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PREDICTION OF TRIBOCORROSIVE PROPERTIES OF ADI CONTAINING Ni-Cu-Mo

In the case of mining machines, tribocorrosion damage is often observed. This type of consumption is caused by the joint action of mining environment factors such as abrasive and water. The search for methods to counteract tribocorrosion is of great practical importance, but it must be combined with the knowledge of methods of forecasting the value of wear. This paper presents a model of prediction of tribocorrosive wear adapted to corrodible materials – ADI containing Ni and Cu, with the strength class of 800 MPa – and results of a two-stage study on the tribocorrosive wear. Presented results indicate a distinct effect of synergy between friction and corrosion in the total wear of ADI. The tribocorrosion tests confimed the adequacy of the model developed for the ADI.

Keywords: ADI, tribocorrosion, wear

1. Introduction

Tribocorrosion is one of significant causes of damage to elements of machines and equipment working in difficult operating conditions (Fig. 1) characterized by the action of hard grains of abrasives, water and various types of salts contained in water. The combined action of these factors leads to a synergistic effect that intensifies the negative impact of individual factors.

The occurrence of an excessive tribocorrosive wear may significantly reduce the durability of machines [1,2]. An important factor that can significantly contribute to a better protection of machine joints against tribocorrosion may be the development of computational tools that allow predicting the course of the wear process. The availability of such simulation tools will allow selecting an appropriate material combination as early as at the design stage, ensuring a minimal wear in the conditions of

A **B**

Fig. 1. Examples of tribocorrosive damage to: A – teeth of chain drums used in mining, B – sections of conveyor routes; designation: 1 – wear zone [26]

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simultaneous actions of corrosive and mechanical factors. The necessity of developing predictive models (computer programs) is currently one of the main areas of the activity in the scope of studies on tribocorrosion [9-21].

The main problems associated with an effective mathematical description of the course of the tribocorrosion process are as follows:

– identification of areas of the actual contact of friction pair elements – these are areas where friction wear takes place and electrochemical processes are initiated,
– description of electrochemical processes (corrosive digestion, passivation) in conditions of friction contact,
– proper reflection of the effect of synergy between friction and corrosion in the area of the actual contact.

This study is a part of a cycle of publications by the Authors concerning the properties of austempered ductile irons (ADI) in operating conditions [3-8]. In particular, this paper is a continuation of the work [8], which presents the results of laboratory and experimental tests of ADI. The paper presents a method for predicting the process of tribocorrosive wear, which was verified on the basis of previously obtained test results.

2. The current state of knowledge in the area of prediction of tribocorrosive wear

Many researchers in various centres [12-21] attempted to develop a model describing the process of tribocorrosion. The purpose of these activities was to reflect the main relationships between the process conditions and the wear of materials. The most significant achievements in this area are briefly characterized below – along with the indication of the aspects important for a comprehensive mathematical description of the effects of the tribocorrosion process.

T.A. Adler and R.P. Walters [12] have developed – for a ball-on-disc pair – a model that allows estimating the area of the surface deformed at a friction contact and the share of the area with removed layer of passive oxides. They obtained a solution that allowed describing the impact of the load on a friction pair on the process of mechanical wear (micro-cutting) and corrosive wear. These researchers also demonstrated a variation in the intensity of tribocorrosive wear along the friction path and during the course of the test. This last conclusion may suggest that one of the most effective calculation methods may be the iterative method – predicting the wear for successive movement phases of the pair.

An interesting model of tribocorrosion for a pin-on-disc pair was proposed by H. Abd-El-Kader et al. [13,14]. They put a particular emphasis on the kinetics of rebuilding of passive layers on surfaces uncovered as a result of micro-cutting. The authors paid attention to the cyclic character of elementary interactions at the sliding contact: the structure of the passive layers and their removal as a result of friction. They also used a logarithmic model to describe the changes in the intensity of electrochemical processes in the areas uncovered as a result of contact interactions.

In turn, S. Mischler et al. [15, 16] formulated a model for predicting the corrosive wear in the friction conditions for a pin-on-disc pair at polarization with a passive potential. It is the first mathematical model of passivation kinetics in a friction area, which takes into account the size of the area. The solution was obtained by combining two different concepts of formation of a passive layer:

– surface coverage – lateral growth of the oxide layer with an „elementary" thickness,
– layer growth – uniform growth of the layer thickness in the whole area, determined by the electric field (difference between the passivation potential and the potential of the wear surface).

