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Wear research on frictional couples of C80U/145Cr6 under conditions of stabilized friction area temperature

Key words

Tribological wear, wear resistance, dry friction.

Słowa kluczowe

Zużycie tribologiczne, odporność na zużywanie, tarcie suche.

Summary

Research into wear resistance is based on analysing thermodynamic transformations in an open thermodynamic system and is designed to determine conditions under which a system shows the greatest resistance. The verification of theoretical considerations makes possible the utilisation of suitable exploratory positions. At present, a new device has been built to test the resistance of interface systems. In this paper, the design and research possibilities of the new tester are discussed. The device is a modified pin-on-disk system modelling typical working conditions of a disc braking system or a disc clutching system, but with control over the temperature of the friction zone. Beside the mechanical part, the stand is equipped with a cryo-circulator used for setting and stabilising temperatures in the friction zone.

Structurally, the new tester uses a physical model that assumes that the tribological system is able to exchange energy and matter with its environment, where friction is the cause of all transformations in the system and on its boundaries. The friction increases the system's internal energy and its dissipation as heat that compensates for mechanical dissipation, that is, wear.

Data presented in handbooks concerning tribological properties of materials are given for operating conditions in positive temperatures, which may lead to errors when the data are employed to select materials for friction joints working in low temperatures. Our device enables the prediction of low-temperature tribological behaviour of friction couple materials.

The research has proven that there is a precise temperature at which a given matching of materials shows minimum wear, e.g. -25°C for the tribosystem C80U/145Cr6.

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1. Introduction

Research into wear resistance is based on analysing thermodynamic transformations in an open thermodynamic system and is designed to determine conditions under which this system shows maximum resistance. Considering the process of friction, wear, and the issue of resistance to wear at the macroscopic level of matter, the energy balance is accepted as the fundamental starting point. The phenomenological approach results in an analytical description of wear resistance, where microscopic structure and properties of matter are not taken into consideration. The friction coefficient and temperature in the friction area are the parameters set in phenomenological experiments.

A number of tribological research projects by many authors, including most recent publications [1], indicate that it is traditional to accept that friction and wear of elements are affected by set operating parameters of a friction centre (load, sliding velocity, friction distance) as well as uncontrolled (e.g. machine vibrations) and environmental factors (humidity, type of surrounding medium, vacuum, and temperature). This method does not allow the possibility of stabilising, for instance, temperature in the friction area and the friction coefficient itself, which can be quite precisely controlled and stabilised.

Assuming a stabilised friction area temperature and friction coefficient enables one to define the greatest resistance for a given frictional system, that is, the specific work of the friction of the same system. In this case, the specific work of friction is the quotient of the friction work and mass wear of the system (i.e. of both the elements). The remaining parameters of the friction process, that is, pressure, sliding velocity, and friction distance, can be set at random. Thus, optimum parameters of friction can be determined in such a way that the system's resistance is, or approaches, maximum.

The ambient temperature of a frictional centre affects physical and resistance characteristics of sliding materials and the formation of secondary oxide structures [2, 3, 4], which is reflected in the frictional characteristics and wear of sliding elements.

Catalogues presenting tribological properties of materials do not provide temperature ranges for which they were defined and are most often given for operating conditions in positive temperatures. These properties may vary dramatically at low temperatures [5]. Therefore, the data cannot be employed for materials for frictional joints designed to operate at low temperatures.

Engineering practice suggests that the issue of the durability of friction centres at low (below 0°C) temperatures has not been resolved. Oil or plastic lubricants cannot usually be applied to friction centres working at low temperatures, because their solidification points are too high. As a consequence, friction joints are frequently 'dry'. Testing at sub-zero temperatures is required to determine the effects and processes taking place when such friction centres are in

operation. Only then can wear mechanisms be explored and appropriate cooperating materials be selected.

Tribological research at low temperatures requires special apparatus. It was designed and utilised in the 1990s at the Institute of Machine Building, Technical University of Radom [6, 7, 8]. New structures for this type of research have also been developed – TT-3 tester, which is discussed in this paper.

A series of experiments employing the TT-3 have been conducted, some of which are presented in this article. Tribological characteristics of common structural materials were compared at temperatures above and below 0°C. The results may contribute to the development of materials engineering, particularly in the area of modern constructional materials for elements of friction centres operating at low temperatures.

2. Experimental methods

The testing station was designed on the basis of a mathematical model of a tested object which defines resistance to tribological wear, or specific work of wear, as in Equation (1) [6, 8, 9].

$$e_R^x = \frac{1}{-a + b \cdot \Theta} \quad (1)$$

Where: a [g/J] and b [g · J⁻¹ · K⁻¹] – tribological system constants,
 Θ – absolute temperature of surface dF [K].

