779. Structural determinants maximising wear resistance of friction joints

Wojciech Żurowski
Faculty of Mechanical Engineering, Technical University of Radom
Malczewskiego 29 str. 26-600 Radom, Poland
E-mail: *wojciech.zurowski@pr.radom.pl*

Abstract. The paper addresses the issue of maximising resistance of tribological system elements against wear in the conditions of dry friction. A method of virtually multiplying wear resistance of solid bodies, particularly metals, has been found. This effect appears where the temperature of a friction area is equal to the characteristic temperature, and thus markedly different than temperatures applied in typical tribological experiments. Increased wear resistance of a system of bodies is effected by a system transfer of material between surfaces of rubbing bodies and stabilisation of the friction coefficient.

Resistance to abrasive wear in conditions of dry friction and oxidational wear was tested in selected frictional systems (specimens from steels C45 and counter-specimens from 145Cr6, in different structural states of the material). In order to identify composition and structure of the friction products and the types of ferrous compounds arising from friction present on the surface of rubbing components, especially secondary oxide structures, Mössbauer spectral analysis was applied.

The wear testing required construction of an original test device to measure wear in conditions of formation and regulation of the isothermic limit of temperature variation at a precisely determined distance from a contact of rubbing bodies by means of release (by cooling) or supply (by heating) of heat energy.

Keywords: Mössbauer spectral analysis, oxide structures, dry friction, tribological wear.

Introduction

Research into wear resistance is based on analysis of thermodynamic transformations which occur in an open thermodynamic system and intended to determine the conditions in which a system resistance is maximum. The equation of energy balance is adopted as the starting point for considering processes of friction and wear and the issue of wear resistance at the macroscopic level of matter organisation. The phenomenological approach leads to an analytical description of wear resistance where the structure and microscopic properties of matter are not taken into account. Load, friction coefficient, and temperature in the friction area are the set parameters in experiments conducted in accordance with this phenomenological approach.

A range of tribological studies (including by the most recent authors) [1] suggest that ambient factors (humidity, type of surrounding medium, vacuum, and temperature) have substantial impact on friction and wear of elements. Such arguments fail to account for the possibility of stabilising temperature in the friction area, for instance, or the friction coefficient itself, which can be quite precisely controlled and stabilised.

Assuming a stabilised temperature in the friction area and a stabilised friction coefficient allows for determining the greatest resistance of a friction system, defined as wear's specific work for the given system. In this case, specific work of wear is the quotient of work of friction and mass wear of the system (i.e. both the elements). The remaining parameters of the friction process, that is, pressure, sliding velocity, and friction path can be set freely. In effect, optimum friction parameters can be determined so that resistance of the system is or approaches maximum.

The ambient temperature of a friction joint affects physical and resistance properties of rubbing materials and formation of secondary oxidational structures. Many authors have undertaken research in conditions of oxidational wear. Theories of the oxidational wear have been developed [2-5]. Impact of temperature in the friction area on formation of oxidational structures has been assessed [6-9]. The temperature in the friction area was not stabilised in all these cases. This article presents results of research that help to explain phenomena and processes in the friction joints under conditions of dry friction and oxidational wear with a stabilised temperature in the friction area. Wear mechanisms can be determined and cooperating materials can be properly selected only in this manner.

Research into wear resistance

Tribological research at low temperatures requires special apparatus. This type of equipment was designed and has been employed at the Institute of Machine Design, Technical University of Radom, since 1990s [10-12]. New rigs have been designed for such testing, including TT-3 tester described in this article.

A series of experimental testing, some of which is discussed in the present paper, has been conducted using TT-3. The research was designed to determine if and what structural transformations in cooperating elements determine increased resistance to wear.

A system of rubbing metallic bodies constituted the object of testing. A ring and slider system became the physical expression of the object, like in earlier testers. The ring is the rotating element of the friction couple. Two fixed sliders have been applied in the form of a sample with a flat contact surface to the ring. The sample material may be selected for each separate matching in order to determine impact of physical properties, chemical composition, hardness, and structure of a material on increasing resistance to wear. The rig is schematically shown in Figure 1.

Resistance to wear was tested in conditions of oxidational wear and dry friction in order to determine at what temperature (referred to as the characteristic temperature) a given matching of materials exhibits greater resistance to tribological wear. The article presents testing of the following system: steel C45 in various conditions of heat treatment in association with hardened 145Cr6 steel (63HRC). Characteristics of the materials are provided in Tables 1 and 2.

