THE INFLUENCE OF THE CAST-IRON AND STEEL MICROSTRUCTURE AND HYDROGEN CONTAINING ENVIRONMENTS ON THE DESTRUCTION INTENSITY DURING SLIDING FRICTION

PART 2. A GENERALISED MODEL OF STEELS AND GREY-IRON BEHAVIOUR DURING SLIDING FRICTION

Key words
Microstructure, hydrogen, sliding friction, graphitized steel, cast iron.

Summary
A generalised model of materials behaviour during friction is presented. It represents a certain approach resulting from the unified theory of friction and deterioration. Based on the relevant literature and our research data, which includes the behaviour of Fe-C alloys during friction, the basic stages and reasons of the alloy operational stability are shown.

Model of materials behaviour during friction
The operational stability of industrial machines and devices is much determined by the intensity of the deterioration of the interacting surfaces, and
up to 80% of machinery failures occur due to the deterioration of materials in units of friction [1–3]. At present, some of the main problems of tribology include the absence of an unified and consistent theory of friction and deterioration and methods of deterioration testing [1].

For a long time only “mechanical” approaches (without taking into account material aspects) prevailed in tackling the problem of the deterioration of mechanically interacting surfaces, which could be sufficient only at early stages of technical equipment service [6]. The collections of experimental data and theoretical works in the field of tribology have allowed the creation of some theories of friction. Among scientists who have contributed to these theories there are G. Polosatkin, D. Konvinsarova, V. Kislik, G. Yepifanov, N. Davidenko, and others.

A significant contribution to the development of tribology has been brought by Kragelsky and his school. The molecular and mechanical model of dry external friction created by him has been widespread. This model took into account the dualism of friction forces that result from two processes: the overcoming of intermolecular interaction forces, and the simultaneous deformation of a relief of friction surfaces.

According to “classical representations,” described in monographs issued by B.I. Kostetsy and other authors, the change of the intensity of deterioration can be presented in the following scheme (Fig. 1).

![Fig. 1. Change of the intensity of wear (I) in time (t)](image)

There are three stages of the wear process, which takes place under the constant conditions of friction: 1 – initial stage; 2 – stationary process; 3 – catastrophic destruction of a material of a piece.

The intensity of wear Process I, because of the complexity and the variety of processes, is usually represented as a function, i.e. as the operator of the whole complex of the processes occurring at various speeds of sliding V, loading P parameters as materials and environment conditions etc. [4–6, 22].

1 They use authors “deterioration” as more generally as “wear”, which their takes into consideration phenomena related with waste of material only.
It is possible to express the intensity of the destruction of alloys during friction in the following units: g/cm², mm³/cm², g/cm² at 1000 meters distance, etc. That allows one to compare the received results with the data of various researches.

One of the most common theories of friction is the structural and power theory (created by B. I. Kostetsky and his colleagues), which is based on the postulate that a physical basis of the general law (in the range of normal friction) is the universal phenomenon of adaptation. The essence of the structural adjustment of materials consists in the following: during normal friction the dissipative structure possessing properties of the minimal manufacture entropy occurs in the zone of contact [6]. Thus, the intensity of deterioration decreases on 4 … 5 orders in comparison with damageability. However, the given theory abstracts from properties of the basic material of a piece and passes basically to processes occurring only in thin superficial layers, the so-called secondary structures, that is not quite objective. The developing structural mechanics of destruction of materials [7], and also metallic and physical approaches in studying the problem of deterioration of materials [5], along with a complex combination of other factors [8] will allow the investigation of the micro-mechanism of the destruction of materials more deeply. At the same time, apart from external conditions and applications of materials, processes of contact interaction during friction always activate the action of the fatigue mechanism of materials damageability of the superficial layer [9, 10]. Metal alloys continue to be a significant part of constructional materials, used for manufacturing units of friction. Taking into account the fact that their wear resistance in tribo-conjugation greatly depends on structurally-phase structure, we shall try to generalise the scheme presented in Figure 1 in terms of the results of our own investigations and literary data for such materials as grey-iron and steel (Fig. 2). Thus, we shall combine the evolution of degradation of the material of a piece with the presence of a lubricant in tribo-conjugation. It is divided into four conditional periods:

1. (Intervals I, II) extra earnings (a detail only has been installed in the mechanism);
2. (Interval III) - the installed (stationary) deterioration (the period when the necessary lubricant in tribo-conjugation is supplied);
3. (Intervals IV V) - during limited submission of oil (oil starvation - when for some reasons a limited supply of a lubricant is observed);
4. (Intervals VI, VII) - during dry friction (as the boundary case of friction in oil after full disappearance of the lubricant remains from tribo-conjugation).

