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Influence of the microstructure of cast iron on the rheological properties of frictional contact and wear-resistance

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Abstract

The influence of sliding speed and contact load on wear-resistance of cast iron in the unhardened state (cast without heat treatment) and in the state after surface hardening by electroarc plasma (GTAW method) is investigated. This method provides formation of composite hardening structure in the process of fast crystallization. It is shown, that during friction of hardened cast iron the contribution of mechanical-thermal hardening with simultaneous development of relaxation processes prevails over mechanical peening. It provides high level and stability of wear-resistance

Keywords: GTAW method, martensite, wear-resistance, relaxation, internal friction, dissipation, dynamic ageing.

1. Introduction

Wear-resistance of friction pairs is defined not only and not so much by initial properties of materials of tribosystem. First of all, it depends on the dynamic processes activated by a friction, which change rheological properties of a metal and its resistibility to destruction. It is reflected in stability of superficial films and efficiency of their protective action. Thus, wear-resistance of tribological conjunction is closely associated with rheology of contact phenomena in metal substrate and is defined by an optimum combination of its strength and ability to relax the dynamic stresses (to dissipate the mechanical energy) [1].

The stress relaxation during cyclic dynamic loading of metals proceeds according to mechanisms of internal friction [2]. These mechanisms are caused by the phenomena of imperfect elasticity of contacting materials during distribution of strain waves, which are generated in the zone of discrete frictional contact, and characterise ability of a solid body to dissipate input mechanical energy, translating this energy to heat. Presence in the tribosystem of the effective sources of energy dissipation, working according to the mechanisms of internal friction, is the important factor of decrease of dynamic intensity of interacting surfaces [1]. Depending on the nature of the materials, load-speed and temperature conditions of external friction various mechanisms of internal friction (relaxation processes) are realised.

2. Experimental procedures

Tribotechnical tests were carried out using the friction machine, which realised the pin-disk scheme without lubricant [3]. The fixed specimen (pin) was pressed with controlled load to the flat surface of the rotating disk, which was made of white cast iron and had hardness 60 HRC. Wear rate of the specimen was calculated using the formula:

$$Z = \Delta m / (\rho \cdot S \cdot l)$$

where: Δm is a decrease of the specimen mass; ρ is a density of the specimen material; S is a contact area; l is a sliding distance.

Influence of the sliding speed and the normal load on the wear process of unalloyed cast iron (3.49 % C; 2.30 % Si; 0.66 % Mn; 0.019 % S; 0.039 % P; 0.17 % Cu, 0.01 % Ni; 0.084 % Mg) was studied. The cast iron was investigated in two states: after pouring into sand molds and after pouring into sand molds followed by zonal fusion by electric arc in the protective atmosphere of argon (GTAW method) with simultaneous fast cooling [3]. To increase the cooling speed the iron tiles were placed in the water-flow calorimeter, which allowed washing their lower surfaces by water flow. Scanning speed of an electric arc was V_s = 200 mm/min, current strength was I = 300 A. As a result of fast crystallisation of the melted zone of cast iron the quench martensitic-bainitic structure is formed, which is a metal matrix of cementite eutectic. In an initial state the cast iron had ferrite-pearlite matrix with spherical graphite inclusions.

Tribological properties of materials and their acoustic emission ability were investigated by scanning of the studied surface with Rockwell diamond indenter using Revetest Scratch Tester from CSM Instruments. Level of acoustic emission was estimated in relation to the reference specimen, which was covered by titanium nitride.

3. Experimental results and discussion

In the first stage, the influence of the sliding speed and the contact load on the wear rate (Fig. 1) was investigated.