Table 1. Characteristics of slider (items 1 and 2) and ring (item 3) materials

No.	Material	Condition of heat treatment	Hardness	Chemical composition, %
1.	Steel C45	normalised	18 HRC	C – 0.5; Mn – 0.67; Si – 0.21; Ni – 0.08; Cr – 0.15
2.		hardened and tempered at 600°C	19HRC	
3.	Steel 145Cr6	hardened	63 HRC	C – 1.4 ; Mn – 0.59 ; Si – 0.28 ; Ni – 0.08 ; Cr – 1.6 ; V – 0.17

C45 is a constructional carbon steel, most commonly used heat-treated in medium-loaded machinery elements (axles, cranks, gears, and discs). Structures of both normalised and heat-treated C45 steel were tested.

145Cr6 is a cold-work tool steel, oil-hardened and with stable dimensions once hardened, resistant to abrasion.

Testing of wear resistance of C45/145Cr6 matchings has demonstrated a significant (and expected) dependence of wear resistance on friction area temperature. The wear increased at a temperature of c.–5°C in the case of C45 (norm)/145Cr6 matching. This value is in line with earlier publications [10]. With regard to the matching of C45 (600)/145Cr6, the temperature of

maximised resistance was different, and the maximum specific work of wear reached 70 MJ/g. Values of characteristic temperatures and the corresponding wear resistance are listed in Table 3.
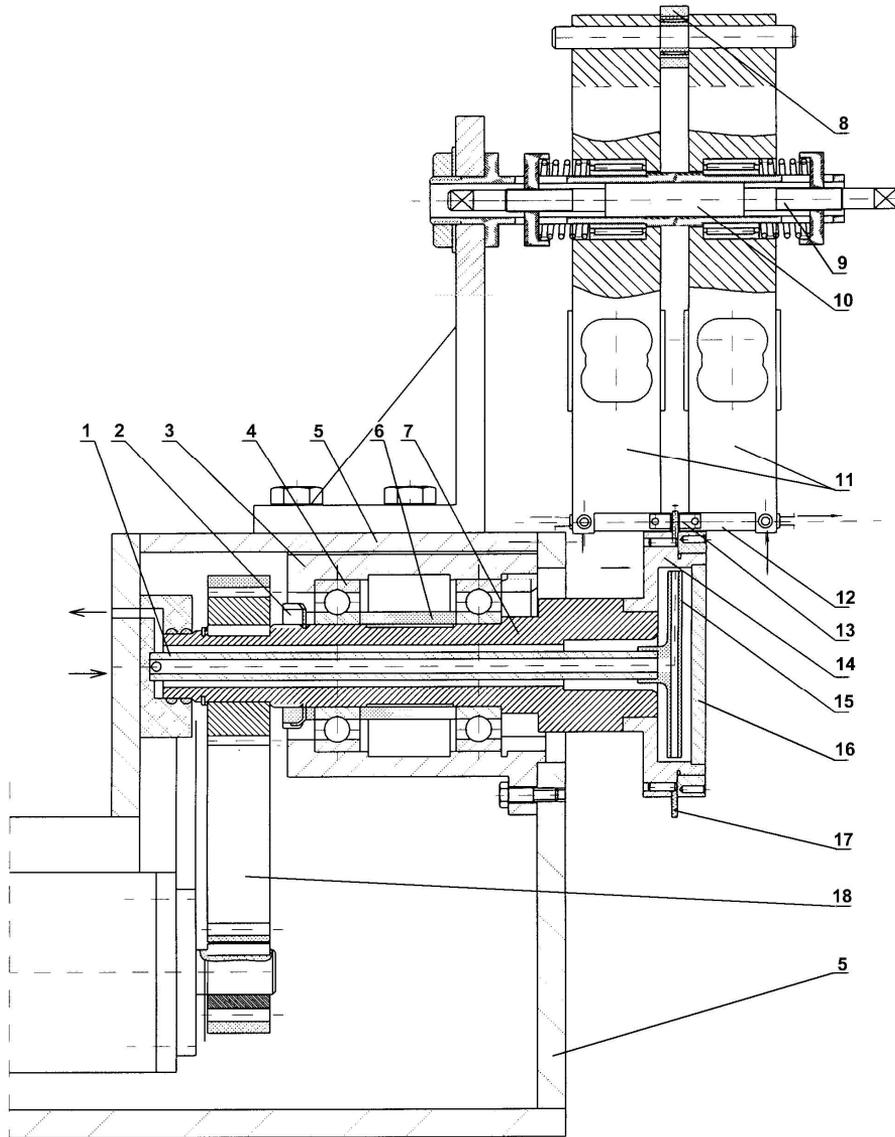
Fig. 1. Diagram of TT-3 tester: 1 – cooling pipe, 2 – lock nut, 3 – bearing sleeve, 4 – ball bearing, 5 – body, 6 – distancing sleeve, 7 – cylinder, 8 – mainstay of the moment of friction measurement, 9 – Roman screw, 10 – sliding sleeve of the clamp against the specimen, 11 – extensometer bridge of loading, 12 – clamp of the specimen, 13 – specimen, 14 – cooling disc, 15 – internal cooling disc, 16 – cover of the cooling disc, 17 – counter-specimen, 18 – driving cogbelt