Testing involved a system of sliding metallic bodies. The object of testing was realised, like in earlier testers, as a system of rings – slider. The ring is the rotating element of the frictional joint. Two fixed sliders, samples whose flat surface is in contact with the ring, were applied as well. The sample material can be selected for each separate matching so that the effect of physical properties, chemical composition, hardness, and structure of the material on increased wear resistance can be assessed. A sample made of both metallic and other materials can be used. The flow diagram of the control and measurement system is illustrated in Figure 1, and a diagram of the device is shown in Figure 2.

A system of two samples that are symmetrically pressed against a disc is a good model of coupling systems and provides for even distribution of loading. Sample loads are internal forces of the loading system. The system guarantees equal loading of both the samples and facilitates the measurement of the friction force and, if necessary, the measurement of the total linear wear of the samples.

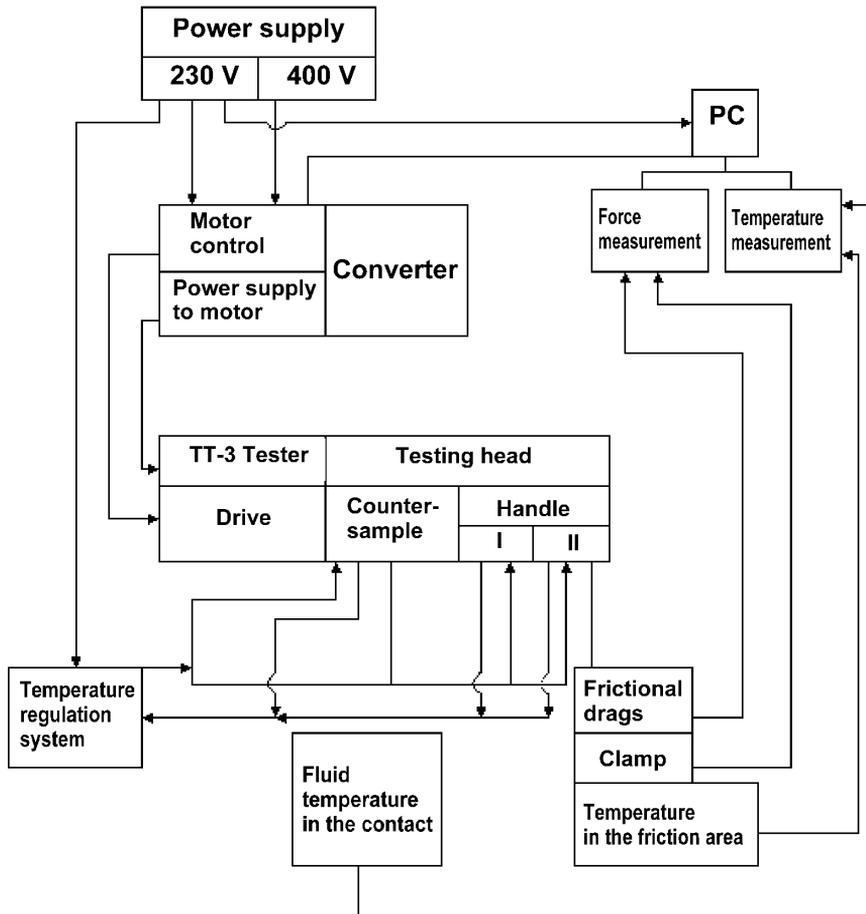


Fig. 1. Flow diagram of the control and measurement systems

Rys. 1. Schemat blokowy układów sterowania i pomiaru: PC – komputer, I i II – uchwyty próbek

The friction couple comprises sliders, made of a selected material, and a ring of 145Cr6 steel of hardness 63 HRC. This design solution enables the application of rings made of both steel and steel covered with layers that increase resistance to wear. The ring is a rotational element, and it is fixed to a disc containing a cooling system and powered by an electric motor including a rotation regulator and a planetary gear. A Stoeber type PA312ED servomotor assembly was employed. Rotational velocities of the discs are regulated by a controller that is connected to a personal computer. A CF-40 circulator was used to stabilise the disc's temperature. The sliders – surface area $F = 5, 15$ or 25 mm^2 (sliders of surfaces in the range $3 - 25 \text{ mm}^2$ may be utilised) and thickness 0.5 mm – are mounted in dedicated copper clamps. The clamps help to build an isothermal limit $0.5 - 0.1 \text{ mm}$ away from the friction area (Fig. 3).