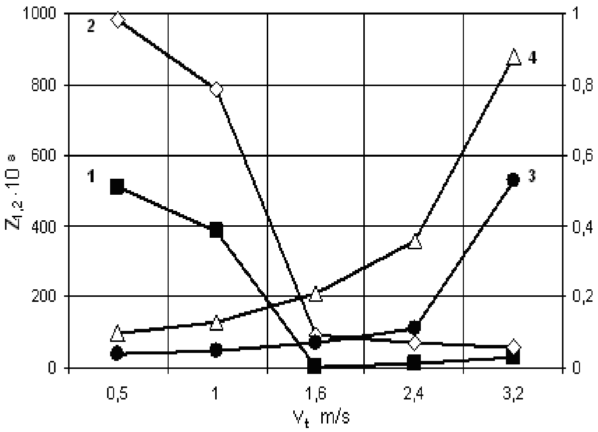

Fig. 1. Dependences of the wear rate of the cast iron on the sliding speed and the contact load: 1, 2 – cast iron in an initial state; 3, 4 – thermally strengthened cast iron (1, 3 – P = 1 MPa; 2, 4 – P = 2 MPa)

The following conclusions are made from the experimental data.

1. The hardened cast iron shows higher wear-resistance in comparison with cast iron in the initial state at the given unit load in all investigated range of the sliding speed. This difference is shown specifically at small sliding speeds ($V_t \leq 1$ m/s).
2. Unlike monotonous growth of wear rate with increase of sliding speed for the hardened cast iron (Fig. 1, curves 3, 4) nonmonotonic dependences with a wear minimum in a certain speed range are typical for the unhardened cast iron (Fig. 1, curves 1, 2).
3. In a range of low speeds (0.5 … 1.0 m/s) the unhardened cast iron is characterized by high intensity of the wear process with development of seizure. On the contrary, the hardened cast iron shows stably high wear-resistance at low speeds which starts to decrease essentially only with the increase of speed by more than 1.5 … 2 m/s (Fig. 1, curves 3, 4). On the other hand, the unhardened cast iron shows essential increase of wear-resistance with increase of sliding speed (Fig. 1, curves 1, 2).
4. The efficiency of hardening of the cast iron by electroarc processing increases with reduction of sliding speed. So, at speeds V_t = 0.5 … 1.0 m/s wear-resistance of the strengthened cast iron exceeds wear-resistance of the unhardened cast iron (7 … 10) $\times 10^3$ times (depending on a specific load). At the elevated speeds the specified ratio decreases to 40... 100 times (at V_t = 3.2 m/s).

Electroarc processing raises hardness of the cast iron from 180 HV_{100} to 880 HV_{100}, i.e. almost 5 times. Obviously, increase of wear-resistance of the cast iron should not be associated with initial hardness only. It is necessary to also consider changes of strength and relaxation properties of a material in the process of dynamic loading taking into account the influence of contact temperature and tribovibration amplitude in near-surface layers. Thus the increase of wear-resistance of the unhardened cast iron during theincrease of sliding speed (Fig. 1, curves 1, 2) is associated with thermomechanical triboactivation of the processes causing hardening and improvement of rheological properties of surface layers. Fig. 2 shows the influence of friction mode on acquired wear-resistance of the unhardened cast iron: after preliminary tests at speeds V_t = 1; 1.6; 2.4 m/s (P = 1 MPa, t = 1 hour) re-testing (V_t = 1 m/s, P = 1 MPa, t =1 hour) shows the increase of wear-resistance of the material 30, 38 and 85 times accordingly in comparison with the initial condition.

It is necessary to take into account that the increase of the sliding speed is accompanied by the increase of frequency and amplitude of fluctuations of actual contact areas, and also by the rise of temperature of friction surfaces, that lead to change of the mechanism and the level of internal friction (of the dissipation of mechanical energy) in the near-surface and the subsurface layers of tribo-elements. Specified changes should correspond to the character of frequency, amplitude and temperature dependencies of internal friction, which are characteristic to the contacting materials. In addtition it is necessary to take into account that elastic-plastic deformation of near-surface layers at the elevated temperatures can be accompanied by hardening as a result of development of dynamic strain ageing (DSA).

