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Dynamic Processes of Substructural Rearrangement under Friction of Carbon Steel

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ABSTRACT

The effect of heat treatment (tempering temperature after quenching) of medium carbon steels (steel 45 and steel 50) on tribological indicators at sliding friction without lubrication in connection with the change in strength and rheological elastic properties of steel, controlling the dissipative properties of the frictional contact has been studied. Tribotechnical tests were conducted according to two schemes. A high-temperature tribometer was used for "soft" friction according to the "ball-plane" scheme, which allowed varying the temperature of the friction contact. Influence of load-rate modes was studied in more "hard" conditions on the friction machine under the "finger-disk" scheme. Substructural transformations of steel caused by heat treatment were evaluated by changes in amplitude-dependent internal friction on a torsion pendulum-type machine, which also allowed measuring frictional damping (contact internal friction) in the preliminary displacement mode. The interrelation between hardness, elastic modulus and internal friction of steel and wear resistance, wear capacity, friction coefficient and the level of frictional damping has been established. It is shown that the growth of elastic modulus and increase of steel relaxation resistance after the appropriate heat treatment are conjugated with the development of adhesion and setting, which, as topochemical reactions in the solid phase, are the leading forms of contact stress relaxation under the above conditions. Correlation of tribological indicators of external friction with amplitude-dependent and relaxation (temperature-dependent) internal friction taking into account structural state of steel and friction temperature regime is established. Substructural preconditions, dynamic relaxation mechanisms of hardening and load-temperature friction conditions under which martensitic structures exhibit abnormally high wear resistance and significant growth of frictional damping level are considered. The tribological analogue of the Porteuen - Le Chatelier effect, manifesting in the form of frictional self-oscillations in the range of temperatures of dynamic deformation aging is established. A treatment of the nature of the Kael-Ziebel effect, the temperature-rate and load localization of which in friction is associated with the temperature range of dynamic strain aging with Snook-Kester relaxation superimposed, is proposed.

Keywords: quenching, martensite, tempering, dynamic strain aging, relaxation, internal friction, wear resistance

INTRODUCTION

The durability of mechanical tribosystems is determined not only by initial properties of friction couple materials, but also in a greater manner it also depends on dynamic processes of substructural rearrangement activated by friction, which affect on the rheology of contact interaction and dynamic strain of frictional contact [1-3]. Therethrough the effective leveling of contact loads in areas of their concentration is possible as a result of the development of diffusional and shifting relaxational processes, which dynamic mechanisms are described in definitions of internal friction

[4-6]. Indicated processes damp vibration load of friction zone and facilitate surface localization of deformation. Furthermore, depending on structural state of steel and load and speed external friction regime as way as temperature regime the realization hysteresic and relaxational mechanisms of internal friction is possible that affect on dissipative processes and are capable of significant increasing of the effect of mechanical and thermal substructural strengthening [7-8].

In tribosystems that work without lubrication (for example, friction clutch coupling, friction dampers and friction shock absorbers, brake assemblies) materials with high dissipative (damping) ability, sufficient dynamic strength and wear resistance should be used and often one does not accompany the other. The main function of indicated devices lies in the prevention of resonance oscillations with vibration and noise suppression up to the level of sanitary standards in such components of installation equipment as pumps and ventilators. In a number of cases, the main disadvantage of such dry friction units is the rapid irrecoverable wear of the friction contact and loss of damping properties. In particular, it can be a consequence of insufficient frictional strength and unfavorable elastoviscous rheological properties, responsible for contact damping at the given load and temperature-rate operating mode of tribosystem.

Dynamic strengthening and softening relaxational processes that have an effect on the rheology of contact interaction, dissipative ability and wear resistance of steel were understudied and constitute pressing theme in physics of metals of contact strength and frictional damping. In particular, it is of interest to research distinctive features and mechanisms of dynamic mechanical and thermal strengthening under conditions of quenched martensite friction and low-temperature tempering of quenched steel (tempered martensite) compared to the structures of medium-temperature and high-temperature tempering.

The aim of the work is to study the tribological indicators of contact strength and dissipative capacity of carbon steel depending on heat treatment, as well as on the load-rate and temperature friction regimes, taking into account the effect of dynamic processes of substructural restructuring of the friction contact.

BACKGROUND

In case of steady regime (after breaking in) friction assembly works in macroelastic regime when relaxational processes and dissipation of input mechanical energy is predominantly controlled by nonelastic phenomena (by internal friction), and also by topochemical reactions at the solid body interface (adhesion, gripping, oxidization). The study of the rheology of viscoelastic frictional contact, i.e. that has imperfect elasticity, allows explaining the nature of ambiguous dependences of friction force and steel wear resistance on temperature and speed friction regimes having consideration for steel structure and its level pf metastability [4,7]. In connection therewith strengthening processes of dynamic strain aging (DSA) and dynamic tempering (DT) – stressed tempering – promote special interest [9-12]. The effectiveness of the development of independent processes is determined by the coherence of the diffusion of interstitial atoms and the dynamics of dislocational rearrangement. Such processes pf deformational and thermal strengthening providing diffusional and dislocational nature, are most typical for metastable structures (for example, quenching martensite, tempering martensite) [11-13].

High effectiveness of combined mechanical and thermal strengthening of materials is known that envisage plastic deformation (3-5%) after steel quenching with following low tempering – strain aging ("marforimng") [14]. Mechanical and thermal treatment have shown even greater efficiency of steel strengthening, which lies in deformation with drafting in DSA temperature range (150…300°C) [9]. Apparently, dynamic loading of steel under conditions of friction within the limits of corresponding temperature range, similar strengthening processes can be realized both at the stage of preliminary frictional treatment (or breaking in), and at the stage of the following work of friction assembly. Thus, accordingly to [15,16], tribological properties of quenched steel can be significantly improved by nanostructuring frictional treatment by sliding light-alloy indenter or fastened abrasive material without significant heating of the surface. As in case of any intensive surface working (SPW) of grain grinding, mechanical peening and probable development of DSA promote growth of strength, hardness and formation of compressive residual stresses. To preserve the necessary ductility of quenched steel, the authors [16] introduce combined mechanical and thermal treatment with the addition of tempering at 350°C to the frictional SPW.