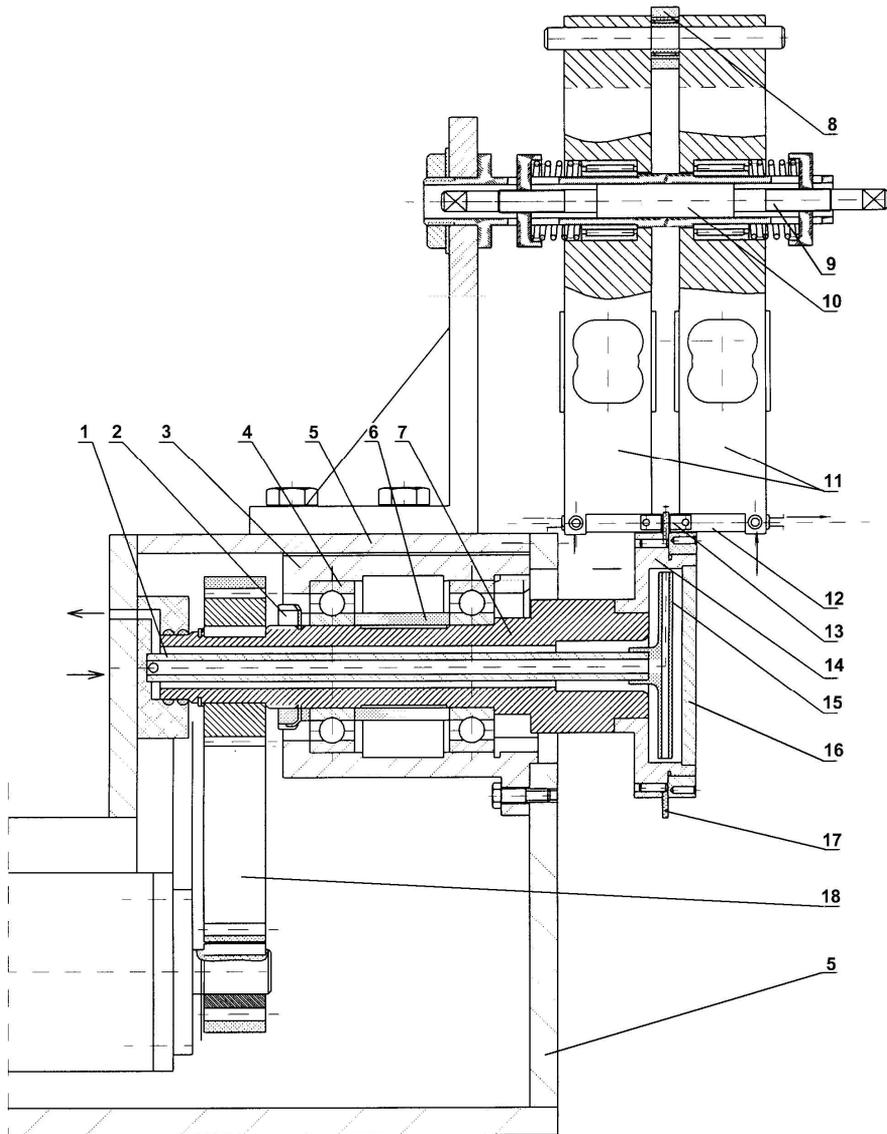


Fig. 2. Diagram of TT-3 tester: 1 – cooling pipe, 2 – lock nut, 3 – bearing sleeve, 4 – ball bearing, 5 – body, 6 – distancing sleeve, 7 – cylinder, 8 – mainstay of the moment of friction measurement, 9 – Roman screw, 10 – sliding sleeve of the clamp against the sample,

11 – extensometer bridge of loading, 12 – clamp of the sample, 13 – sample, 14 – cooling disc, 15 – internal cooling disc, 16 – cover of the cooling disc, 17 – countersample, 18 – driving cogbelt

Rys. 2. Schemat konstrukcyjny testera TT-3: 1 – doprowadzenie cieczy chłodzącej, 2 – nakrętka zamykająca, 3 – tuleja nośna, 4 – łożysko, 5 – korpus, 6 – tuleja dystansowa, 7 – wałek, 8 – opora przetwornika pomiaru momentu tarcia, 9 – śruba rzymska, 10 – tuleja ślizgowa, 11 – przetwornik tensometryczny obciążenia, 12 – uchwyt próbki, 13 – próbka, 14 – tarcza chłodząca, 15 – wewnętrzna tarcza chłodząca, 16 – pokrywa tarczy chłodzącej, 17 – przeciwpółka, 18 – pasek zębaty napędu

A slider is fitted in the clamp socket using a screw. The end of an iron-constantan thermocouple, in physical contact with the slider, is fitted in the clamp. Cooling fluid is fed and drained via a duct inside the copper clamp.

Temperature characterising the isothermal limit is measured by means of the iron-constantan thermocouple. The measurement is executed during the friction; therefore, the impact of friction heat and heat exchange via the CF-40 circulator is taken into account. The sliders and the clamp are mounted in a head that allows for pressure regulation.

The tester's loading assembly consists of a dynamometer in the form of a Roman screw. A tensometric force measurement sensor on the dynamometer enables accurate setting of the intended pressure.

A tensometric friction force measurement system connected to a measurement card is used to measure friction resistance.