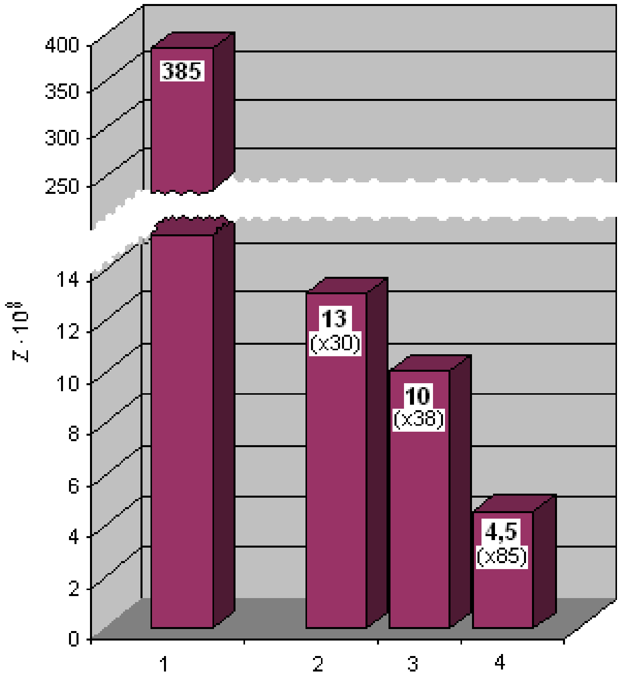

Fig. 2. Wear-rate of the cast iron (V_t = 1 m/s, P = 1 MPa, t = 1 hour): 1 - in an initial state; 2, 3, 4 - after preliminary test at V_t = 1; 1.6; 2.4 m/s accordingly

Let's compare the laws of observable speed dependences of wear rate with amplitude and temperature dependences of internal friction and change of strength properties of the cast iron. In general amplitude-dependent internal friction (ADIF) of iron-carbon alloys at low temperatures may be interpreted as superposition of three mechanisms: magnetomechanical (magnetoelastic hysteresis), dislocation (dislocation hysteresis), and structural: $\delta = \delta_M + \delta_D + \delta_S$ [2, 4]. Hence it is necessary to distinguish magnetomechanical, dislocation and structural mechanisms of the stress relaxation under the influence of cyclic dynamic loadings in the conditions of external friction. The degree of each of the specified kinds of relaxation depends on the microstructural condition of the material, amplitude of cyclic deformation, temperature and degree of peening.

Magnetoelastic hysteresis (MEH) is caused by irreversible displacement of boundaries of magnetic domains in the field of acting cyclic stresses. Contribution of MEH into internal friction depends on the structure (heat treatment) of the alloy and amplitude of the cyclic deformation [4]. The mechanical losses caused mainly by magnetoplastic hysteresis, are characteristic of the unhardened cast iron. At high amplitudes of deformation the contribution of MEH to the general level of internal friction is dominating and reaches 80 %.

Dislocational internal friction is caused by movement and generation of dislocations and can reach a significant value even at low amplitudes of deformation in the alloys, which have martensitic structure.

Structural mechanism of internal friction is connected with relaxation appearing in structurally-metastable alloys (for example, during quenching) and caused by the physical-chemical processes, which bring the system to the equilibrium state (disintegration of the oversaturated solid solution, ageing, etc.).

Low losses on MEH and low amplitude dependence of internal friction are characteristic of the hardened state resulting from the phase peening. They are a result of high microdistortions of crystal lattice sharply reducing border mobility of magnetic domains. Thus, it is possible to assume that at low oscillation amplitudes of the microasperities, corresponding to low friction speed, the hardened cast iron has the highest internal friction of structural-dislocation nature. At increased amplitudes (speeds) the unhardened cast iron has higher damping ability, having generally magnetomechanical nature.