The solution obtained enables effective prediction of the impact of pressure in the contact zone, speed of sliding, and the polarization potential on the tribocorrosion current and corrosion wear in friction conditions. However, the model does not allow calculating the mechanical component of the loss of the material. An important element of the S. Mischler's model, which provides a premise for a comprehensive approach, is the analysis of the interactions that cause the wear (friction, corrosion) in relation to individual protrusions in the roughness of the real surface of contact of the friction pair elements.

In the tribocorrosion models described above, it has been assumed that the mechanical separation of the material at the friction contact essentially takes place as a result of micro-cutting. Almost every contact interaction in a sliding pair leads to immediate removal of the deformed volume of the material. Other mechanisms determining the wear are proposed in the following works:

– G.E. Lazarev [17] – low-cycle fatigue,
– G.P. Cherepanov [18], M. Stack et al. [19] – propagation of corrosion-fatigue crack.

According to G.E. Lazarev [17], the separation of the micro-volume of the material deformed at the friction contact (crest of the roughness of the actual surface of contact) does not occur immediately (after each contact), but requires a certain number of interactions. In turn, in [18, 19], it has been assumed that the crack propagation results from corrosive fatigue. Separation of wear particles occurs when the gap reaches a length corresponding to the dimension of the structural element of the material. The average size of wear particles was determined for the needs of computational analyses. G.P. Cherepanov assumed that the structural element of the material (also the wear particle) has the shape of a cube. However, the authors of the work [19] proposed a ball as a model of the wear particle. The mechanism of the wear of the sliding pair resulting from the propagation of the corrosion-fatigue crack, which was described by G.P. Cherepanov, M. Stack et al., has not been identified experimentally yet.

In order to use most of the existing models, it is necessary to perform specialist experiments earlier to determine the data necessary for the calculations. These models are basically created on the basis of data obtained during experimental research. They primarily approximate the results of experiments. Currently, studies on models that allow predicting the effects of tribocorrosion on the basis of basic data on material properties and operating conditions of the pair (pressure in the contact zone, character of the corrosive environment, geometry and movement of the friction pair elements) are undertaken more and more often. Such models are to enable prediction of the specificity of tribocorrosion without carrying out any specialist tests. The original model proposed below involves an attempt to perform such tests.

3. Original computational model

The authors of the paper have developed a model for predicting the tribocorrosion for ADI in a pin-on-plate sliding pair at the free corrosion potential. For this purpose, there was adapted a solution created for corrosion-resistant steel (showing the ability to passivation) in conditions of polarization with a potential from the passive range (the model described in [22-25]).

The base model assumes an analysis of elementary interactions in the frictional contact within the roughness protrusions in the real surface of contact (Fig. 2).

For this purpose, rough surfaces of mating elements in the pin-on-plate pair have been represented as a system of adjacent cuboids (roughness protrusions). For a given position of the pin on the friction path, the projections forming the real contact surface (black rectangles) are identified. The criterion for the selection is the evenness of the material hardness and the actual contact stresses. The analysis of the state of strains and stresses is carried out only for the roughness protrusions constituting the real surface of contact. The model takes into account two mechanisms that lead to the detachment of the deformed "crest" of the roughness protrusion: micro-cutting and low-cycle fatigue. In the case of micro-cutting, the mechanical wear in conditions of tribocorrosion of the roughness protrusion of the sample ($V_M = V_f + \Delta V_f$) is equal to the volume of the material in the crest deformed by the hard protrusion in the pin's roughness.

Material loss caused by electrochemical processes ($V_K = V_{cor} + \Delta V_{cor}$) in tribocorrosion conditions is determined on the basis of the Faraday's equation. The value of the current from the area of friction, which is necessary for the calculations, is generated on the basis of the concept proposed by H. Abd-el-Kader et al. [13,14]. This concept concerns a mathematical description of the kinetics of oxidation of the metal surfaces uncovered as a result of cyclic abrasion. According to [13], the intensity of oxidation can be expressed by the following dependence:

$$h = C \cdot \log(\tau) \tag{1}$$

where:

h – depth of the layer of the material removed as a result of the action of corrosive factors,
C – constant,
τ – time.

In turn, the loss of material caused by electrochemical processes is described by the Faraday's equation:

$$h = \frac{k}{\rho} \cdot i_a \cdot \tau \tag{2}$$

where:

k – Faraday constant,
ρ – material density,
i_a – current density.

