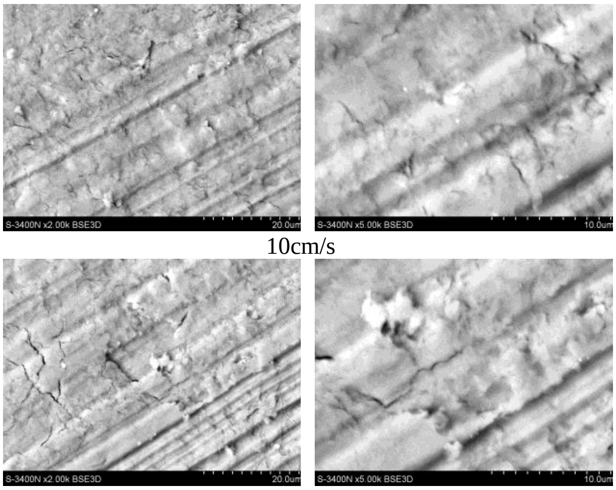


Fig. 6. Topography of the friction surface of graphite C iso under load of 10 N and speed of 10cm/s and 50 cm/s

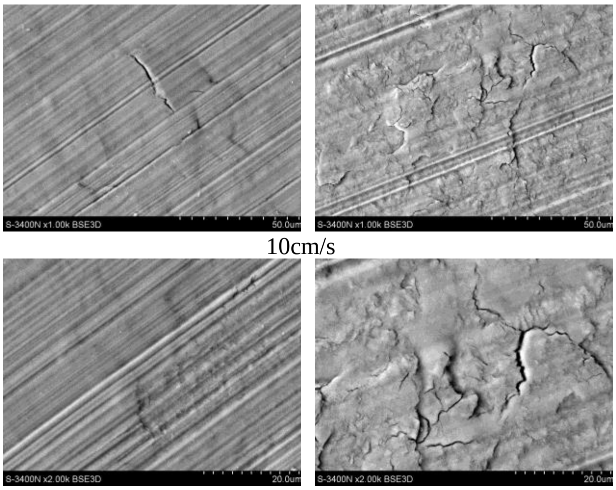


Fig. 7. Topography of the friction surface of graphite R iso under load of 10 N and speed of 10 cm/s and 50 cm/s

The confirmation of the degradation of the structure of graphite materials are the test results obtained with a scanning microscope. The wear surface analysis was carried out for all groups of the graphite materials tested after tribological tests at the speed of 10, 25 and 50 cm/s. The article presents only the test results for isostatically pressed graphite materials with the most different microstructure, namely C and R material at the lowest and highest speed. As it can be observed at low speed (Fig. 6 and Fig. 7), grooves and scratches appear on the graphite surface, and at higher magnification, small cracks perpendicular to the direction of sliding are visible. Increasing the speed caused that, in addition to marks of micro-cutting, areas with a large number of cracks, delamination of large areas of graphite and adhesion of wear products to the surface (Fig. 6) can be noticed. In the case of material R, only micro-cutting scratches are visible at low speed. On the other hand, at high speeds, micro-cutting is accompanied by cracks formed between the graphite grains and the detachment of small plastically deformed grain fragments caused by delamination. In such places of the track of interaction (Fig. 7), scratches and grooves created by abrasive wear do not occur.

Fig. 8 shows the friction surface topographies obtained with the use of an optical profilometer. On their basis, it can be traced how increasing the sliding speed affects the changes in the wear mechanism. In the case of low speed (10 cm/s), only the grooves and scratches characteristic of wear as a result of micro-cutting are visible (Fig. 8A). However, at the speed of 50 cm/s, no abrasive wear processes were observed. Graphite grains crack, deform plastically, are torn out and removed from the friction surface (Fig. 8B).