Increase of wear-resistance of the unhardened cast iron in the friction speed range from 1 to 1.5 m/s is associated not only with demonstration of losses on magnetoelastic hysteresis δ_M, which are localised mainly in near-surface region, but also with activation of relaxation (amplitude independent) internal friction δ_P in subsurface layers at frictional heating of the contact zone (Fig. 3). Formed near 200 °C internal friction peak (deformation peak of Koester) grows out of interaction between the dislocations, happening during plastic deformation of metal with interstitial impurity atoms ($C + N$) [2]. The relaxation is caused by reorientation of interstitial atoms in the elastic field of dislocations and also by the movement under the influence of external periodic force of the dislocations pulling after themselves the atmospheres from interstitial atoms. The more the height and the area of Koester peak are, the more relaxation ability of cast iron is. Maximum of magnetomechanical losses δ_M (Fig. 3, b) is formed because at temperatures more than 200 °C the losses on MEH are decreased considerably. In addition it is promoted by the increase of peening, which reduces of domain-wall mobility [4].

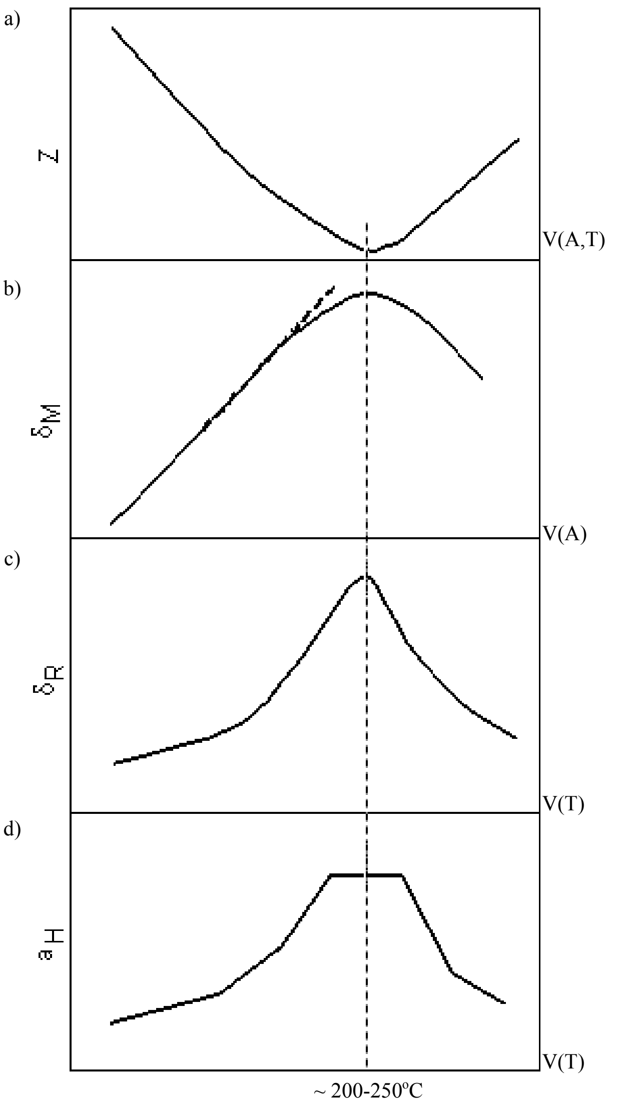

Fig. 3. Scheme of formation of minimal wear rate of the unhardened cast iron (a) depending on temperature-speed modes of friction: b – amplitude dependence of magnetomechanical losses δ_M; c, d - temperature dependences accordingly of relaxation internal friction (δ_R) and impact strength (a_n)

With the increase of sliding speed in contact temperature range from 200 to 250 °C along with the increase of relaxation abilities of the alloy the process of dynamic strain ageing (DSA) is developing, causing hardening of near-surface layers and increasing of fracture toughness [5, 6]. Development of DSA occurs under effective interaction of impurity atoms (carbon, nitrogen) with dislocations generated in the course of friction. This is possible only under certain temperature-speed conditions of deformation when the movement speed of dislocations at pulse loading is commensurable with the diffusion speed of interstitial atoms. Thus there is a dynamic blocking of dislocations by impurity atoms with the formation of atmospheres on dislocations and segregations of these atoms.