MATERIALS AND METHODS

Thermal treated steel 45 and steel 50 (quenching in water from the temperature 850°C with the following one hour tempering at temperature from 200 to 700°C) were studied. Hardness and elasticity modulus were measured by the method of continuous indentation of Berkovich pyramid on OPX NHT/NST device of CSM Instruments company (Switzerland).

Structural changes of steel caused by thermal treatment, as well as frictional mechanical losses were studied by volumetric and contact amplitude-dependent internal friction method on the torsional pendulum type device (Fig. 1), which was designed on the basis of instrumental measuring microscope with three-dimensional anti-backlash table [7].

The device was used in two modes. In first mode sample 1 (Fig. 1a, b) was fixed by the upper end, and equal-arm pendulum 3 with two balancing weights on its end was attached to the lower part of the sample. By passing through the inductance coil 6 a short electric pulse generated by the block 8, the pendulum was driven into a torsional oscillatory motion in the horizontal plane. Studied sample represents elastic part of the system that performed free damping oscillations. These oscillations were recorded by capacitance sensor 5, signal from which is transmitted in recording system with software, consisting of analog-digital converter 9, computer system unit 10 and display 11 (7 – supply units). Initial amplitude, frequency and damping logarithmic decrement, which served as an index for internal friction, were measured.

In second mode the dissipative properties of frictional contact in preliminary displacement regime were estimated by the change of logarithmic damping decrement in the coupling of two polished samples (Fig. 1c) as per flowchart: butt end of hollow cylinder (upper fixed sample 1) – butt end of the disk (lower moving sample 2). Sample 2 was fixed in pendulum, which in this case rested with a controlled force on the needle support 4.

Tribotechnical researches in case of “soft” sliding friction without lubrication were carried out on high-temperature friction machine TRIBOMETR (THT) of CSM Instruments company as per flowchart “plane of rotating disk (sample) – fixed ball (ШХ15, *HV* = 1050)”. After thermal treatment working surfaces of samples of frictionally treated (grinding + polishing). Test conditions: basic load – 5 N, friction speed – 0.2 m/s, friction path – 1000 m. Automatic record of friction force and friction coefficient was made during the research, as well as weight wear of the sample and wear spot diameter of the ball (counterbody) were determined. In case of high-temperature tests the

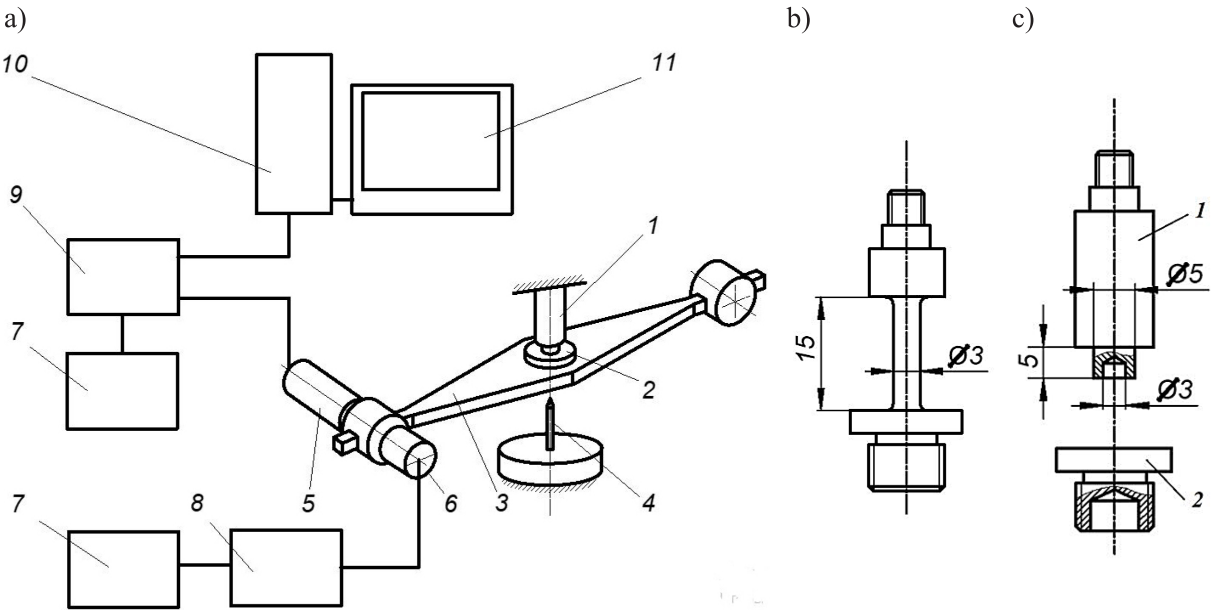

Fig. 1. Device flowsheet (a) and samples for measuring volumetric (b) and contact (c) internal friction in case of torsional oscillations: 1 – fixed sample; 2 – moving sample

temperature of sample and counterbody temperature were recorded as a result of external heating.

The influence of load and speed friction regime on steel wear resistance in case of more rough conditions, allowing the realization of temperature range of frictional contact in a wider range. Such tribotechnical test were carried out on friction machine as per flowchart "pin-disk" without lubrication. Fixed sample (pin) was pressed with controlled force to the plane of rotating disk, casted from cast iron and strengthened to 60*HRC*. Sample wear was measured by weight method and wear resistance was calculated by the following formula:

$$R = \frac{\rho \cdot S \cdot L}{\Delta m},$$

where: Δm – sample loss in weight, g; ρ – steel density, g/cm^3; S – area of contact surface, cm^2; L – friction path, cm.

