ARCHIVES
of
FOUNDRY ENGINEERING

ISSN (1897-3310)
Volume 14
Special Issue
1/2014
193-198

39/1

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

Effect of the Viscoelastic Properties of Treated Steel on the Rheology and Dissipative Properties of Frictional Contact

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Received 03.03.2014; accepted in revised form 31.03. 2014

Abstract

Effect of the tempering temperature of hardened carbon steel and conformable structural changes on physical-mechanical properties and tribological characteristics during dry sliding friction was researched. It is shown, that relation between adhesive and deformational components of the frictional force depends on acquired during tempering viscoelastic properties that influence on mechanism of the contact interaction and dissipative processes. Viscoelastic properties are detected by two basic rheological parameters: modulus of elasticity and damping capacity, with which the viscoelastic coefficient is connected. The theoretical analysis of dissipative properties of the viscoelastic frictional contact dissected subject to the structure of tempered steel on the base of examined standard rheological models.

Keywords: Frictional contact; Wear resistance; Coefficient of friction; Hardening; Tempering; Rheology; Relaxation; Internal friction; Deformation; Tension; Viscoelasticity.

1. Introduction

The effectiveness of transformation of mechanical energy in heat by tribosystems is determined by the relationship between external and internal friction. The process of energy dissipation is realized by different mechanisms of internal friction during the formation of adhesive and deformational components of friction, depending on the level of functional contact tensions.

Adhesive and deformational processes as main initiators of the mechanical energy dissipation during sliding friction flow on different dimensioned levels and observe the different rheological laws [1]. First type of the dissipation is conditioned by contact (adhesive-shearing) internal friction, caused by imperfect elasticity of volumes that fit to discrete actual contact patch, undergone to impulse cyclic loading. In spite of adhesive and deformational processes follow their laws, they are interconnected and described in united term – deformation and tensions. It is obvious, that ratio between adhesive and deformational components of the friction force depends on initial rheological properties of contacting metals and properties, obtained during contact interaction.

2. Research technique

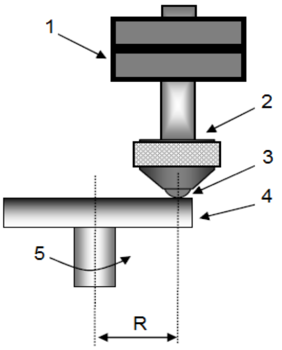
Medium-carbon steel 50 (water hardening after the temperature 850 ºC with following tempering during one hour from 200 up to 700 ºC) were studied.

Vickers hardness and elasticity modulus of Young were studied by continuous indentation of the Berkovich pyramid method on the facility OPX NHT/NST of CSM Instruments company (Switzerland). The speed of weighting and unweighting was 900 mN/min.

Structural changes of steel caused by thermal treatment were studied by amplitude-dependent internal friction method on the torsional pendulum facility [2]. Logarithmic vibrational damping decrement of the sample was the main characteristic of internal friction.

Viscoelastic properties and acoustic emission activity of operating surfaces were defined during their scanning by Rockwell adamantine indenter (scratch-method), using tribosclerometer REVETEST-RST of CSM Instruments company.

Tribotechnical trials during dry sliding friction were examined on the TRIBOMETR (THT) friction machine of CSM Instruments company (fig. 1.) fitting the scheme “rotating disk (sample) – fixed bead” (ШХ15 (1.3505 100 Cr 6), HV_5 = 1050).



1 – weights;
2 – holder;
3 – bead;
4 – disk (specimen);
5 – axis.

Fig.1. Scheme of tribotechnical trials

Working surfaces of the specimens were grimded and polished after thermal treatment. Automatic recording of the friction force and friction coefficient were realized during trials. Wear of the friction pair was estimated by the changing of specimen’s mass and diameter of the bead’s wear track. Trial conditions: normal loading – 5N, friction speed – 0,2 m/sec, friction path – 1000m.

3. Experimental results and discussion

Changing of the studied physical-mechanical properties of the steel depending on the tempering temperature is shown on fig. 2.