Taking into account stated above, three factors are connected with the nature of display of minimisation of wear rate of the unhardened cast iron (Fig. 3, a):

– amplitude dependence of magnetomechanical losses (of magnetoelastic hysteresis) (Fig. 3, b);
– temperature dependence of relaxation internal friction (formation of Koester peak) (Fig. 3, c);
– temperature dependence of impact strength as a result of development of dynamic strain ageing (Fig. 3, d).

Change of wear-resistance of the hardened cast iron with the increase of the sliding speed first of all should be associated with temperature conditions of contact interaction. Thereupon conditionally it is possible to allocate three characteristic temperature ranges: less than 100 °C; from 150 to 300 °C; more than 350 °C. First two ranges correspond to relatively high wear-resistance of the hardened cast iron (Fig. 1). At small sliding speeds and accordingly at low contact temperatures (below 100 °C) the superficial plastoelastic deformation directly at martensite friction is accompanied by a relaxation of local stresses, the decrease in level of microdistortions, the increase of structurally-deformation uniformity. This is accompanied by the increase of brittle fracture resistance (fracture toughness is increased). In the layer strengthened by friction as a result of early appearance of martensite microyeild the ratio of the general density of the locked and mobile dislocations is created, which forms an optimum combination of strength and relaxation ability (dislocational internal friction).

During friction of the hardened cast iron in the range of the average contact temperatures (150... 300 °C) so-called dynamic ageing (DA), or tempering under load is developed. Dynamic ageing or tempering under load is a disintegration of the oversaturated solid solution in the stress field, created by the external dynamic load which is not exceeding yield strength σ_y is developed [7]. In the given temperature range the following phenomena create relaxation processes:

– diffusional relaxation, i.e. diffusional redistribution of atoms of carbon and nitrogen in the field of operating cyclic stresses (Snoek relaxation) or in the field of moving dislocations (Koester relaxation);
– structural relaxation (physical-chemical reactions of disintegration of supersaturated solid solution with release of highly dispersed carbides and transformation of residual austenite in martensite also);

– dislocational relaxation caused by redistribution of dislocations with possible formation of microdiscontinuity flaws in the places of localisation of peak stresses.

Under the conditions of sufficient mobility of interstitial atoms, commensurable with the speed of moving of dislocations under the influence of cyclic loading, simultaneously with DA the dynamic strain ageing (DSA) develops, causing the decrease in mobility of dislocations by interstitial atoms (or them segregations), that additionally stabilises the structure. The greatest strengthening action of DA and DSA is shown in the temperature range of 150 … 300 °C, when the level of operating stresses does not exceed (0,6 … 0,7) σ_y [5, 7].

Upon the further increase of the sliding speed and contact temperature (to 300 … 450 °C) the morphology (dispersion and density) of separations is changed because of the intensification of dynamic ageing (overageing). It causes embrittlement of the hardening structure with the decrease of its wear-resistance. Wear-resistance decrease can also be associated with development of the irreversible temper brittleness causing sharp decrease of impact strength.

It is known [8, 9] that physical-mechanical properties of metal and its reaction to force action find reflexion in parameters of the acoustic emission caused by the dynamic local reorganisation of a structure with internal stresses relaxation. Thus there is an energy release (dissipation) in the form of elastic waves with changing mode of deformation. At microlevel the relaxation phenomena with emission of acoustic impulses are caused by the processes of formation and transformation of microstructure of metal during mechanical loading.

Figure 4 shows the change of movement characteristics of diamond indenter of microtribometer at transition from the strengthened (flowed) zone of the cast iron to the initial material at two normal loads. Despite low friction coefficient and small depth of indenter penetration the strengthened zone is characterised by a considerably higher acoustic emission activity. At the same time at larger penetration depth of indenter and higher friction coefficient on the initial structure the general level of acoustic emission is low. Hence, in the strengthened zone with metastable martensite matrix, during indented scanning the local relaxation of stresses proceeds more intensively, as a result of movement and change of energy state of dislocation clusters and point defects (interstitial atoms).