Sclerometric properties of samples under surface scanning by diamond Rockwell indenter was studied on scratch-tester RST (Revetest + Scratch Tester) of CSM Instruments company. Sample movement speed was V_S = 10 mm/min, basic load on indenter – 5 N.

RESULTS AND DISCUSSION

Figure 2 shows the influence of tempering temperature of quenched steel 50 with the following frictional treatment (grinding + polishing) on researched physical and mechanical properties (HV, E, δ) and damping (dissipative) ability of reversive frictional contact (δ_f).

As the hardness of steel decreases with the increase of tempering temperature, the elasticity modulus E changes cyclically, forming its first maximum near tempering temperatures 200–250°C, and the second, which is less delineated, near the temperature of 600°C. Internal friction of steel (oscillation decrement δ) also changes cyclically, but in antiphase with the elasticity modulus.

Viscoelastic properties of steel (E, δ) are determined by structural stability and motion freedom of dislocations, which depends on blocking effect of interstitial impurity atoms (C+N) and carbide precipitates generated by tempering [8,17]. Quenched steel (quenched martensite) has increased internal friction, conditioned by relaxational restructuring of dislocations, which were formed as a result of phase hardening. At high hardness and frangibility martensite also shows viscoelastic properties due to the presence of residual austenite.

Tempering at the temperatures of 200–250°C causes significant growth of steel elasticity and decrease of internal friction as a result of martensite decaying with the release of highly dispersed particles of hexagonal ε-carbide, coherently bonded with the matrix and forming a dense grid. At the same time the austenite transforms into a mix of ferrite and carbide. The result is a formation of the composition of low-carbon martensite and ε-carbides – tempered martensite [17]. The discharge of carbides weakens solid solution by carbon, which reduces the local microstresses of latitude and decreases its tetragonality. However, martensite twins retain a high density of dislocations, which are fixed by segregations of

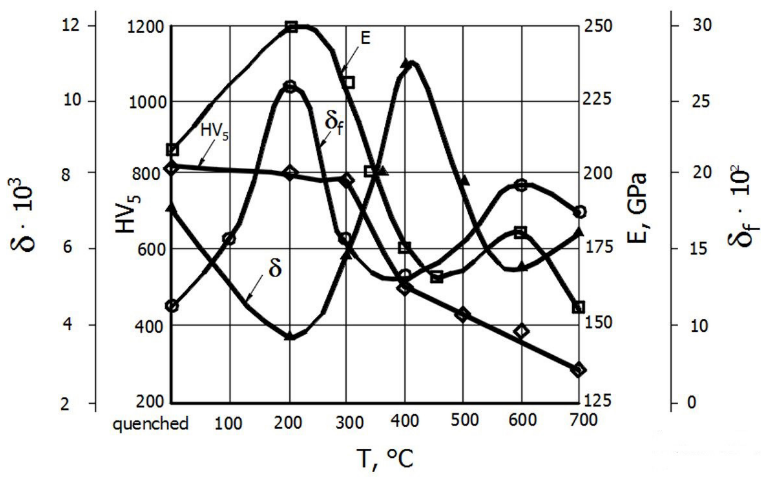

Fig. 2. The influence of tempering temperature of quenched steel 50 on physical and mechanical properties: E – elasticity modulus; HV_5 – hardness; δ – damping logarithmic decrement of free oscillations; δ_f – logarithmic decrement of frictional oscillations (A_0 = 0.6 μm)

interstitial impurity atoms (C+N) and discharged carbide particles. In case of limited mobility of dislocations (δ minimum), the structure stabilizes and acquires high elasticity and relaxational resistance (E maximum).

Growth of internal friction and decrease of elasticity modulus within the tempering temperatures 250–400°C are conditioned by the increase of dislocations mobility as a result of further decrease of carbon concentration in solid solution due to its transition into carbides, which is also facilitated by the carbide transformation (ε-carbide → cementite Fe_3C), culminating in the formation of a highly dispersed ferrite-cementite mix near the tempering temperature of 400°C – tempering troostite. Cementite is discharged in a form of small plastic dendritic crystal.

When tempering temperatures are higher than 400°C, plastic ferrite transforms into grained and forms so called secondary sorbite. Moreover, the density of mobile dislocations decreases as well as internal friction, and elasticity increases at T_{temp} = 600°C. New growth of internal friction at tempering temperatures higher than 550–600°C is conditioned by the increase of ferrite volume, which is free of carbides (as a result of coalescence of cementite particles) and growth of losses for magnetoelastic hysteresis [18].

The change of viscoelastic properties of steel after tempering has an impact on frictional dissipative indices. Mechanical losses of energy during friction were estimated by logarithmic decrement of torsional frictional oscillations δ_f (Fig. 2) under conditions of radial preliminary displacement of the plane of disk sample, which was rigidly connected with the pendulum, relatively circular butt end of fixed liner made of quenched steel (Fig. 1c). It appears that as tempering temperature increases, the change in frictional mechanical losses δ_f corresponds to the change of elasticity modulus E and internal friction of steel δ. Similarly to the elasticity modulus, the energy dissipation index δ_f acquires maximal value for tempering temperatures of 200–250°C. From our point of view, the increase of steel elasticity is accompanied by the decrease in microplasticity reserve and loss of relaxation capacity, due to which the leading mechanisms of energy dissipation and relaxation of contact stresses in case of friction becomes processes of formation and destruction of adhesive bonds. Adhesion strengthening leads to the increase of integral frictional bonds on shear, increasing the molecular component of the friction force, which is associated with an increase of the contribution to the total friction force and deformation component.

The influence of steel thermal treatment on tribological indices in case of "soft" monodirectional sliding friction as per flowchart "ball (ШХ15) – plane of rotating disk-type sample" is shown on Figure 3.