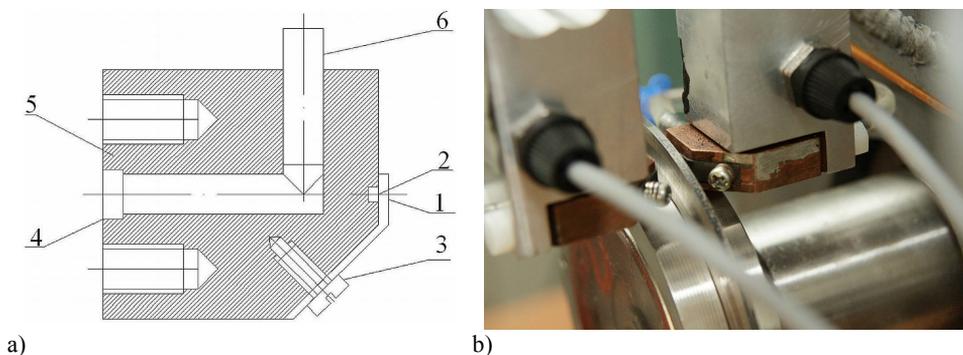


Fig. 3. Couple fixing clamp: a) drawing of the clamp 1 – slider, 2 – thermocouple, 3 – screw to fasten the slider in the clamp, 4 – fluid supply pipe, 5 – copper clamp, 6 – fluid drain pipe, b) view of the clamp - wire endings of the pressure force measurement system and screws fixing the couples can be seen

Rys. 3. Uchwyt do mocowania próbek: a) rysunek uchwytu 1 – ślizgacz, 2 – termoelement, 3 – wkręt mocujący ślizgacz w uchwycie, 4 – przewód doprowadzający płyn, 5 – uchwyt miedziany, 6 – przewód odprowadzający płyn, b) widok uchwytu (widoczne wyprowadzenia przewodów układu pomiaru siły docisku i śruby mocujące próbki)

The wear of the sample and the countersample are measured by high-precision scales with an accuracy of 0.01 mg. Before the measurements, the samples were ground under a loading equal to the anticipated measurement loading. Based on earlier experiments [8], the grinding time was set at 3600 s. Depending on a tested friction couple, the sliding velocity was adjustable in the range 0 - 2 m/s.

The Cryo-Compact CF40 circulator was manufactured by Julabo Labortechnik. This device helps to supply fluids at constant temperatures to external circuits. The circulator can provide temperatures within the range of -40 to +150°C, a temperature stability of $\pm 0.03^\circ\text{C}$, and a flow velocity of 15

L/min. The control system is equipped with a microprocessor controller to provide for high temperature stability. Thermal S oil designed for use within the temperature range of $-50 - +150^{\circ}\text{C}$ serves as the coolant.

A polycarbonate climatic chamber can also be mounted on the friction system head when testing is conducted below ambient temperature.

A felt sweep-off gear is used for controlled removal of friction products from the friction area and the resultant stabilisation of friction resistance. The friction coefficient was maintained at 0.4 ± 0.04 for the duration of the test.

3. Results

Wear resistance was tested under conditions of dry friction and oxidative in order to establish the temperature (referred to as characteristic temperature) at which a given matching of materials displays greater resistance to tribological wear. The following assembly was tested: C80U steel in various conditions of heat treatment in association with hardened 145Cr6 steel (63HRC). Characteristics of the materials are provided in Tables 1 and 2.

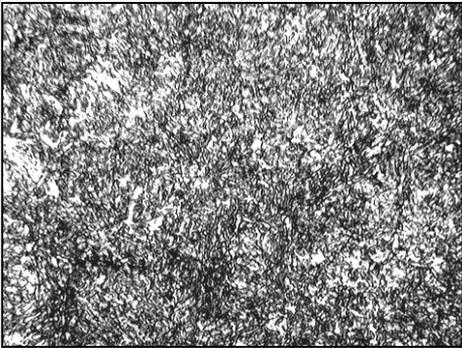
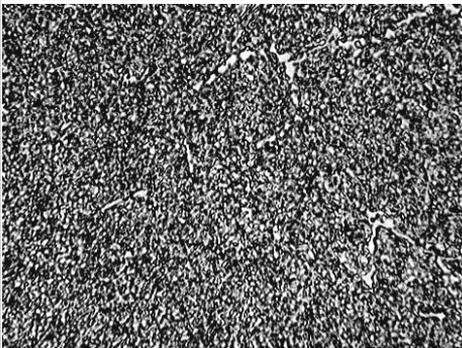
C80U is a cold-work tool steel. Structures of both normalised and heat-treated C80U steel were tested.