Testing structure and composition of abrasion products

Wear measurements for matchings of heat-treated C45 showed a significant dependence between resistance obtained at a given friction area temperature and structure of a material. Matching of a heat-treated C45 tempered at 600 °C with a structure characterised by fine

divorced pearlite in a ferritic matrix proved the best, with a resistance approx. 160 % greater than in the case of normalised C45 steel.

Table 2. Structures of C45 and 145Cr6 steels

Material	View of the structure	Description of the structure
Normalised C45 steel		Pearlite-ferritic: ferrite around equiaxial pearlite grains of high dispersion; pearlite grains are medium-sized
C45 tempered at 600°C/1h		Fine divorced pearlite; cementite balls are evenly distributed in the ferrite matrix
145Cr6 hardened 63 HRC		Structure of fine-acicular (cryptoacicular) martensite with low quantity of very fine carbides $(Fe, Cr)_3C$
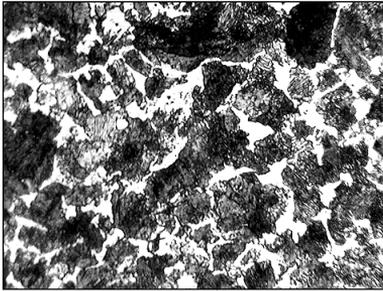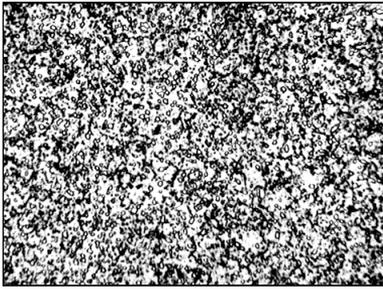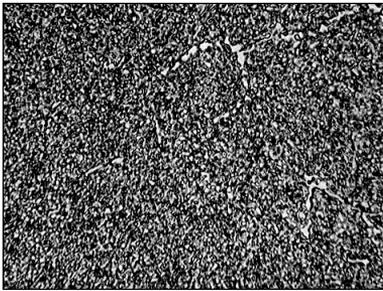
Table 3. Values of maximum specific work of wear for tested matchings

Matching	Characteristic temperature, °C	Specific work of wear, MJ/g
C45(norm)/145Cr6	–5	36
C45(600)/145Cr6	5	70

A measurable accumulation of particles over the cooperating elements could be observed in a majority of cases under testing. The accumulation could (and most likely did) occur where no mass increments were recorded as well. In the circumstances, migration of material particles between the cooperating surfaces took place, as in the transfer model described in [12]. On the basis of Mössbauer spectral analysis, nanometric particles and native material (ferrite and martensite) particles could be detected in the wear products, which further confirms this scenario. Occurrence of austenite, on the other hand, points to presence of counterspecimen particles.

Presence of the nanoparticles, a result of abrasion in the system, can reinforce the material [13] and modify the degree of heterogeneity of mechanical properties. In effect, the refinement of structure can be expected to alter, to a lesser or greater extent, both the weight and operation of the individual component mechanisms of the reinforcement, i.e. dissolution, deformation, and dislocation mechanisms. Above all, scaling down the grain from micro to nanometric dimensions improves its resistance properties.

Mechanisms of the material's phase transitions at the time of friction must be clarified. Results of Mössbauer spectral analysis suggest diffusive supersaturation of ferrite with carbon as a result of elastic-plastic interactions at the contact of rough surfaces of cooperating elements. Thermal phenomena at the frictional contact play a certain role, too, although they are not decisive due to intense heat escaping from the frictional contact. Principles of self-organisation of tribological systems described by Kostecki [14] are important to explanation of this issue. Kostecki cites formation of secondary structures in effect of metals accumulation at the time of friction as an example of a practical application of the self-organisation.

Where values of wear's specific work are great, it is interesting to explain how the material of rubbing bodies behaves in their contact area and what properties their surface layer exhibits in this situation.