Comparison of the data on Figures 2 and 3 shows that as the tempering temperature increases, there is a general pattern of the decrease of

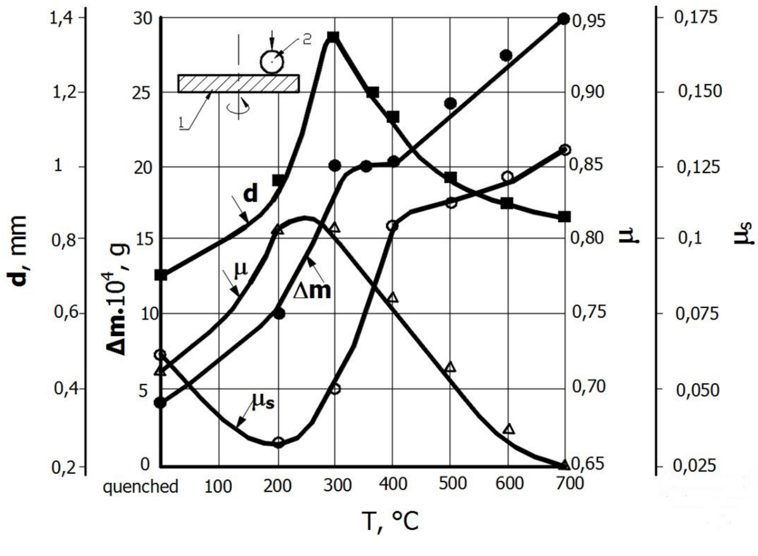

Fig. 3. The influence of tempering temperature of quenched steel on tribological indices: Δm – weight wear of the sample; d – wear spot diameter of counterbody; μ – friction coefficient (v = 0.2 m/s; F_N = 5 N; $L = 10^3$ m); μ_S – sclerometric friction coefficient (F_N = 5 N; V_S = 1 cm/s); 1 – moving sample; 2 – counterbody

steel wear resistance as the hardness decreases. At the same time wearing ability *d* and coefficient of internal friction μ increase synchronously to the increase of steel wear Δm only up to tempering temperatures 250–300°C. Within whole range of studied tempering temperatures indices *d* and *μ* more closely correlate with the elastic (rheological and dissipative) properties of steel (E, δ, δ_f). Coherent change of external friction coefficient, wear ability and index of frictional losses δ_f conditioned by the increase of steel elasticity with the decrease of damping ability that leads to activization of adhesive processes, which maximum lies within the limits of tempering temperatures near 250°C. In case of low friction speed, the adhesion acquires the character of seizure (microwelding) with a deficit of non-damaging stress relaxation processes, mainly realized by the mechanisms of relaxation and hysteresis internal friction [7,19]. Adhesion and gripping being topochemichal reactions of formation of metallic bonds in the solid phase at the interface, in these conditions act as leading mechanisms of the relaxation of contact stresses [3,20]. On the rigid elastic substrate, the protective films of secondary structures are unstable and rapidly degrade during friction, causing increased adhesive wear on the counterbody.

At tempering temperatures greater than 250–300°C the increase of sample wear Δm (Fig. 3) is related to the decrease of both hardness and elasticity modulus of steel. Concurrently friction coefficient and wear of counterbody progressively decrease, which may indicate on the change in the leading processes of contact interaction – adhesive to deformation and oxidation.

Quenched martensite is characterized by a number of features. Thus, in case of insignificant difference in hardness of tempered martensite (T_{temp} = 200°C) and quenched martensite, the last one is more than twice as good at wear resistance. And in comparison with the highly tempered structure – secondary sorbite (T_{temp} = 700°C), quenched steel have shown 8 times better wear resistance with only a threefold difference in hardness of these structures formed after heat and friction treatments. Quenched martensite is also characterized by minimal wear capacity with a significantly reduced friction coefficient (Fig. 3).

Structural metastability of “fresh” martensite creates thermodynamic backgrounds for the development of relaxational processes during friction, which are accompanied by additional strengthening with increase of viscoelastic (rheological and dissipative) properties. It is known [13,15] that after thermal treatment of martensite by contact methods of surface plastic deformation (SPD), lifetime of parts increases tenfold due to the increase in endurance and wear resistance. Grain refinement during martensite fracture SPD leads to the increase in dynamic strength and fracture toughness, because developed grain boundaries and mosaic blocks improve damping properties of steel and serve as effective pathways for the diffusion of point defects (carbon atoms and quenched lattice vacancies).

Relaxation processes, accompanied by strengthening are connected with the development of dynamic strain aging (DSA) [9,21]. DSA strengthens steel more efficiently than cold deformation or usual strain aging, i.e. dislocations generated by impurity atoms (carbon, nitrogen) are dynamically blocked and atmospheres and segregations of these atoms are formed on dislocations. Therefore, plastic deformation develops mainly due to the generation of “fresh” mobile dislocations, whose density rapidly increases, ensuring the preservation of sufficient microplasticity and relaxation capacity. The efficiency of DSA depends on the structural state of steel, moreover quenching significantly increases its propensity for this type of dynamic hardening compared to annealing and normalization, i.e. martensite, in addition to the high concentration of carbon, has a high density of quenching lattice vacancies. The pair “interstitial atom – vacant lattice site” has much greater diffusion mobility than a single interstitial atom [19]. Having high bonding energy with interstitial atoms, lattice vacancies facilitate the transport of last ones to dislocations.

Usually after running-in the friction assembly operates in “operational” condition, which causes mainly macroelastic deformation of the friction contact zone. In combination with heat dissipation, such elastically stressed friction regime of martensite is accompanied by the relaxation of local stresses as a result of dynamic stressed tempering [10-12]. In comparison with usual tempering, particles of ε-carbide, released during dynamic tempering (DP) have a higher dispersion and higher concentration due to the increase in the number of nucleation centers of the carbide phase. This leads to the formation of regions with limited mobility and higher elastic limit. At the same time, carbide precipitations, causing the decrease in the concentration of carbon adjacent matrix regions, lower the density of fixing points of some dislocations.