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

Table 1. Characteristics of slider and ring materials
Tabela 1. Charakterystyka materiałów ślizgaczy (pozycje 1÷2) i pierścienia (3)

No.	Material	Condition of heat treatment	Hardness	Chemical composition, %
1	C80U steel (slider)	normalised	27 HRC	C – 0.81 Mn – 0.3 Si – 0.27 Ni – 0.05 Cr – 0.16
2		hardened and tempered at 160°C	55HRC	
3	145Cr6 steel (ring)	hardened	63 HRC	C – 1.4 Mn – 0.59 Si – 0.28 Ni – 0.08 Cr – 1.6 V – 0.17

Table 2. Structures of C80U and 145Cr6 steels
 Tabela 2. Opis struktur stali C80U i 145Cr6

Material	View of the structure	Description of the structure
normalised C80U steel		Pearlitic structure: pearlite of low dispersion and with partly visible spheroidisation process
C80U tempered at 160°C/1h		Martensitic structure (low-tempered martensite): martensite of a fine acicular structure
145Cr6 hardened 63 HRC		Structure of fine-acicular (cryptoacicular) martensite with low quantity of very fine carbides (Fe,Cr) ₃ C

Research into the characteristic temperature described in [6, 8, 10, 11, and 12] has indicated friction process parameters for selected matchings of engineering metals. The effects of temperature, pressure, and sliding velocity on the specific work of wear have been detected and characterised. According to results of optimisation experiments, it was determined to test wear resistance in the friction zone's temperature range of $-25 - +15^{\circ}\text{C}$, with a constant friction coefficient, sliding velocities and pressures provided in the respective papers.

Specific work of wear was calculated from the formula:

$$e_R^x = \frac{\mu \cdot N \cdot v \cdot t}{\Delta m_c} \quad [\text{J/g}] \quad (2)$$

where: μ – friction coefficient, N – load [N], v – sliding velocity [m/s],
 t – testing time [s], Δm_c – variation of the system's mass [g].

Each measurement was repeated six times and statistically developed. Sample results of the measurements are illustrated in Figures 4 and 5.

The temperature of increased resistance (+10°C), obtained in earlier measurements, was confirmed concerning the couple C80U(norm)/145Cr6 (Fig. 4) as well. However, a new range of increased resistance was found for this matching. This was obtained for -25°C and caused specific work of wear to grow from approx. 45 MJ/g to approx. 109 MJ/g, that is, by 240%. Values of characteristic temperatures and their corresponding wear resistances are summarised in Table 3. This means that the originally determined temperature of increased resistance, though defined correctly, applied solely to the range for which the sliding pair had been tested before. The new value is merely an approximation. As Figure 4c clearly shows, once the temperature of the friction zone falls below -25°C, the specific work of wear may be even greater. In addition, it appears possible that the resistance to wear may vary cyclically as dependent on the temperature of the friction zone.

Table 3. Maximum specific work of wear for tested matchings
 Tabela 3. Wartości maksymalne pracy właściwej zużycia dla badanych skojarzeń

Matching	Characteristic temperature, °C	Specific work of wear, MJ/g
C80U(norm)/145Cr6	-25	109
C80U(160)/145Cr6	-25	22

Wear measurements of heat-treated C80U demonstrated (Fig. 5) a significant dependence of resistance obtained for a given temperature of the friction area on the material structure. Matching of heat-treated C80U that is tempered at 160°C and has a structure of pearlite of low dispersion and with partly visible spheroidisation process proved the worst. The resistance was approx. 20% less than that of normalised C80U.