Surfaces of sliders made of normalised C45 steel, hardened and tempered at 600 °C post friction in a regime of heightened resistance, were tested in a matching with a 145Cr6 steel ring (the so-called optimum conditions). Friction surfaces of each matching were tested prior to and after wear testing. The tests were carried out at the laboratory of the Department of Physics, Mechanical Faculty, Technical University of Radom.

Mössbauer testing employed spectroscopy using the isotope ^{57}Fe as the source of radiation and ^{57}Co in a rhodium matrix displaying activity of approximately 40 mCu.

Conversion Effect Mössbauer Spectroscopy (CEMS) was utilised to test steel surfaces. Powder friction products were tested by means of transmission method in a vertical system. A proportional counter served as a detector.

Speed of the vibrator head, on top of which the source of radiation was positioned, varied in line with time until reaching a selected maximum and then diminished (also in line) to reach zero in both cases. The variations recurred as motion reversed its direction. A full cycle of the variations recurred many times during the tests, which generally continued for several to a dozen days.

In order to identify phases in the specimens and to estimate their percentage contribution, Mössbauer spectra were analysed numerically by means of special software NORMOS, designed according to the minimisation procedure and the method of least squares with additional constraints [15-18]. Phases occurring in the entire series specimens (though not necessarily in each specimen) were specified in this way. These were: ferrite (α-Fe), martensite, iron carbide Fe_3C, iron oxide $Fe_{1-x}O$ (wustite), magnetite Fe_3O_4, hematite Fe_2O_3, austenite (γ-Fe). Set hyperfine parameters defined in [19, 20], identical (or within a definite range) for a full series of measurements, were applied to these phases in the second stage.

Shape of the spectra is characteristic of crystalline materials: they comprise sharp lines of a width slightly more than double the natural width. The number of components (i.e. single lines, doublets or sextets) as well as their hyperfine parameters depend on the number and type of phases in the specimen. For instance, the spectrum of pure iron of bcc (body centred cubic) structure has the shape of a single sextet with a hyperfine magnetic field (at room temperature) equal to 33.0 T (Tesla), an isomeric shift equal zero, and quadrupole split equal to zero. Alloy materials normally exhibit a certain degree of chemical disorder related to varied chemical environment of ^{57}Fe atoms and possibly some topological disorder – in the case of interstitial alloys. This leads to appearance of additional components (sextets) in the spectrum that represent iron atoms which have one or more atoms of alloy additions in the nearest coordination zones, where hyperfine parameters of these components depend, among other factors, on types of additions, whereas the numbers and intensities of components are primarily

connected to concentration of alloy additions.

An example of Mössbauer spectrum, generated by means of TMS (Transmision Mössbauer Spectroscopy) for friction products in the form of powders. These spectra, beside the components representing the phases listed above, comprise a component of much broader (fuzzy) lines which corresponds to a wide range of hyperfine magnetic field values, $5 \div 40$ T. It is designated as a continuous component in Table 5 in view of a continuous or quasi-continuous nature of the hyperfine field's magnetic distribution. This component comprises from approximately 10 % to nearly 30 % of the spectrum and is most clearly visible in the specimen C45/145Cr6 (opt). Interpretation of this component's origin is ambiguous. It is likely to represent not a homogenous phase but a variety of phases (including those discussed above), and its 'fuzziness' is due to an enormous number of structural defects of the crystalline web, tensions, and presence of nanometric particles. This interpretation is supported by the fact that fuzziness of the lines also applies to the line of the greatest values of hyperfine magnetic field (with the outside lines corresponding to velocity of c. 8 mm/s), which certainly represents magnetite. It cannot be ruled out that the continuous component is a result of a partial amorphisation of the powder (wear products) generated by friction.

Minor quantities of hematite, beside wustite and magnetite, have been identified in some specimens of wear products.