Therefore, as a result of dynamic stress aging and dynamic tempering of martensite a composite structure is formed within the friction zone, in which elastic regions with high hardness and relaxation resistance are separated by zones with increased microplasticity (tribomarforming). Such heterogenic structure has a significant dynamic strength and high damping (relaxational) capacity and effectively counteracts the occurrence of high local stresses and the development of brittle fracture zones.

It is generally accepted [9,10] that, depending on strain rate, DSA occurs to a greater or lesser degree at any temperature (from 20 to 700°C), when the dislocation displacement rate is commensurable with the diffusion rate of interstitial atoms. DSA is most effectively developed in the temperature range, which stimulates increased diffusion mobility of interstitial impurity atoms. Such conditions may also be favorable for the development of SK (Snook-Kester) relaxation (Fig. 4) [19,22].

Figure 4 shows the temperature dependences of the damping logarithmic decrement of thermal treated steel 45, obtained on the kilohertz frequency range device [5,7]. In the range of 200–350°C, the so-called deformation maximum of internal friction, typical for metals with body-centered cubic lattice, Snook-Kester peak (SK-relaxation) appears in the range of 350°C, which is caused, on the one hand, by diffusive redistribution of interstitial atoms in the elastic field of induced ("fresh") dislocations under the action of periodic load (Kester model), and, on the other hand, the movement of dislocation segments whose bending rate is limited by the migration rate of impurity atmospheres which fix the dislocations (Shoek's model) [6]. The greater the height and area of the Snook-Kester peak, the higher the relaxation capacity of the material [22]. With increasing tempering temperature this internal friction peak decreases, and tempering at 600°C leads to its disappearance, indicating the absence of interaction of dislocations with the introduction atoms, most of which have moved to carbides and nitrides.

Temperature dependences of dissipative properties ща frictional contact (the force of external friction) are largely depend on the influence of relaxational internal friction [5], as evidenced by the results of high temperature experiments that are shown on fig. 5 and were made on tribometer THT of the joint "ball (ШХ-15) – the plane of rotating disk (sample made of steel 45)".

At the selected friction speed ($v = 0.2$ m/s) and friction path radius (R = 8 mm), each element of the contact zone is subjected to impulse function on the side of fixed counterbody (ball) with frequency 4–5 Hz. The vibration frequency of the ball was within kilohertz range.

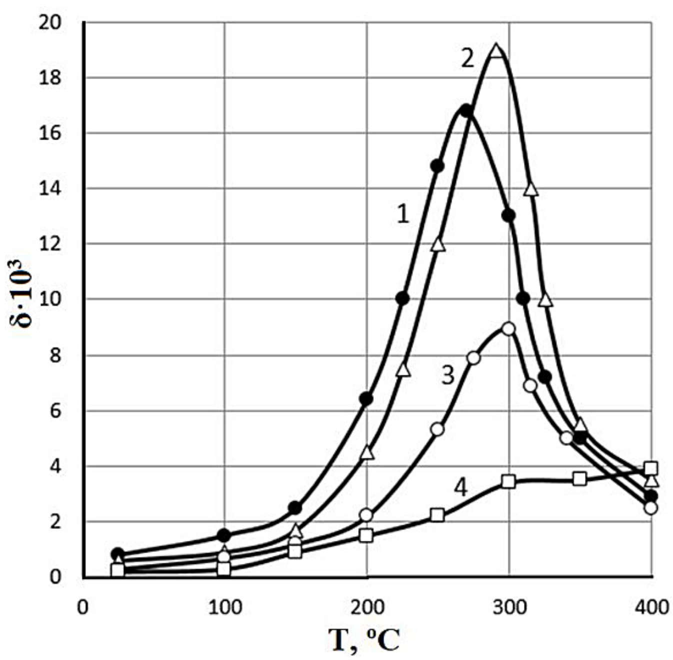

Fig. 4. SK-relaxation: 1 – quenching; 2, 3, 4 – tempering, respectively, at temperatures of 200, 400, 600°C ($f \approx 1$ kHz)

During friction of martensitic structures (Fig. 5a, b), the maximum of external friction force is formed near 60°C, which for the vibration frequency of 4 Hz corresponds to the carbon peak of relaxational internal friction – Snook relaxation (SR), caused by the diffusion redistribution of interstitial atoms in the field of acting cyclic stresses [6]. The height of Snook peak and corresponding mechanical losses are proportional to the concentrations of carbon atoms in solid solution and decreases with the increase of steel tempering temperature. The widening of the Snook peak is affected by the increased density of dislocations (dislocation-enhanced Snook effect).

The observed changes in the external friction force are the result of summation of the contributions due to the action of different mechanisms of internal friction with close values of the activation enthalpy and located next to each other on the temperature scale. Thus, the maximum of friction force in the region of 80°C in the research of quenched steel (Fig. 5a) can be associated with the superposition of the peak of internal friction, distinctive for residual austenite, on the Snook peak. The friction force maxima near temperatures 160–170°C and 220°C apparently are caused by the influence of a counterbody (ШХ-15), which temperature was 50–70°C below the sample temperature and which forms corresponding peaks of internal friction typical for hardened steels alloyed with chromium [8]. The temperature localization of friction force peaks due to internal friction is also affected by the change in the vibration frequency of the friction contact zone of the counterbody with an increase in the tempering temperature of the samples.

In a range of temperatures 250–350°C there is an unstable jump change of friction force connected with development of DSA when dynamic blocking of dislocations by impurity atoms alternates with generation by sources of "fresh" dislocations that creates heterogeneity and change in time of local rheological properties of a friction zone (the tribological analog of the Porteven-Le Chatelier effect [5,10]). When impurity atoms accumulate near dislocations in the temperature range of 250...350°C the hardening effect of DSA is accompanied by Snook-Kester relaxation (see Fig. 4). Relaxation processes at DSA, preventing setting and reducing friction force, cause sharp decrease in the counterbody temperature by 25°C with its subsequent accelerated growth by 85°C at the exit from the DSA temperature range (Fig. 5c), which was proved by thermocouple readings T_K, fixed on a motionless counterbody. The favorable rheological properties of the metal substrate stabilize the protective effect of secondary oxide formations formed during friction in the DSA mode. During friction of high-temperature steel (Fig. 5d) SK relaxation and DSA occur in a limited temperature range without a sawtooth character of friction force fluctuations. The strengthening effect created by atmospheres, which fix dislocations, seems to be provided by carbon supply in the process of deformation dissolution of cementite.