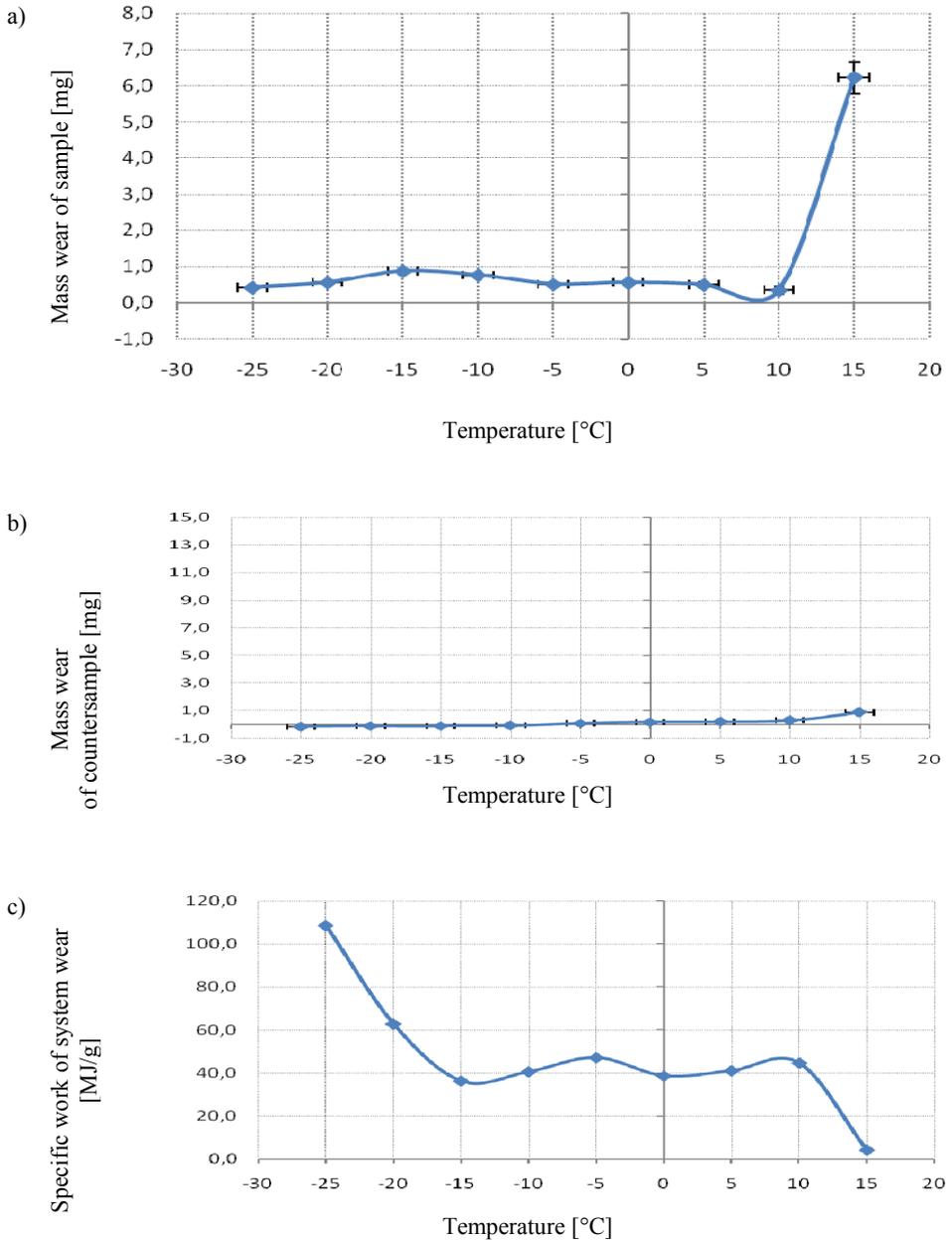


Fig. 4. Testing of the wear resistance of C80U(norm)/145Cr6(63 HRC) friction couple as a function of friction area's temperature: a) mass wear of the sample, b) mass wear of the countersample, c) specific work of the system's wear

($p = 0,98$ MPa, $v = 0,8$ m/s, $\mu = 0,4$)

Rys. 4. Badanie odporności na zużycie pary trącej C80U/145Cr6(63 HRC) jako funkcji temperatury strefy tarcia: a) zużycie masowe próbki, b) zużycie masowe przeciwpróbki, c) praca właściwa zużycia układu ($p = 0,98$ MPa, $v = 0,8$ m/s, $\mu = 0,4$)