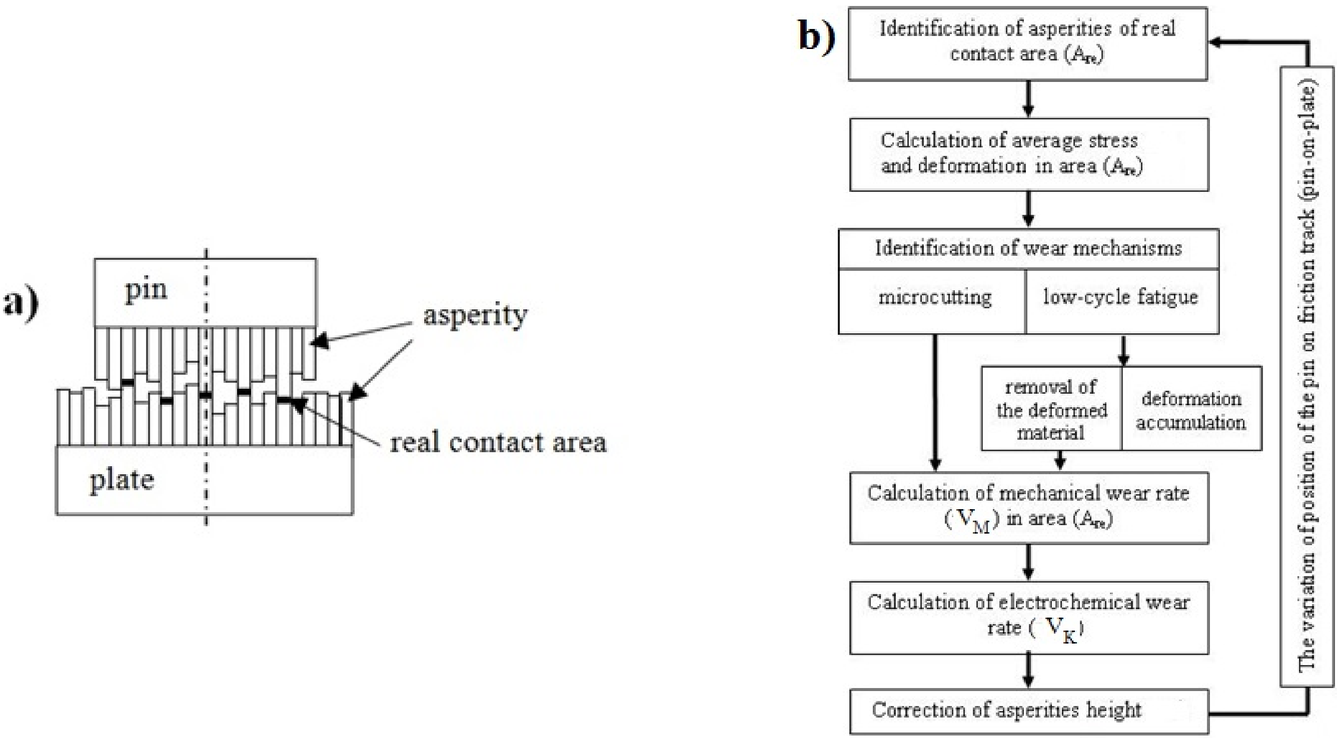


Fig. 2. Computational model: a) axial cross-section of the pin-on-plate combination, b) computational algorithm of tribocorrosion process in sliding pair

Using the equations (13-14), it is possible to describe the change in the current density on the friction surface as a function of time. Calibration of the model – determination of the coefficient (C) – is performed for the time (τ) corresponding to the movement of the pin between the extreme positions and for the corrosion current density. Corrosive wear is determined only in those areas where the base material had been previously uncovered due to the action of friction factors.

The total wear (V_t) in conditions of tribocorrosion is determined as the algebraic sum of the wear caused by friction (V_M) and by electrochemical processes (V_K):

$$V_t = V_M + V_K = (V_f + \Delta V_f) + (V_{cor} + \Delta V_{cor}) \quad (3)$$

After completing the analysis of elementary interactions for the roughness protrusions of the real surface of contact (at a given position of the pin on the friction path), the height of the protrusions is corrected with the calculated value of the total wear. The actions of mechanical and corrosive factors are analyzed cyclically in accordance with the rule that friction wear initiates electrochemical processes on newly uncovered surfaces. Each of the elementary interactions changes the geometry of the sample surface and thus affects the further course of the wear process. The „inheritance" of the effects of the previous stage of interactions was used in the model in order to take into account the interaction between friction and corrosion (components (ΔV_f) and (ΔV_{cor})).