The level of acoustic emission depends to a greater degree not on the density of dislocations, but on their mobility and free path [9]. Therefore under big plastic deformations undergone by cast iron in the unhardened state during plowing by indenter, movement of dislocations is blocked by the big number of barriers, and operation of the free dislocations sources is depressed. As a result, intensity of acoustic emission tends to zero (Fig. 4, b). Besides, low level of acoustic emission of rough (more plastic) cast iron is caused by not high local overstresses because of the low potential barrier of deformation.

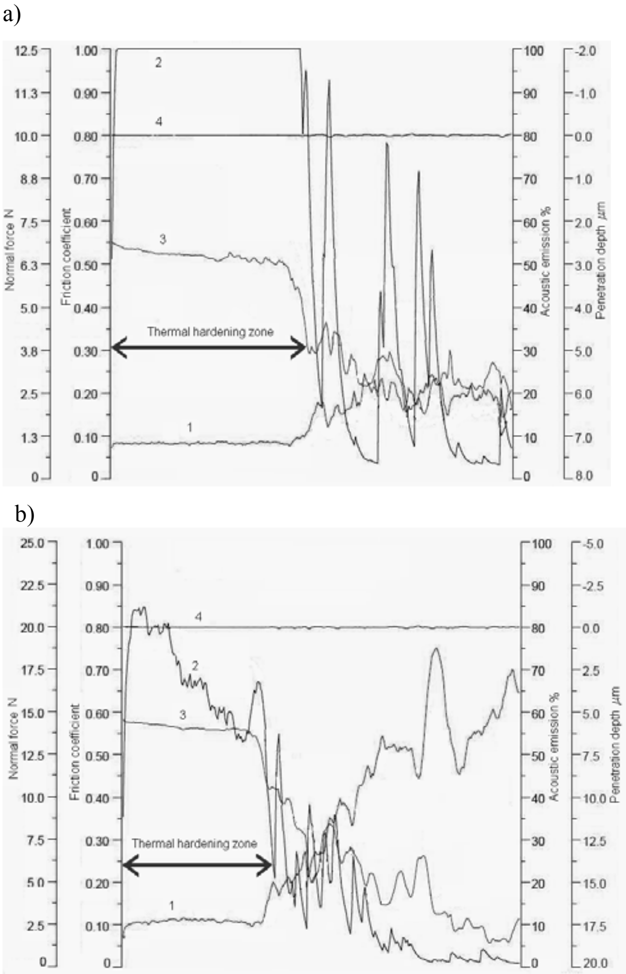

Fig. 4 – Change of friction coefficient (1), level of acoustic emission (2), and depth of indenter penetration (3) along the scanning line: a - F_n = 10 N (4); b - F_n = 20 N (4)

4. Conclusion

Relaxation processes are effective mechanisms of decrease in dynamic intensity of interacting surfaces and increases in their resistibility to wearing. Their pheology is provided by diffusion and dislocation mobility of material substructure in the contact zone. As a result the smoothing of peak stresses and the decrease of their concentration occur. The phenomena connected with imperfect elasticity, which is caused by amplitude-independent and amplitude-dependent internal friction, underlie the appearance of relaxation (damping) properties in the material. Realisation of high internal friction in a combination with hardening as a result of development of processes of dynamic strain ageing (DSA) promotes essential increase of wear-resistance of material. If friction conditions violate the boundaries, where the materials display high damping properties, the decrease of wear-resistance occurs as a result of accumulation of the critical stresses, which causes embitterment of the friction surface and development of adhesion.

During processing of the cast iron by the concentrated heat flow created by plasma of an electric arc the specific structure of a composite (carbides + martensite), possessing considerable hardness at high relaxation abilities, is formed after fast crystallisation. It provides multiple increases (on 2 degree) of wear-resistance. During friction of high-carbon martensite in the process of superficial deformation the contribution of relaxation processes prevails over peening, which differs from friction of ferrite-pearlite structures. Therefore martensite is additionally strengthened, passing into more viscous state and keeping high relaxation properties, which provide the development of undamaging dissipative processes.

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