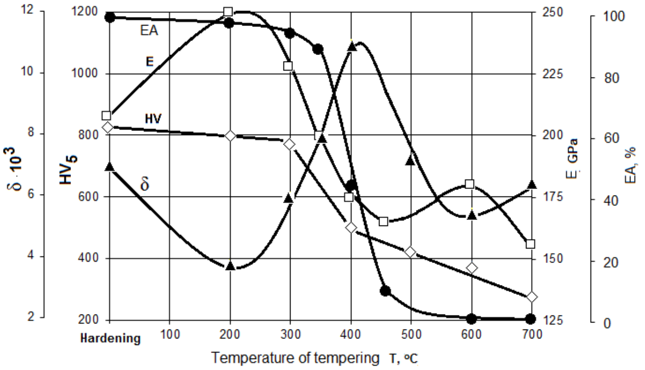


Fig. 2. – Effect of the tempering temperature of hardened steel on physical-mechanical properties: HV_5 – hardness; *E* – modulus of elasticity; δ – logarithmic decrement of vibrations; *EA* – indicator of acoustic emission activity

During monotonous descent of hardness (HV_5) with tempering temperature raising the modulus of elasticity *E* of steel changes cyclically, forming first near tempering temperatures 200…250 ºC, and second less expressed maximum – near 600 ºC. This character of changing of elasticity modulus is conditioned by microstructural changes, that form viscoelastic rheological properties of the material, that also influence on amplitude-dependent internal friction (ADIF). Really, dependence of internal friction (vibration decrement δ) on tempering temperature of the steel also has cyclic character, but in antiphase and with changing of elasticity modulus.

The level of ADIF is defined by structural stability of steel and dislocation degree of freedom, that depends on blocking action of impurity atoms and carbide-nitrid extraction, that accompany tempering of hardened steel. After hardening steel has relatively high internal friction, because martensite has bigger density of movable dislocations, that were formed in result of phase hardening. In this conditions steel has considerable microplasticity with high hardness. Elevation of the tempering temperature up to 200…250 ºC causes significant internal friction decreasing and increasing of elasticity modulus of steel as a result of martensite disintegration with fine-grained fractions extraction of the metastable ε-carbide, that is coherently connected with the matrix (I transformation), and also after disintegration of the residual austenite ($\gamma_{\text{ост}} \rightarrow \alpha + \text{К}$) with the formation of low-carbon austenite and dispersed carbide (II transformation) [3]. Dislocations are fixed by segregations of foreign atoms of penetration (C+N) and separated out carbide parts. Mobility of dislocations reduce (minimum δ), structure stabilize, acquiring high elasticity and relaxation resistance (maximum E).

Increasing of internal friction and decreasing of elasticity modulus in the range from 250…400 ºC are conditioned by increasing of the mobility of dislocations as a result of significant decreasing of the carbon concentration in the solid solution because of its transition in carbides. Carbide transformation (ε-carbide → cementite) assists to this factor, and completed by formation near tempering temperature 400 ºC of fine-grained ferrite-cementite mixture – troostite of the tempering (III transformation).

Under tempering temperatures higher than 400 ºC lamellar ferrite is transformed to granular, forming so-called secondary sorbite. Herewith the density of mobile dislocations decrease, internal friction falls and elasticity grows up. New growth of the internal friction under tempering temperatures higher than 550…600 ºC is conditioned by increasing of the ferrite volume free from carbides (owing to coalescence of carbide fractions), by the increasing of plasticity of ferrite because of its depletion by carbon, and also by increasing of loss on magnetomechanical hysteresis [4].

Hardened structure and tempered martensite ($T_{отп}$ = 200-300 ºC) at relatively small depth of indenters introduction and low friction coefficient (during scratch-analysis) show maximum acoustic emission activity. Meanwhile, structures of high temper ($T_{отп} \geq 450$ ºC) due to chosen scanning parameters shown absence of acoustic emission. Intensity of acoustic emission during mechanical weighting reflects the dynamic of local restructuring of the metal with relaxation of microstresses [5]. During this process release (dissipation) of energy in elastic-formed wave happens with changing of tensely-deformed condition. On microlevel relaxation processes with emission of acoustic impulses are conditioned by the processes of formation and transformation of microstructure of the metal during mechanical weighting. Martensite structure is inclined to this type of reorganization during the deformation as a result of twinning, changing of energy state of dislocations, unblocking of blocked and appearing of new lightly mobile dislocations, microalligatoring, that becomes apparent in heightened of the relaxation ability. In highly tempered steel ($T_{отп} > 450$ ºC) owing to more deep plowing of the specimen's surface by indenter and more plastic deformation, motion of dislocations is blocked by bigger number of barriers and work of the sources of free dislocations is suppressed. Owing to this, acoustic emission rushes to zero, because of her intensity during micro reorganization first of all depends on the mobility and length of free path of dislocations [6].

The effect of tempering temperature of steel on tribological indicators of studied tribosystem is shown on fig. 3. Minimum sclerometrical friction coefficient (f_{sk}) responses to tempering temperatures 200-300 ºC. During this temperatures the system acquires maximum elasticity.