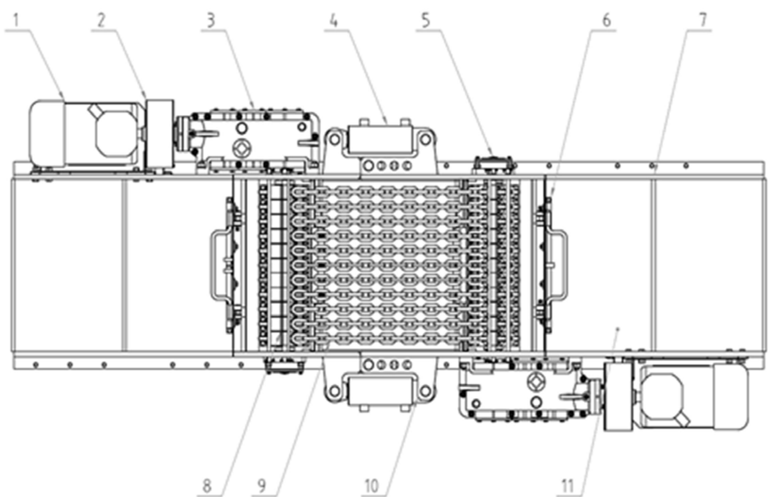
5. Results and discussion

In order to verify the results of calculations, the results obtained during the experiments carried out in laboratory conditions were used. The concept of the research has been described in detail in [8]. A pin-on-plate pair was used in the laboratory tests. The pin made of cemented carbide (in the shape of a truncated cone) has been sliding against the surface of a cubic sample of the cast iron. The diameter of the flat tip of the pin was approx. 0.5 mm and the edge of the sample – approx. 10 mm. The pin moved in a reciprocating motion on a 6 mm section, with a frequency of 5 Hz. All the tests were carried out for the pressure of 45 MPa and consisted of 54,000 movements of the pin. The tribocorrosion process was tested in 3.5% NaCl. The main result of the test was the intensity of the wear expressed as the increase in the depth of the wear trace related to one movement of the pin.

Operating tests were carried out with the use of an original test rig [3,4,7] which allowed reproducing the combined action of destructive factors. A schematic diagram of the test rig is shown in Fig. 4A. The action of the loose quartz abrasive and water containing 3.5% of NaCL was reproduced by filling the box of the test rig with dry abrasive, NaCl and by adding fixed amount of water periodically. The initial content of water in the abrasive was determined by measuring out 1000 kg of washed quartz sand with a grain size up to 1 mm and adding 100 liters of water. During the operation of the test rig, water evaporated from the abrasive mixture. In order to prevent the possibility of operating the test rig with dried abrasive, 10 liters of water were added to the mixture every 2 hours, which restored its initial consistency (Fig. 4B). However, at the end of the wear tests with a hydrated mixture of sand, a qualitative change in the consistency of this mixture was observed, which was caused by the fact that the removed oxide layers were present in it.

Two identical sets of chain wheels made of ADI_800 were used for the wear tests. One of them was used in the test in the presence of abrasive only, while the second was tested in conditions of combined action of the abrasive and water with salt.

Table 2 contains values describing the intensity of the tribocorrosive wear and its components calculated with the



A

B

Fig. 4. Schematic diagram of the test rig: 1 – Induction motor 22 kW, 2– Flexible coupling, 3 – Conical–cylindrical reduction gear, 4 – Hydraulic cylinder, 5 – Axle shaft, 6 – Sprinkler system for the test chamber, 7 – Body of the test rig, 8 – Test samples, 9 – Chain, 10 – Mounting bracket of the hydraulic cylinder, 11 – Additional chamber for aggregate.

use of the original model described in the previous section as well as the results of the tests (operating and laboratory tests) presented in [8]. The summary of the results of the experiments and calculations enables verification of the effectiveness of the predictive model.