Table 4. Occurrence and shares of phase components on the surface of test specimens

Specimen (slider / ring)	Share of structural component [%]					
	bccFe + bctFe ferrite + martensite	fcc austenite	Fe_3C	Fe_3O_4	Fe_xO	Other
C45(norm) / 145Cr6 post friction	76.6 + 7.1 = 83.7	0.1	0.1	2.9	7.8	5.4
C45(norm) before friction	90.0 (±1%)	0.0	5.5 (±15%)	0.6	0.7 (±15%)	3.2
C45(600) / 145Cr6 post friction	89.5 + 1.2 = 90.7	0.2	3.8	0.7	1.5	3.1
C45(600) before friction	90.9 + 0.8 = 91.7	0.0	3.6	0.0	0.9	3.8

Note: bcc – body centred cubic, bct – body centred tetragonal, fcc – face centred cubic

Results of research into occurrence and composition of abrasion products with respect to the matching C45/145Cr6 indicate that under suboptimum conditions (temperature in the friction area lower or greater than the temperature of maximised resistance to wear), micro-machining prevails as the wear mechanism – relatively low quantities of iron oxides arise. Significant quantities of oxides appear after the system has reached its optimum operating conditions (temperature in the friction area corresponds to the temperature of maximised resistance to wear). Fe_2O_3 is virtually impossible to detect (its quantities are minimum). Fe_3O_4 and FeO are the most common. The very high share of magnetite in the abrasion products may be due to the fact that FeO particles are 'oxygenated' as they repeatedly migrate between the rubbing surfaces. A substantial share of the native material (ferrite and martensite originating from steel) particles suggests that the native material particles migrate in the frictional system (as well as oxide particles). Moving particles can adhere to the contact surface. Surfaces of rubbing elements can be reproduced in this way. The native material may originate from both the slider and the counterspecimen. Austenite as an abrasion product comes from the counterspecimen of the tested friction couple, i.e. the ring made of 145Cr6.

Table 5. Occurrence and shares of phase components among abrasion products

Products of matching abrasion	Share of structural component [%]							
	bccFe + bctFe ferrite+martensite	fcc austenite	Fe_3C	Fe_3O_4	Fe_xO	Fe_2O_3	Other	Continuous component
C45/145Cr6 in optimum conditions ($T = -5°C$)	11.9 (±5%)	~0.0	part of continuous component	39.5	21.4 (±10%)	~0.0	~0.0	27.2 (±10%)
C45/145Cr6 in suboptimum conditions ($T = 15°C$)	81.1 + 0.5 = 81.6 (±2 %)	8.4 (±50%)	~0.0	0.2	3.1 (±50%)	1.2	~0.0	5.5
C45/145Cr6 in suboptimum conditions ($T = -20°C$)	81.5 + 0.2 = 81.7 (±2 %)	3.3 (±50%)	1.0	1.5	3.8 (±50 %)	1.3	~0.0	7.4

Note: bcc – body centred cubic, bct – body centred tetragonal, fcc – face centred cubic

Lack or trace quantities of hematite among the abrasion products under optimum conditions accords with the results presented in [21], where the presence of hematite was shown to enhance intensity of wear, with the presence of magnetite reducing this intensity.

Conclusion

The results of Mössbauer analysis presented here allow for some generalisation of the wear process. They indicate that martensite deposits on the sample surface while the share of magnetite is approximately $2 \div 3$ times greater than of wustite at the time of friction in the regime of maximised resistance to wear. Share of cementite prior to and post friction varies irregularly. Martensite settling on the slider surface may originate (by way of migration) from the counterspecimen's surface, though it may also be the frictional martensite discussed by other authors [22]. Processes of frictional hardening and/or tempering of rough peaks, producing the so-called secondary frictional structures, may occur in the case of steel. It is currently impossible to determine clearly what share of martensite is a product of friction. The wear mechanisms generally correspond to the classic method of increasing resistance to wear: soft particles set in a hard matrix arise while oxides build an intermediary layer that relieves the friction.

Depositing of magnetite on the slider surface may be related to magnetic properties of the system. Since the friction couple under consideration consists of magnetic elements, it is easier for Fe_3O_4 particles to adhere to rubbing surfaces. Lack of significant (measurable) quantities of Fe_2O_3 is interesting. According to the recognised mechanism of oxidational wear, all the three types of iron oxides should occur on the specimen surface. Yet only trace amounts of hematite appear in the regime of friction at a temperature that assures enhanced resistance to wear. Similar mechanisms of oxide generation in various regimes of friction have been described in [23-28]. Appearance of relatively substantial quantities of the native material particles (originating from phase components of steel) may be a result of the oxide wear particles acting upon the material of both the slider and the counterspecimen. Ferrite is a rather soft phase (hardness of c. 90 HB). Iron oxides are relatively hard, on the other hand, and can therefore have an abrasive effect on ferrite. Presence of austenite points to transfers of the counterspecimen material particles to the slider, since austenite is not found in the structure of the specimen material.

Particles that leave a system and reduce its weight are treated as wear. Particles remaining within the system do not cause its weight to reduce. They migrate between cooperating surfaces, settle on their surfaces or in the frictional contact.

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