Therefore, the intervals I and II correspond to the period of extra earnings of the material. There is increased wear, and the factors of friction can correspond to this mode, in comparison with the period of built-in deterioration. It is quite obvious that, during extra earnings, there are processes of seizure [11], which can lead to critical damage - see Point A (Fig. 2). The first basic investigations in
In the field of extra earnings were carried out by Khrushchev [12]. The process of extra earnings goes through some stages. At the first stage, intensive wear or superficial plastic deformation on the adjoining surfaces takes place. Consequently, in the contact, the planimetric and actual areas increase. Further, we can observe the change of the microgeometry of roughness and, according to works by Kragelsky [13], this process is finished when the optimum roughness for the operating conditions and materials, which are independent of the size and character of the initial roughness, is reached.

The highest speed of the process of extra earnings is considered to be carried out in friction modes, which come nearer to critical ones. The extra earnings "on the verge of jamming" in due time is presented in paper [14]. In such a process, extra earnings of the surface friction adapt to the perception of a high level of load at this point. The presented statement can refer to the conditions of boundary or dry friction. The authors of the present work have revealed that, during friction the hardening of austenitic manganese cast irons can occur in 1.2 … 1.9 times at depths of 0.10…0.15 mm [15]. Thus, if alloys are metastable, there can occur hardening and transformations of $\gamma \rightarrow \alpha + K \rightarrow \gamma + K$ type, which promotes the increase of hardness and raises the wear resistance of a material in the conditions of dry and boundary friction [16–20].

Interval III corresponds to the stationary mode of deterioration. The mode of the constant deterioration of connected surfaces of a detail usually has rather stable values of friction and deterioration factors [13]. However, as the termination of the process of extra earnings is determined by reaching, not only...
the greatest possible area of rubbing surfaces by contact, but also by the carrying ability of the pair. It is obvious that superficial layers of the alloy will demonstrate certain properties [21], i.e., there will be an adaptation of a material to the conditions of external friction. This property has received the name “structural adjustment” [4, 6, 22]. However, even at this stage of material degradation can be “wear-fatigue mechanism of damage and destruction” (Point B on the Fig. 2) [9].

There are some hypotheses according to which the intensity of destruction of a material can be caused due to the localisation of pressure and the occurrence of cracks in the superficial and near surface layers of the friction zone. These are due to differences in specific volumes of the martensite of deformation and austenite (initial phase) [23, 24, 25]. Essential distinctions in microhardness are noted [25]. Thus, it is possible to assume that, at the initial stage, the transformations accompanied by hardening and increased hardness of the superficial layer cause the reduction in intensity of the wear process and can operate in the opposite direction. The dashed line indicates the reduction in intensity of deterioration during boundary lubrication under such factors as additives in a lubricant [26, 27]. For cast irons this reduction can be caused by intercalations of graphite present in the lubricant [28], this affects the intensity of the wear process. Fluctuations of the friction factor and a rise in lubricant temperature prove this process occurs [29].

Interval IV shows that, when oil is lacking, the material is efficient for a long period of time, and can hold the working capacity during sufficient greasing. So the authors of the present work have established that the layer consists of oil and graphite (at supply of 2–3 drops of oil) I–20A in tribo-conjugation (pin made of graphitized manganese cast-irons, \( P = 2.5 \text{ MPa}, V = 0.628 \text{ m/s} \)) on a disk made from the steel 45 can be maintained for 1–1.5 hours, and on manganese austenetic cold working steel for 2–3 hours, after which intensive seizure begins. Interval V shows the ability of the material to collapse (stroke and dashed line) and to maintain working capacity (single bold type and single thin type, respectively). Interval C characterises the beginning of the catastrophic deterioration and destruction. It is necessary to note that the weight method (when deterioration is characterised by the quantity of the destroyed material) refers to the intensity of the destruction of a material as shown in the analysis of deterioration products and a micro-relief of friction surfaces [30, 31].

Interval VI shows the reduction in the intensity of the wear process during dry friction. This process can occur due to secondary structures on the surface of friction [6, 32]. These structures are often known to be naturally oxidised [6]. The authors of the paper have also observed the reduction in the intensity of the wear process due to the presence of oxides on the surface of friction. Their stoichiometric structure has been revealed by an X-ray structural analysis (Fig. 3). The colours of overheated surface on the pin edge and the dimness of
friction surface due to raised temperature in the zone of friction - attributes of secondary structures - are known to have an oxide nature.

Fig. 3. Difractogram (FeK\(_\alpha\)) of alloy before the friction test

The reduction in the intensity of the wear process is also possible due to the allocation of graphite on the friction surface. Having carried out many experiments, these authors have observed the law mentioned above [15]. Apart from this, it is necessary to note that the said law essentially depends on the parameters of the graphitic phase and type of alloy metal matrix. It means that, if the graphitic phase makes up a significant volume in an alloy, the destruction will take place more intensively. Ideally, there should be an optimum of graphite, carbides, and a metal matrix content in the structure of cast irons.