TABLE 2

The results of experimental tests and calculations of tribocorrosion wear

	Operational test	**Laboratory test**	**Calculation results (prediction)**
Total loss of material V_t (avearage), nm/cycle	1,18	0,093	0,081
Wear caused by frictional impact of the abrasive V_f (avearage), nm/cycle	0,786	0,056	0,056
Ratio V_f/Vt, %	66,6	60,0	69,1
Corrosive wear in the presence of stationary abrasive and electrolyte V_{cor}, nm/cycle	0,089	0,007	0,0068
Ratio V_{cor}/V_t ,%	7,5	7,5	8,4
The increase in the wear resulting from the synergistic effect of the abrasive on corrosion ΔV_{cor}, nm/cycle	0,162	0,013	0,011
The total value of the corrosive wear component in the presence of stationary abrasive and an increase in the wear as a result of the synergistic effect of the abrasive on corrosion, $\Delta V_{cor} + V_{cor}$, nm/cycle	0,250	0,020	0,018
Ratio $(\Delta V_{cor} + V_{cor})/V_t$,%	21,9	21,4	22,2
The increase in the wear resulting from the synergistic effect of corrosion products on the composition of the abrasive, ΔV_f, nm/cycle	0,144	0,017	0,007
Summary effect of the synergy of the action of the abrasive and corrosion, $\Delta V_f + V_f$, nm/ cycle	0,930	0,073	0,063
Ratio $\Delta V = \Delta V_{cor} + \Delta V_f$, nm/cycle	0,306	0,030	0,018
Ratio $\Delta V/V_t$,%	25,9	32,7	22,2
Ratio $\Delta V_f / \Delta V$,%	47,1	57,0	38,9
Ratio $\Delta V_{cor} / \Delta V$,%	52,9	42,9	61,1

One of the aims of this study was to verify the effectiveness of the laboratory test in reflecting the nature of the tribocorrosion wear process, which occurs in real operating conditions. The authors believe that tribocorrosion by its very nature involves the relationships between the effects of mechanical and corrosive factors resulting from the properties of the material tested. These relationships are measured by the percentage of the wear of the components (V_f, V_{cor}, ΔV) in the total material loss. The absolute effect of the two tests (expressed in nm/cycle) is different. However, this is due to the fact that the elementary wear mechanisms in the tribocorrosion process are intensified to different extents depending on the specificity of the friction node (geometry, dynamics of relative displacement, etc.). The test methods presented in the article are designed chiefly to carry out a comparative assessment of engineering materials used in different machine nodes. The essence of the analysis is to assess the effects of material properties on the intensity of tribocorrosion (different materials tested under the same conditions). In the laboratory test, the authors attempted to imitate the enforcements ensuring the maintenance of relative relations between the components of tribocorosion (compared to the results of the in-service test). Despite differences in wear intensity between laboratory and operational tests, the laboratory test can be considered as an effective method to assess tribocorrosion resistance in the comparative assessment of engineering materials.

The results of the laboratory test reflect the main trends in the relationships between the components of the tribocorrosive wear identified during the tests conducted in conditions similar to real operating conditions. When comparing the results obtained in the laboratory and operating tests, a satisfactory compliance in the scope of the effect of synergy between friction and corrosion (32.7% for laboratory conditions and 25.9% for operating conditions) was found. The laboratory test can be an effective method in the comparative assessment of the resistance of materials to tribocorrosive wear.

A comparison of the test results and the results of the analytical prognosis of the effects of tribocorrosion allows formulating the following findings:

1. The difference between the experimentally determined (laboratory test) and calculated value of tribocorrosive wear (V_t) is approx. 13%. In the area of the tribological studies, such a level of effectiveness in predicting the loss of material can be considered satisfactory.
2. The results of calculations of the tribocorrosive wear accurately reflect the most specific aspect of the tribocorrosion process – a distinct effect of synergy between friction and corrosion (components: $\Delta V_f > 0$, $\Delta V_{cor} > 0$).
3. The shares of the calculated values of the tribocorrosive wear are similar to the levels found on the basis of the results of experimental studies. They indicate a predominant share of the mechanical wear (V_f) – over 60%. The developed model accurately reflects the relationships between the actions of frictional and corrosive factors in the process of tribocorrosive wear.
4. The computational model of the wear process (as well as the laboratory test) developed by the authors can be used for comparative assessment of materials in the scope of the resistance to tribocorrosion.

It should be noted that the computational model developed by the authors was verified positively only for one material – Austempered Ductile Iron – and for the selected friction pair (pin-on-plate sliding joint in 3.5% solution of NaCl at the free corrosion potential). In the future, the tests should be conducted for a larger group of materials and a wider range of excitations.

5. Conclusions

1. The results presented in the paper indicate a distinct effect of synergy between friction and corrosion in the total wear of ADI. This effect was identified in the studies in the model and real conditions, and was also reflected in the computational prediction.
2. The model for predicting the wear developed by the authors can be considered as an effective computational tool for the process of tribocorrosion of ADI in a pin-on-plate sliding joint in 3.5% solution of NaCl at the free corrosion potential. The model accurately reflects the intensity of the loss of material as well as the relationships between the processes that determine the wear.
3. The results of tests and calculations presented in this paper indicate that the test conducted in laboratory conditions and the prognostic model can be used for a comparative assessment of resistance of materials to tribocorrosive wear equally effectively as the operating test.

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