Considering dependence of development of tribodynamic processes of structural rearrangement of only from heat treatment of steel, but also from load, speed and temperature conditions of friction, comparative tests of steel 45 low-tempered (T_{temp} = 200°C, HV_5 = 790) and normalized (HV_5 = 230) at more "hard" regimes on the scheme "finger (sample) - plane of rotating disk" in a range v = 0.2–3.2 m/s at two specific loads – 2 MPa and 4 MPa were conducted. Samples before tests were subjected to friction treatment (grinding with fixed abrasive + polishing).

The following conclusions are derived from the experimental data (Fig. 6).

1) At change of friction speed of normalized steel the maxima of wear resistance (Kell-Siebel effect [1,7]) are formed in area of speeds 1.3 m/s at P = 2 MPa and 0.7 m/s at P = 4 MPa (Fig. 6, curves 2,4). With the increase of contact pressure, the maximum of wear resistance shifts to the region of lower velocities.
2) Quenched steel (tempered martensite) at small friction speeds (v = 0.2–0.5 m/s) shows anomalously high wear resistance in comparison with the normalized steel, not commensurable with difference of initial hardness (Fig. 6, curves 1,3). So, at load P = 2 MPa the wear resistance of quenched and normalized steel differs at v = 0.2 m/s in 55 times and at v = 0.5 m/s in 23 times. At the same time at increase of contact load up to P = 4 MPa these indexes essentially increase, accordingly, up to 210 and 40.
3) The wear resistance of quenched steel with increase of friction speed monotonously decreases and at speeds more than 1–1.5 m/s differs from wear resistance of normalized steel only in 1.5–4 times at P = 2 MPa and in 3–4 times at P = 4 MPa that on the average approaches to their difference of initial hardness (HV_{quench}/HV_{norm}= 3.4). Presumably, the maxima of hardening martensite wear resistance are in the range of friction speeds less than 0.2 m/s.

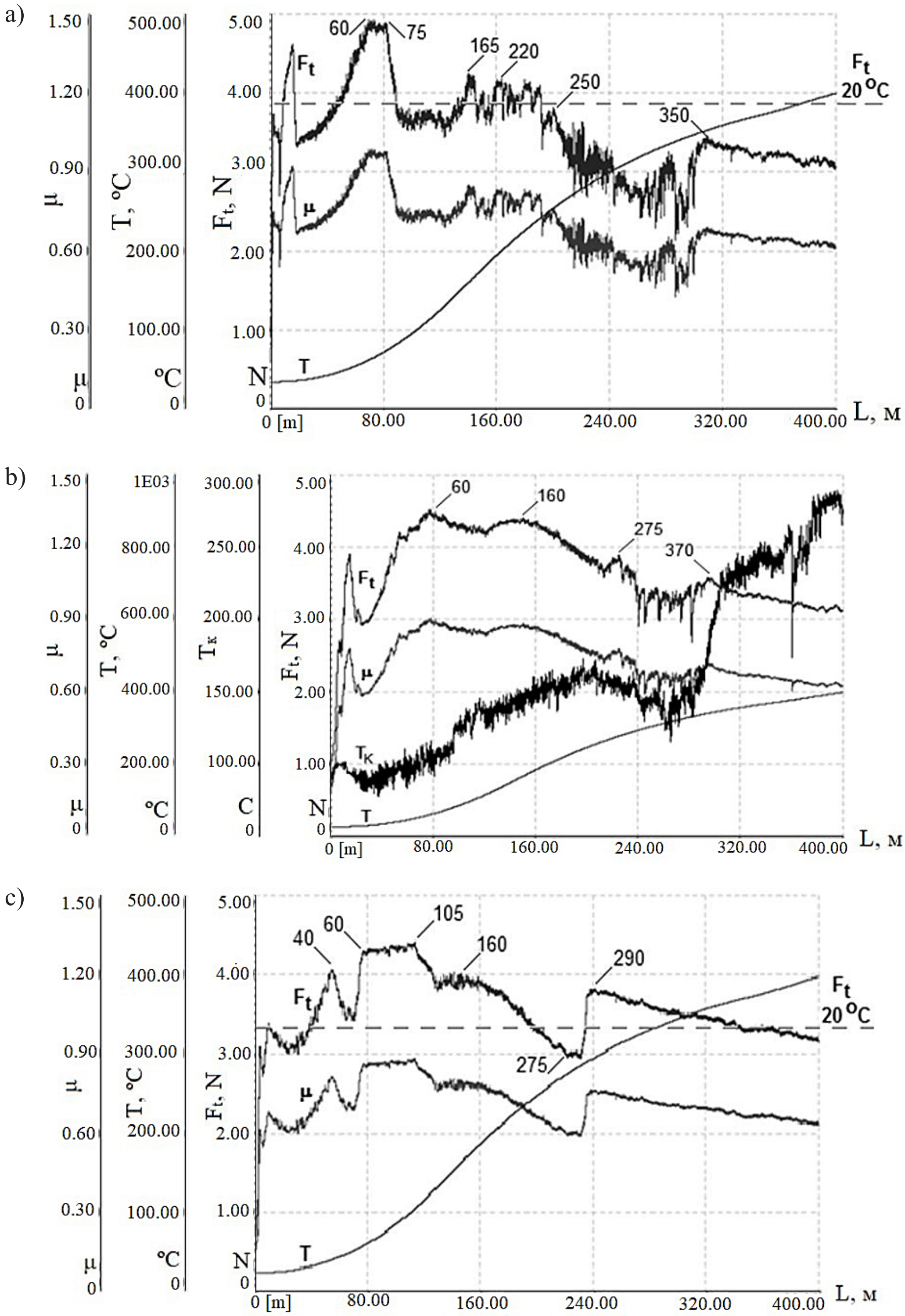

Fig. 5. The change of force (F_t) and coefficient of friction (μ) depending on temperature (*T*) and friction path (*L*): a) tempering at 200°C; b) tempering at 300°C (T_K – counterbody temperature); c) tempering at 600°C. The curves selectively show the values of heating temperatures of moving sample. Dashed lines correspond to steady friction force without heating (at the temperature of 20°C)