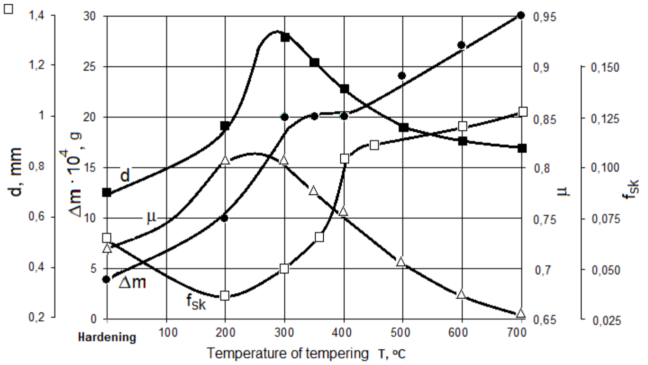


Fig. 3. Effect of thermal treatment of steel on tribological indicators of friction pair: Δm – weighting wear of the specimen (disk); d – diameter of wear spot of rider; μ – friction coefficient; f_{sk} – sclerometrical friction coefficient (F_n = 5N, V_{sk} = 100 mm/min)

After comparison of fig. 2 and fig. 3 is visible, that wear resistance of steel increases with increasing of hardness. Hardening that triples hardness of steel, increases its wear resistance 8 times. It is connected with higher mentioned specificity of initial martensite structure of hardening and with peculiarity of dynamical processes of substructure reorganization during friction, accompanied by additional strengthening and improvement of dissipative (relaxation) indicators.

Steel in hardened state (martensite) is characterized by structural metastability. During thermo-mechanical influence in friction conditions martensite endures dynamic deformational aging (DDA), which strengthen material more effectively, than cool hardening or usual deformational aging [7]. Tempering under tension or dynamic tempering (DT) promotes growth of strengthening effectiveness [8], during which disintegration of martensite (with formation of fine-grained carbide fractions) accelerates. On one hand, blocking of dislocations by the atmospheres of interstitial atoms and carbide extractions calls additional strengthening. On the other hand – growth of diffusional mobility of interstitial atoms (C+N), and also processes of DDA and DT cause relaxation of peaks of contact tensions directly in process of friction.

As a result of thermal treatment of steel synchronous changing of viscoelastic properties of steel (E, δ) and tribological indicators of frictional contact (μ, d) are observed. Until 400 ºC coefficient of external friction μ changes inversely to hysteresis internal friction δ and in direct proportion to modulus of elasticity E.

Initial growth of elasticity of steel and stability of microstructure is accompanied by decreasing microplasticity stock and by the loss of relaxational ability, decreasing of internal friction δ also testifies to that. Under such conditions main mechanisms of energy dissipation and relaxation of contact tensions become physic-chemical abilities of adhesive connections formation accompanied by increasing of adhesive (molecular) component of friction force and decreasing of contribution in general friction force of deformational component. Therefore, observed regularities of changing of friction coefficient μ and wear-out ability of steel d in the first place should be connected with changing of steel elasticity E and activation of adhesive processes, maximum of which fits to tempering temperature range near 250-300ºC. Adhesion acquires character of gripping (bonding process) under conditions of undamageable processes of tension relaxation deficit, realized by mechanisms of relaxational or hysteresis internal friction [2]. Adhesion and gripping act as form of structural relaxation of contact tensions during rhe development of topochemical reaction of metallic bounds formation on interface. Defensive film of secondary structures on hard elastic substrate are unstable and collapse in process of contact interaction, what causes increased damageability of rider. As a result coordinated growth of specimen Δm, rider d and coefficient of friction μ occur up to tempering temperatures 250-300ºC. At higher tempering temperatures decreasing of elasticity modulus and friction coefficient with simultaneous decreasing of wear of the rider accompany growth of wear of steel.

Thereby, relation between adhesive and deformational components of friction force depends on viscoelastic properties of frictional contact defined by two main rheological parameters of friction pair materials: modulus of elasticity and internal friction (damping capacity). In condition of high modulus of elasticity and low internal friction of less firm element of friction pair its wear ability and summary friction force are mainly defined by adhesive component; in condition of internal friction growth and decreasing of elasticity modulus of the tribosystem elements the contribution of deformational component rises, that turn to dominating on the structure of steel, formed at the tempering temperatures higher than 400 ºC.