Besides, for Interval VI (Fig. 2), the reduction in intensity of the wear process can be common because of the phenomenon known as “selective carrying,” which is carried out due to structurally-free inclusions that contain copper (phase) in the structure of an alloy. It occurs in cast-irons with copper (4\% Cu) [33].

Interval VII (Point E) (Fig. 2) characterises the catastrophic destruction of a material during dry friction [37]. As a rule, the material in this case collapses within seizure. The sizes of products of deterioration increase [31]. Microcracks are revealed on products of deterioration [31]. Thus, when analysing physicomechanical conditions of initial cracking at the moment of friction, and connecting them with the dislocations model of cracking, some moments in the wear process can be considered as a process of the appearing and development of cracks caused by the localisation of pressure [38]. An analysis of the sizes and morphology of the products of deterioration has allowed us to put forward a hypothesis that destruction during dry friction can occur because of cracks,
distributions between structural components, in particular, between graphite precipitates and metal matrix [31].

![Image](image.png)

**Fig. 4.** A microstructure of “drops” of high copper ε-phase after deep etching by Gard solution × 6000 [34, 36]

The authors in [39] show that the high tribological properties of nitrogen-containing steels are the result of deformation processes, which characterise degrees of numerical sliding and the activation of planar sliding of dislocation. It is known that introducing concentrations of nitrogen into high nitrogen steels leads to the decreasing of austenite defects. Possible methods of strengthening have been discussed in the papers [29]. Nevertheless, during the increasing of nitrogen content in the DDT 68 steel, higher concentrations of defects appear.

In the wear products of high nitrogen steels fixed more considerable quantity of α – martensite occurs in comparison with thin layers (approximately 50 µm) [40].

The γ → α transformation of products wear, and the creation of α – martensite are not decisive factors in stage of the surface fracture. We have described the relations between wear products morphology and the intensity of loads and fracture mechanisms in the paper [41].

Step by step increased loads of the examined steels (from the lightest to the heaviest loads) leads to the creation of super dispersed structure (nanostructure) in the thin layers (several µm) of high nitrogen steels.

According to the new conception of physical micro mechanics, the surface layer in the deformed solid state is a self-dependent subsystem [42].

In our opinion, the described structure affects the process that takes place in the friction surface layers. The plastic deformation in the high nitrogen steels has been created by the rotation method [43].

The presence of oxygen and hydrogen in the atmosphere influences the fracture intensity during the friction process.

In this way, the oxygen atmosphere gives the possibility of creating a surface passive film and the formation of an under layer surface that is characterised by low displacement stability.
For example, it is possible to present the elasticity module for hydrogen-charged materials and crystalline substrate [44].

The problem of hydrogen wear has not been sufficiently investigated to date, but some data is available in the papers [45–60].

High nitrogen steels can be prospective hydrogen resistant materials, including their applications in the conditions of friction.

Conclusions

The model of the evolutionary way of decreasing the operational stability of materials during sliding friction takes into account the changing conditions of lubrication in tribo-conjugation. Gradually increased loads of high-nitrogen steels lead to the creation of a super dispersed structure in thin layers (several µm). According to the modern conception of the physical micro-mechanics of surface layers, it can be stated that a self-dependent subsystem forms in the deformed solid state.

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References


Recenzent:
Lech STARCZEWSKI
Wpływ mikrostruktury i środowisk wodoronośnych na intensywność zużycia ciernego żeliw i stali. Część II: Ogólny model tarcia w warstwach wierzchnich detali wykonanych z grafityzowanych stali i żeliw

Słowa kluczowe
Mikrostruktura, wodór, tarcie, stal grafityzowana, żelivo.

Streszczenie
W pracy przedstawiono analizę mechanizmów zużycia ciernego, dokonaną w oparciu o źródła literaturowe i wyniki badań własnych. Zапрzedstawiono uogólniony model wpływu mikrostruktury, składu chemicznego i wodoronośnego oddziaływania smarów na procesy zużycia warstwy wierzchniej żeliw i stali grafityzowanych. Jako podstawowe czynniki warunkujące intensywność zużycia określono ciśnienie, prędkość liniową w węźle tarcia oraz skład chemiczny i mikrostrukturę stali. Autorzy używają terminu deterioration jako bardziej ogólnego od terminu wear, który ich zdaniem uwzględnia jedynie zjawiska związane z ubytkiem materiału.

Model stopniowych zmian stabilności eksploatacyjnej uznano za obowiązujący także podczas zużycia ciernego i zmian warunków smarowania w skojarzeniu ciernym. Stopniowe narastanie obciążeń w stali wysokoazotowej prowadzi do utworzenia cienkiej warstwy (kilka µm) o bardzo drobnodyspersyjnej budowie. Warstwa ta może zostać uznana, zgodnie z koncepcjami fizycznej mikro-mechaniki materiału, za odrębny niezależny podsystem.