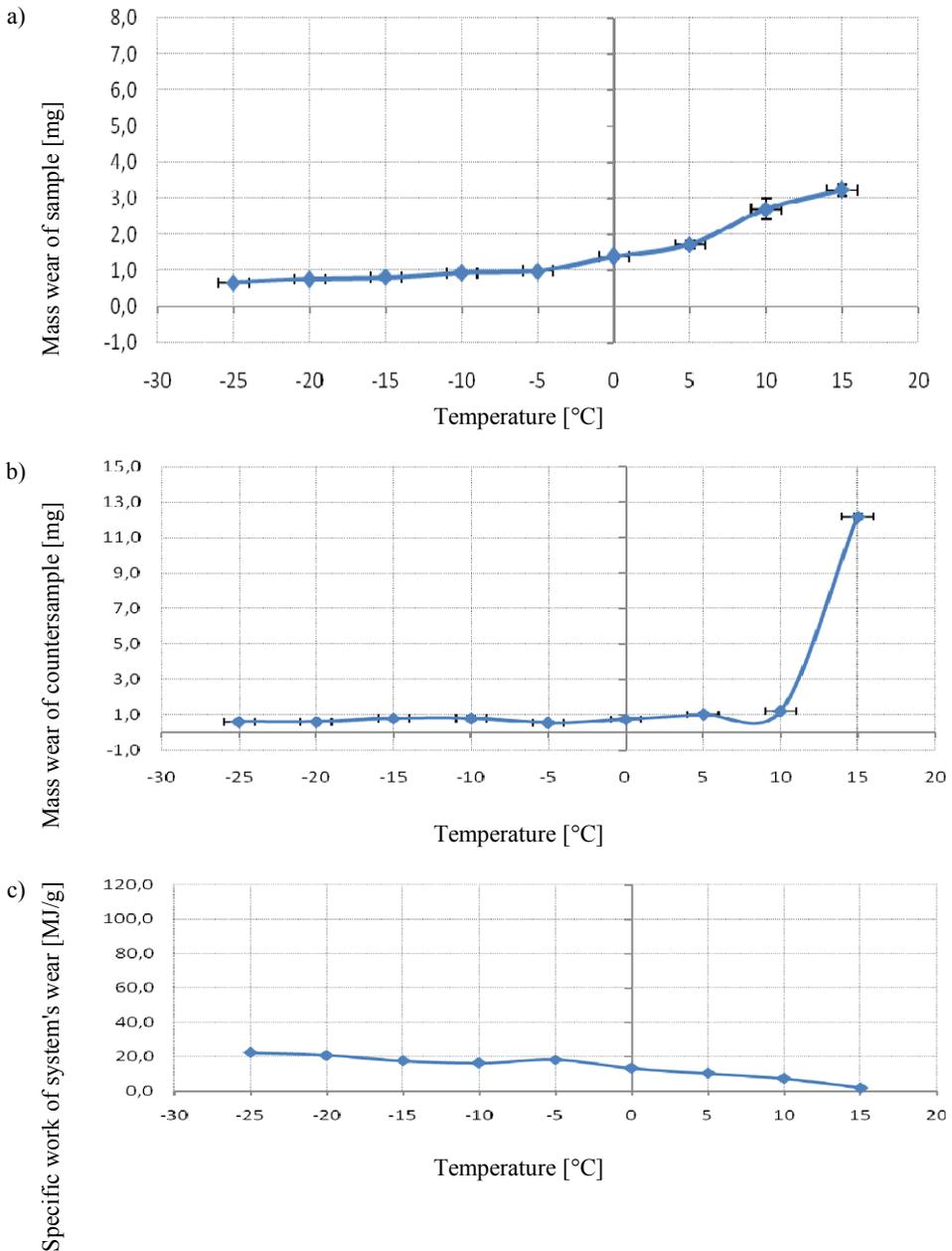


Fig. 5. Testing of the wear resistance of C80U(160)/145Cr6(63 HRC) friction couple as a function of friction area's temperature: a) mass wear of the sample, b) mass wear of the countersample, c) specific work of the system's wear ($p = 0.98$ MPa, $v = 0.8$ m/s, $\mu = 0.4$)

Rys. 5. Badanie odporności na zużywanie pary trącej C80U(160)/145Cr6 (63 HRC) jako funkcji temperatury strefy tarcia: a) zużycie masowe próbki, b) zużycie masowe przeciwnpróbkki, c) praca właściwa zużycia układu ($p = 0,98$ MPa, $v = 0,8$ m/s, $\mu = 0,4$)

4. Discussion

The mathematical model of the tested object (Equation 1) is correct until the characteristic temperature in the friction couple is reached. The tribosystem changes after that point as a result of phase transitions in the material. The systemic constants, a and b , are then modified. A characteristic temperature can again be determined in this altered system. It will be different. This cyclical nature is graphically presented in Figure 6. The new temperature was lower than the original temperature in the case of the systems under discussion. Since the range of the friction area temperatures included in the testing was limited (-25 - $+15^{\circ}\text{C}$), it cannot be determined if the effect will recur at still lower temperatures.

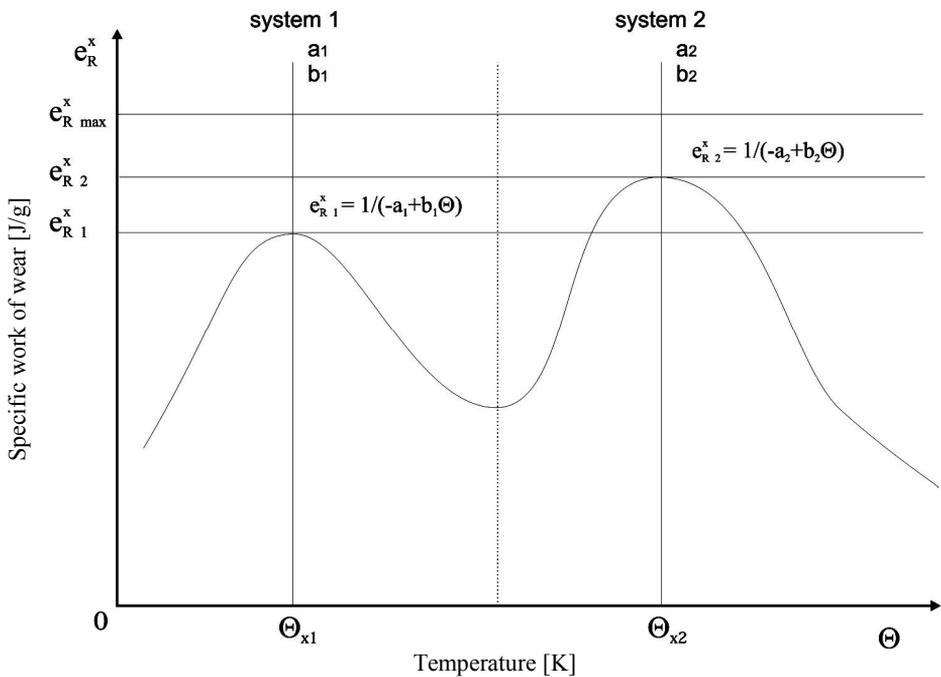


Fig. 6. Schematic representation of the possible cyclical nature of wear resistance increases. The maximum specific work of wear that can be obtained in the given system is marked