4. Rheology of dissipative processes

Discrete actual contact patches during interaction of associated surfaces under conditions of sliding friction are undergone to vibrational influence of sliding tensions with decreasing deep down from the surface speed of viscoelastic deformation. Localized in near-surface layers gradient of shear deformation except elasticity force forms force of internal friction (Newton force), that stipulate dissipation of input mechanical energy [9]:

$$F_N = \eta \cdot \frac{dV}{dh} \cdot A, \qquad (1)$$

where: η – dynamic viscosity; $\frac{dV}{dh}$ – gradient of deformational speed along depth; A – actual acreage of contact. Therefore, shear tension:

$$S = \frac{F_N}{A} = \eta \cdot \frac{dV}{dh} = \eta \cdot grad\ V \qquad (2)$$

Coefficient of viscosity η is connected with two rheological indicators of solid body – with shear modulus G and damping capacity δ, characterizing internal friction.

As example we will examine friction assemblies of working without lubrication machines which act like link that pass efforts across frictional contact (frictional adherence clutch, brake assemblies, frictional dampers and shock absorbers etc.). In dynamic models of such assemblies should be considered interaction of actual contact patches with specified viscoelastic connections which rheological properties depend on structural state of steel.

In consideration of experimentally observed (fig. 2, 3) changing character of viscoelastic properties of steel with tempering and appropriate changes of tribological indicators as dynamic models that describe as a first approximation tensely-deformational state of frictional contact, let’s examine viscoelastic properties of rheological bodies of Maxwell and Kelvin-Voigt (fig. 4) [10].

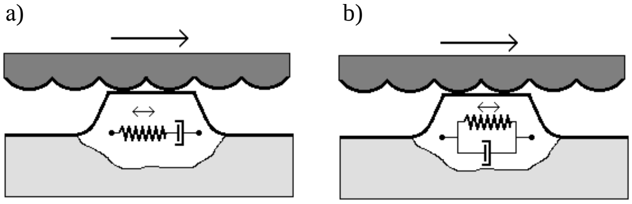


Fig. 4. Dynamic models of single frictional contact with dissipative properties that corresponding to rheological bodies of Maxwell (a) and Kelvin-Voigt (b).

Maxwell model (fig. 4a) characterizes body with ideal viscosity in which viscous deformation is instantly established and relaxational properties are such, that material does not fully restore its original form. This model can be used for description of tensioned state of the frictional contact of materials with heightened viscosity when adhesive component of steel dominates (for example, low- and medium-tempered hardened steel at temperatures not less 400ºC).

Deformation and shear tension in Maxwell model tie up by next differential equation [4]:

$$\dot{s} + \frac{G}{\eta} \cdot s = G\dot{\gamma}, \qquad (3)$$

where s – shear tension; γ – relative shear deformation; η – dynamic viscosity; G – shear modulus.

Tensioned state of actual contact zone is provoked by appearance of adhesive and deformational surface connections. During periodically changing tension with ω frequency action in viscoelastic body

$$S = S_0 \cdot e^{i\omega\tau}, \tag{4}$$

the energy dissipation of mechanical vibrations occurs, as during cyclic deformation of viscoelastic bodies tension S is shifted in phase comparative to shear deformation γ . In this case tension is determined through complex shift modulus G^* [9]:

$$S = G^* \cdot \gamma \tag{5}$$

In turn, G^* it can be represented as sum:

$$G^* = G' + iG'', \tag{6}$$

where G' – actual component of the complex modulus coinciding with deformation (dynamic shear modulus); G'' – imaginary component shifted on 90º relatively to deformation (modulus of mechanical losses). G' characterizes elastic energy reserved and returned by unit of volume per cycle of deformation, and G'' defines that part of vibrational energy, that transforms into heat, that is characterizes the dissipation of input mechanical energy conditioned by internal friction. Indicators of internal friction Q^{-1} are tangent of degree of phase sliding φ between tension and deformation, and also logarithmic decrement of vibrations δ [11]:

$$Q^{-1} = tg\varphi = \frac{G''}{G'} + \frac{\delta}{\pi} \tag{7}$$

After substitution (4) in (3) and next integration we gain connection between amplitude value of tension S_0 and comparative deformation of shear γ_0 :

$$S_0 = \frac{iG\cdot\omega\cdot\eta}{G+i\omega\eta} \cdot \gamma_0 = G^* \cdot \gamma_0, \tag{8}$$

where G^*– complex modulus of shear, transforming which with a glance (6) we obtain:

$$G^* = \frac{G(\omega\eta)^2}{G^2+(\omega\eta)^2} + \frac{G^2\omega\eta^2}{G^2+(\omega\eta)^2} = G' + \mathrm{i}G'' \tag{9}$$