Maxima of wear resistance of normalized steel, corresponding to certain load-rate conditions of friction, are caused by the development in the temperature range 200–350°C of dynamic strain aging (DSA) and related to the aging of Snook-Kester relaxation (relaxation peak of internal friction). Despite the fact that these processes cause a significant increase in strength

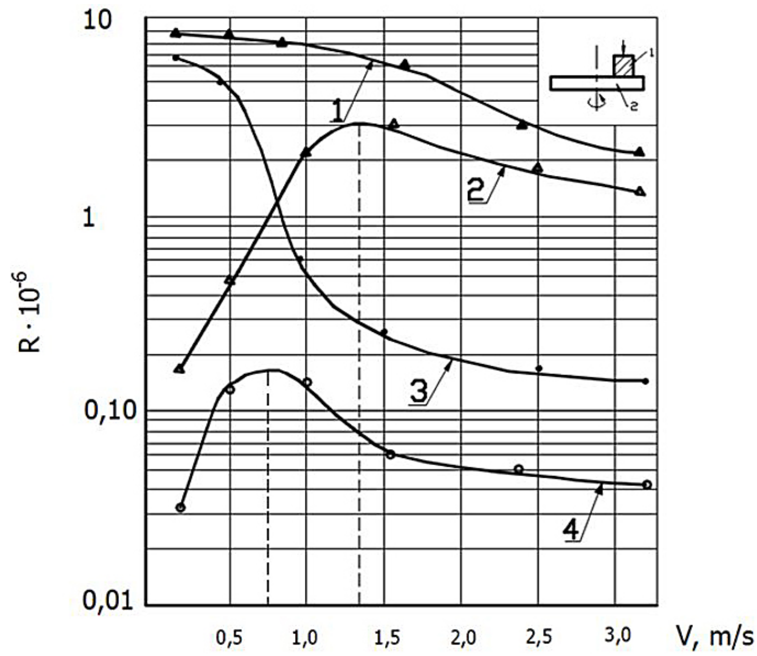

Fig. 6. Dependences of steel 45 wear resistance on friction speed: 1,3 – tempered martensite; 2,4 – normalization (1,2 – P = 2 MPa; 3,4 – P = 4 MPa); 1 – sample (finger); 2 – counterbody (disk)

and hardness of steel, there is no complete loss of ductility and, moreover, the dynamic viscosity increases [23-25].

For the formation of the internal friction peak with increasing temperature, the resonance frequency of the friction contact vibration should also increase. At the same time, from Figure 6 (curves 2,4) by the example of normalized steel we can see: with increasing contact pressure and, accordingly, temperature in the friction zone, the maximum of wear resistance shifts towards lower speeds. As the specific load increases, the optimum range of DSA temperatures is achieved at lower friction velocities, and the increasing proximity of friction surfaces at that contributes to an increase in the number of interacting spots of actual contact and an increase in the frequency of vibration arising in the friction surfaces. Therefore, the dislocation velocity distribution approaching the diffusion velocity of carbon atoms is realized at lower friction velocity when the load is increased.

Taking into account the fact that the amplitude of the actual contact spot vibration increases with increasing friction velocity, the relaxation capability of normalized steel can be significantly affected by magnetomechanical internal friction - magnetoelastic hysteresis (MEH), caused by a periodic irreversible 90° shift of the magnetic domain boundaries in the field of acting cyclic stresses [18]. If the magnetic domain walls are not blocked, this type of mechanical losses has a sharply pronounced amplitude dependence: at large strain amplitudes for normalized and highly tempered steels, the MEH contribution to the total internal friction level can be up to 80%. The maximum of the magnetomechanical losses is formed due to the fact that at contact temperatures above 200°C the MEH losses significantly decrease, which is additionally facilitated by the growth of accretion, which reduces the mobility of the magnetic domain walls.

The exceptionally high wear resistance of tempered martensite at low friction velocities (v = 0.2–0.5 m/s) is associated with a number of features of the hardening structure and the specificity of its behavior under the action of dynamic loading.

Martensite, which has a metastable structure, under load shows a significant difference between the indices characterizing the resistance to large and small plastic deformations and determining, respectively, strength and relaxation (damping) capacity. Dislocations arising in the process of phase hardening during steel hardening create strong zonal stresses and, remaining weakly fixed, behave unstable and can be unblocked and rebuilt under the action of external load. Therefore, martensite at high hardness simultaneously exhibits significant microplasticity and relaxation ability under dynamic loading. This is evidenced by the decrease in the elastic limit and physical width of X-ray lines when martensite is deformed [17]. Moreover, the degree of reduction of these characteristics increases with increasing magnitude of deformation. Therefore, as the martensite elastic limit decreases as it approaches the friction surface due to the strain gradient, forming a positive gradient of elastic properties, which helps to reduce the dynamic tension of frictional contact.