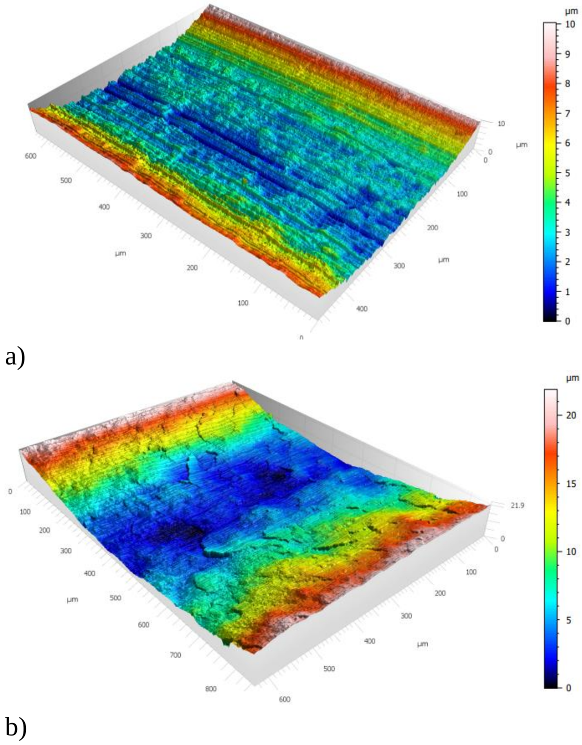
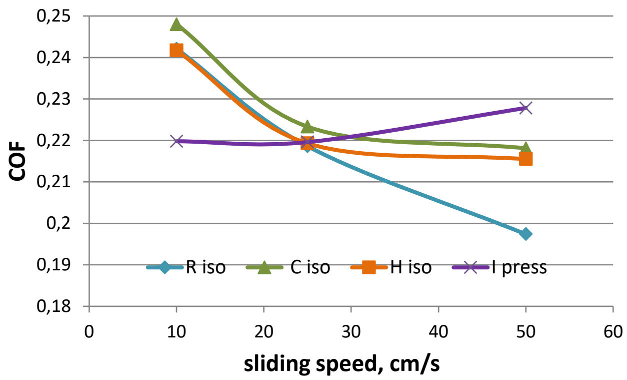


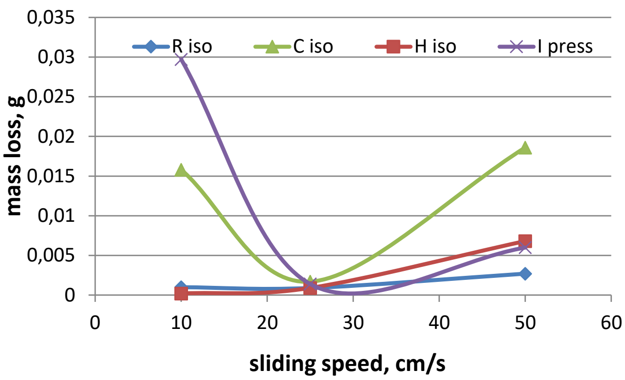
Fig. 8. 3D profile of the friction surface after tribological tests of the R iso material at the speed of 10 cm/s (a) and 50 cm/s (b)

On this basis, it can be concluded that in the case of higher speed, the wear products formed as a result of cutting and delamination adhesively stick to the graphite surface, creating an intermediate layer between the interacting surfaces. The formed layer of wear products acts as a solid lubricant and thus contributes to the reduction of the coefficient of friction. As a result, with increasing speed, the value of the coefficient of friction decreases (Fig. 9A). Only in the case of unidirectionally pressed material (I press) such a relationship does not take place. This is probably due to the fact that the fracture of the large, over 100 μm, poorly bonded graphite grains (Fig. 2) splits into large fragments, which do not fragment further and act as an additional friction element (abrasive material) between the interacting materials.

Increasing the speed contributes to a slight increase in the consumption of H iso and R iso graphites (Fig. 9B), which is the result of an increase in the permissible load, expressed as the product of the sliding speed and the load. In the case of C iso and I press graphites the greatest wear was recorded at the speed of 10 cm/s, the consumption is almost an order greater than at higher speeds. This is probably due to the presence of very large grains, larger than in other materials of R and H type. Large hard grains are well bonded to the carbon matrix, they are not pulled out and removed from the friction surface. However, they are subjected to intensive cutting processes (abrasive wear). Increasing the speed and the accompanying vibrations contribute to the cracking of the grains and their fragmentation. Small, detached grain fragments are further crushed to form wear products adhesively stuck to the surface of the interacting materials, reducing wear.



a)



b)

Fig. 9. Effect of speed on mean coefficient of friction (a) and wear (b)

4. Conclusions

The results of the research allow to state that the tribological properties of graphite materials are determined by their microstructure. A high homogeneity and uniformity of graphite grains ensure a stable value of the coefficient of friction and has a significant impact on the wear mechanism under friction conditions. Small size grains defragment faster into fine wear products. By bonding adhesively with the surfaces of interacting materials, they form a layer of solid lubricant and reduce their wear.

Tribological properties of graphites used for continuous casting crystallisers also depend on friction conditions. An increase in speed contributes to a decrease in the friction factor, stabilises its course, and reduces differences between instantaneous values of friction forces. On this basis, it can be assumed that itis possible to increase the speed of casting the ingot in the continuous casting process and to extend the working life of the crystalliser.

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