In compliance with (7) we can find equation fo internal friction:

$$Q_M^{-1} = \frac{G''}{G'} = \frac{G}{\omega\eta} \tag{10}$$

From which coefficient of viscosity is:

$$\eta = \frac{G}{\omega Q_M^{-1}} = \frac{\pi \cdot G}{\omega \cdot \delta} \quad , \tag{11}$$

where ω – vibrational frequency depending on friction speed and geometrical structure of surface contact. In consideration of (11) and (2) the equation for tension of adhesive connections destruction changes its appearance:

$$S_a = \frac{\pi \cdot G}{\omega \cdot \delta} \cdot grad\, V \tag{12}$$

If σ_n – is normal pressure in contact, then adhesive component of friction coefficient is equal to:

$$\mu_a = \frac{S_a}{\sigma_n} = \frac{\pi}{\sigma_n} \cdot \frac{G}{\omega \cdot \delta} \cdot grad\, V \tag{13}$$

Thus, under different equal conditions (under this friction speed and pressure and identical indicators of microroughness) adhesive component of friction coefficient is in proportion to shear modulus of elements of frictional contact and inversely to damping capacity (the level of internal friction).

Relation between physical-mechanical properties of steel tempered at temperatures more than 400 ºC and its tribological indicators (fig. 2, 3). Then it can be described with the help of rheological model of Kelvin-Voigt (fig. 4b), which characterizes ability of viscoelastic bodies to relax tensions under conditions of creeping. This model can be applied for description of deformational (hysteresis) external friction, when tensioned state of frictional contact surfaces and friction coefficient change corresponding to changing of internal friction of less rigid element of friction pair. For body of Kelvin-Voigt type full shear tension is equal to:

$$S = G \cdot \gamma + \eta \cdot \dot{\gamma} \tag{14}$$

Let deformation γ is periodical function of time:

$$\gamma = \gamma_0 \cdot e^{i\omega\tau} \tag{15}$$

After substitution (15) in (14) and integration we obtain relation between amplitude values of tension and deformation:

$$S_0 = (G + i\omega\eta)\gamma_0 = (G' + iG'')\cdot\gamma_0 \qquad (16)$$

For the reason (6), (7) and (16) we find internal friction:

$$Q_F^{-1} = \frac{G''}{G'} = \frac{\omega\eta}{G} \qquad (17)$$

Whence viscosity appears:

$$\eta = \frac{G \cdot Q_F^{-1}}{\omega} = \frac{G \cdot \delta}{\pi \cdot \omega} \qquad (11)$$

Equation for shear tension in formula (2) takes following form:

$$S_d = \eta \cdot grad\ V = \frac{G \cdot \delta}{\pi \cdot \omega} \cdot grad\ V \qquad (19)$$

Therefore, deformational coefficient of friction:

$$\mu_d = \frac{S_d}{\sigma_n} = \frac{G \cdot \delta}{\pi\sigma_n \cdot \omega} \cdot grad\ V \qquad (20)$$

From which follows, that deformational component of friction coefficient (under closely changing share modulus) changes in proportion to inner friction.

Thus, tensioned state and dissipative properties of frictional contact are mainly defined by relation of two rheological parameters – shear modulus and inner friction (damping capacity). This relation defines comparative contribution in summary friction coefficient of adhesive and deformational components that in turn depend of structural state of steel. i.e., the rheology of frictional interaction and appropriate dissipative processes are changing.

5. Conclusions

The relation between amplitude-dependent (hysteresis) internal friction, modulus of elasticity and coefficient of external friction depending on tempering temperature of hardened steel was determined. Until tempering temperature 400 ºC the coefficient of friction is mainly determined by its adhesive component (μ_a), which value changes inversely to hysteresis internal friction (δ) and in direct proportion to shear modulus (G). After steel tempering at temperatures higher 400 ºC leading hand acquires deformational component of external friction, that changes in direct proportion to internal friction (under the condition of closely changing shear modulus).

Correlations between friction coefficient and wear of thermal treated steel is absent, but then again its wear out ability changes in direct proportion to friction coefficient.

Wear resistance and antifrictionality of steel are determined by different physical-mechanical properties. Wear resistance depends on macroscopic indicators of durability and plasticity (hardness), and friction coefficient characterizing intensity of dissipative processes is mainly formed by rheological indicators of viscoelasticity and microplasticity, that control relaxation properties.

Tensioned state of macroelastic frictional contact connected with friction force is mainly determined by rheological properties of friction pair, formed in coupling with adhesive-deformational relations.

Acknowledgements

The apparatus was purchased under the project No. POPW.01.03.00-18-012/09 from Structural Funds provided in the framework of the Operational Programme 'Development of Eastern Poland' co-funded by the European Unions from the European Regional Development Fund.

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