Rys. 6. Schematyczne przedstawienie możliwego występowania lokalnych maksimum odporności na zużycie (zaznaczono maksymalną pracę właściwą zużycia teoretycznie możliwą do uzyskania w danym systemie)

A measurable depositing of particles onto cooperating elements was noted in most cases. In the figures, this is shown as a negative mass wear of both sample and countersample. Such depositing may have occurred (and was most likely to occur) also where mass increments were not recorded. In these

circumstances, material particles migrated between the cooperating surfaces, as discussed in a transfer model in [8]. Mössbauer spectral analysis helped to detect nanometric particles and particles of the native material (ferrite and martensite) among the wear products, which further confirms this possibility. Presence of austenite, on the other hand, indicates the presence of the countersample particles.

The presence of nanoparticles, a result of abrasion in the system, can help consolidate the material [13] and change the degree of the heterogeneity of mechanical properties. It can therefore be expected that the refinement of structure will, to a greater or lesser extent, modify both the weight and operation of the particular component mechanisms of the consolidation, i.e. solution, deformation, dislocation, substructure, with foreign phase particles, and from grain boundaries. Above all, grain refinement from micro- to nanometric scale improves resistance properties.

The mechanism of the material's phase transitions during the friction needs to be clarified. Results of Mössbauer spectral analysis point to diffusive impregnation of ferrite with carbon as an effect of plastic-elastic interactions at the contact of the rough surfaces of cooperating elements. Heat effects at the friction contact also play a certain role, although they are not decisive owing to intense collection of heat from the friction contact. Principles of tribosystem self-organisation described by Kostecki [14] appear to be a key reference for the clarification of the issue under discussion. Kostecki cites the formation of secondary structures by frictional depositing of metals as an example of a practical application of the self-organisation.

5. Conclusions

Testing by means of the tester TT-03 leads to the following conclusions:

- For each material matching, there is a characteristic temperature (negative or positive) at which an increased (approaching maximum) resistance of a given system to wear is obtained.
- Variations of dependence of wear resistance on a friction area temperature are unique features of a given material matching and depend on the chemical composition and structure of the materials.
- Further physicochemical and material testing is necessary to explain a number of potential dependencies (chemical composition, micro hardness, structure).

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Badania zużycia skojarzenia tarcowego C80U/145Cr6 w warunkach stabilizacji temperatury w strefie tarcia

Streszczenie

Badania odporności na zużywanie opierają się na analizie przemian termodynamicznych zachodzących w systemie termodynamicznym otwartym. Celem opisanych w artykule badań jest stwierdzenie, w jakich warunkach układ trący uzyskuje największą odporność. Weryfikację rozważań teoretycznych umożliwiła wykorzystanie odpowiednich stanowisk badawczych.

Wykonane zostało nowe urządzenie służące do badań odporności układów sprzęgających. W artykule omówiono jego konstrukcję oraz możliwości badawcze. Jest to zmodyfikowany układ typu trzpień-tarcza modelujący typowe warunki pracy tarczowego mechanizmu hamulcowego lub sprzęgłowego, ale z wymuszeniem temperatury strefy tarcia. Oprócz części mechanicznej

stanowisko wyposażone jest w kriocykulator służący do ustalania i stabilizowania temperatury w strefie tarcia.

Założenia konstrukcyjne nowego testera opierają się na modelu fizycznym zakładającym, że system tribologiczny jest w stanie wymieniać energię i materię z otoczeniem, przy czym przyczyną wszelkich przemian zachodzących w systemie i na jego granicach jest praca tarcia. Wywołuje ona wzrost energii wewnętrznej układu, a także jej dyssypację na sposób ciepła kompensująca dyssypację mechaniczną, czyli zużywanie.

Dane zawarte w katalogach materiałowych dotyczące właściwości tribologicznych materiałów podawane są dla warunków pracy w temperaturach dodatnich, co może być błędne w przypadku ich wykorzystania przy doborze materiałów na pary tarciove przeznaczone do pracy w niskich temperaturach. Urządzenie pozwala na sporządzenie niskotemperaturowych charakterystyk tribologicznych par tarciowych.

W wyniku przeprowadzonych badań wykazano, że istnieje temperatura, w której dane skojarzenie materiałowe wykazuje minimum zużycia, np. dla skojarzenia C80U/145Cr6 jest to 25°C.