High wear resistance of martensite is also provided by a high degree of dispersion of its structure in the friction zone. It is known that materials in ultrafine-dispersed (nanocrystalline) state, obtained by severe plastic deformation, have high strength properties and increased damping capacity. The damping mechanism is dislocation mechanism supplemented by grain boundary effects [6]. At low velocities and friction temperatures (40–80°C) an intensive shear plastic deformation and martensite dispersing are facilitated by the increasing microplasticity of steel due to the development of dislocation-enhanced Snook relaxation [6,8]. This type of internal friction and the corresponding mechanism of damping are associated with the diffusion of impurity atoms of implementation (C+N) in the field of cyclic stresses ("diffusion under stress"). The high damping capacity of martensite with its high strength is additionally provided by the reversible movement of twin boundaries, as well as by the dislocation energy dissipation in the finely dispersed residual austenite, stable with respect to $\gamma \rightarrow \alpha$ transformation.

Wear resistance of tempered martensite (Fig. 6, curves 1,3) is also caused by dynamic strain aging (DSA) and moderate dynamic tempering (DT), which, summarized with the initial low-temperature thermal tempering, promotes the growth of carbide precipitation. Carbide particles, being, on the one hand, a hardening factor due to their barrier action, on the other hand, at the initial stage favorably influence the relaxation ability of the material, because they promote the generation of fresh dislocations and cause the reduction of the carbon concentration in the matrix, which leads to a decrease in the density of dislocation attachment points. Apparently, under these conditions such a ratio of the total density of fixed and mobile dislocations is created, which forms an optimal combination of strength and relaxation (damping) ability. The greatest strengthening effect of DT (stress tempering) is manifested under dynamic load not exceeding the yield strength: (0.6–0.7) σ_T [10].

Taking into account that relaxation processes are thermally activated, tribological conditions of realization of hardening at DSA and DT should depend on thermal conductivity of materials of a friction pair. It is known [1,17] that due to the reduced thermal conductivity of hardened steel, the friction zone with its participation can be heated to temperatures 1,5–2 times higher than the friction temperature of normalized steel. This, apparently, is one of the main reasons for the observed shift of martensite wear resistance maximums to the region of lower velocities ($v \approx 0{,}2$ m/s) in comparison with normalized steel (Fig. 6).

The fall of wear resistance of hardened steel with the growth of friction speed and, accordingly, contact temperature (Fig. 6, curves 1,3) is associated with embrittlement due to excessive intensification of dynamic tempering in the temperature range of 150–300°C. The increase in dispersity and density of carbide precipitations during martensite decomposition in the field of dynamic stresses at elevated temperature causes a significant increase in resistance to small plastic strains (relaxation resistance), practically not changing the resistance to large plastic strains (hardness, ultimate strength) [15]. Additional reduction of relaxation (damping) capacity of hardened steel also causes the phenomenon of tempering brittleness, arising from the release on the grain boundaries of carbide plates, around which are formed stress peaks that facilitate fracture [17]. The growth of relaxation resistance with embrittlement effect reduces the ability of steel to resist wear, because the damaging processes of contact stress relaxation are included, accompanied by the formation of relaxation microcracks and seizure. It is not excluded also reduction of the accepted indicator of martensite wear resistance due to reduction of DSA time at increase of friction speed with preservation of constant friction path in experiments.

Ferritic-pearlitic normalized steel at a friction velocity of 0,2 m/s shows low relaxation capacity and the main type of deformation hardening is mechanical sticking with embrittlement as a consequence of self-locking of dislocations and their sources. As a consequence, the damaging mechanism of contact stress relaxation – adhesion – is mainly realized [7]. The relatively low efficiency of DSA in friction of normalized steel is due to the low concentration of carbon atoms in ferrite, the source of which is mainly cementite during its decomposition.

CONCLUSIONS

The influence of tempering temperature of hardened carbon steel on hardness, elastic properties and on tribological indicators has been investigated. Decrease in steel hardness with increase in tempering temperature is accompanied by progressive decrease in wear resistance and ambiguous changes in friction coefficient, wearing capacity and friction damping, which take maximum values in the tempering temperature range of 200–300°C. It is connected with the established cyclic change of the elastic modulus and internal friction level, which is caused by the change of dislocation mobility, which, in turn, is determined by concentration and blocking action of impurity atoms of introduction (C+N) and carbide extractions.

It is shown that the growth of elastic modulus and reduction of internal friction after low-temperature tempering (T_{temp} = 200–300°C), indicating an increase in relaxation resistance of steel, during friction promotes the growth of contact stresses and development of adhesion (with possible transition to adhesion). Adhesion, as a topochemical reaction of formation of metallic bonds in the solid phase at the interface, is the leading form of relaxation of contact stresses during friction steel, which has a high relaxation resistance.

High-temperature tests have shown the relationship of external friction indicators (force and friction coefficient) with the relaxation effects (peaks) of internal friction. Snook relaxation promotes formation of highly dispersed (nanocrystalline) structure during martensite friction, providing growth of damping ability. Snook-Kester relaxation together with dynamic strain aging, changing the rheology of the friction contact, contributes to the reduction of friction force, accompanied by frictional auto-oscillations (a tribological analogue of the Porteuen - Le Chatelier effect).

Anomalously high wear resistance of hardening martensite and tempering martensite, which is formed directly in the process of friction at speeds less than 1 m/s, has been established due to the specific dynamic structural restructuring, causing additional effective growth of contact strength and dynamic toughness. According to the analysis performed, as a result of intensive dispersion of crystal structure and effective development of strengthening dynamic relaxation processes (DSA and DP) martensite at friction is transformed into a heterogeneous composition possessing high dynamic shear strength and significant damping (relaxation) ability of the friction contact zone. In addition, due to the strain gradient, the elastic limit of martensite increases when moving away from the friction surface, forming a positive gradient of elastic properties beneficial for wear resistance.

The hypothesis of the reasons of the observed maximums of normalized steel wear resistance at certain friction modes (Kael-Ziebel effect) is proposed, taking into account that the temperature-speed localization of these maximums corresponds to the temperature-deformation conditions of the most effective development of DSA, conjugated with Snook-Kester relaxation.

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