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A CONTRIBUTION TO THE KNOWLEDGE OF SYNERGY IN TRIBOLOGY SYSTEMS

PRZYCZYNEK DO WIEDZY O SYNERGII W UKŁADACH TRIBOLOGICZNYCH

Key words: tribology, tribocorrosion, friction, corrosion, wear, synergy.

Abstract: The article contains information about the knowledge of synergism in tribology systems. Two examples of analyses of synergism in tribology systems are presented in the article. In the first example, the interaction coefficient (synergy coefficient) was used to evaluate a set of engine and gear oils composed of special lubricating (surface-active) additives to improve the galling load – a measure of boundary layer strength, evaluated on a 4-ball apparatus. Using the interaction coefficient, a 12-element set of oils (compositions) was "separated" into three groups: synergism with additives (K_S>1), sometimes strong, at K_s=2, neutral interaction (K_N=1), antagonism with additives (K_A<1). Analysis of test results using the synergism coefficient also makes it possible to select the optimal additive concentration in commercial oil. In the second case, a three-factor system was analysed, in which the resultant (undesirable) characteristic was a measure of mechanical-corrosion-abrasive wear of metal parts. In specially designed experiments, the components of total wear derived from the three underlying factors (mechanical, corrosion and environmental), and the interaction between them was determined. The contribution of the sum component of the mechanical-corrosion-abrasive interactions was found to range from 40 to 50% of the total wear (at 50%, there is a strong synergism K_S=1).

Słowa kluczowe: tribologia, tribokorozja, tarcie, korozja, zużycie, synergia.

Streszczenie: Artykuł zawiera informacje mające uzupełnić wiedzę o synergizmie w systemach tribologicznych. Przedstawiono dwa przykłady analiz synergizmu w układach tribologicznych. W pierwszym z przykładów posłużono się współczynnikiem oddziaływania (współczynnikiem synergii) do oceny zbioru olejów silnikowych i przekładniowych, które komponowano ze specjalnymi dodatkami smarnościowymi (aktywnymi powierzchniowo) w celu poprawy tzw. obciążenia zatarcia – miary wytrzymałości warstwy granicznej, ocenianej na aparacie 4-kulowym. Posługując się współczynnikiem oddziaływania rozdzielono 12-elementowy zbiór olejów (kompozycje) na trzy grupy wykazujące: synergizm z dodatkami (K_S>1), niekiedy silny, przy K_S=2, współdziałanie neutralne (K_N=1), antagonizm z dodatkami (K_A<1). Analiza wyników badań przy pomocy współczynnika synergizmu pozwala również dobrać optymalne stężenie dodatku w oleju handlowym. W drugim z przypadków analizowano system trójczynnikowy, w którym cechą wynikową (niepożądaną) była miara zużycia mechaniczno-korozyjno-ściernego elementów metalowych. W specjalnie zaprojektowanych eksperymentach wyznaczono składowe zużycia całkowitego pochodzące od trzech czynników bazowych (mechanicznego, korozyjnego i środowiskowego) oraz od interakcji między nimi. Stwierdzono, że udział składowej sumarycznej odziaływań interakcyjnych mechaniczno-ścierno-korozyjnych wynosi od 40 do 50% zużycia całkowitego (przy 50% występuje silny synergizm K_s=1).

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INTRODUCTION

In technical terms, the term synergism began to be used relatively late, only in the second half of the 20th century. Before that, it was used, among other things, in pharmacology to describe the mutual potentiation of the pharmacological effects of two or more drugs used simultaneously or in short intervals. The use of synergism to describe technical systems, mainly in the area of surface engineering, was the subject of numerous works by T. Burakowski **[L. 1–3]**.

An inherent factor in a system is the interaction of system elements, which results in broadly defined properties. Different properties are produced through the interaction of different elements of the system with each other and under different conditions. The interaction of system elements leads to the acquisition of desirable and undesirable properties. The interaction of the elements of the system can have the character of interaction and counteraction, or the elements of the system can behave indifferently (neutrally) towards each other.

In addition to the direction of interaction (interaction-counteraction) for technical systems, it is necessary to know the strength of the interaction, expressed numerically. For this purpose, the concept of interaction coefficient was introduced. The development of this concept was introduced on the basis of the works **[L. 1–3]**.

The interaction of the elements of a system with each other is most easily determined indirectly, through the properties revealed by the action of the system, by considering the individual properties obtained by the action of a single element of the system and collectively when several elements of the system act. For the simplest two-element system, the coefficient of the interaction of system elements k_O can be defined as:

$$k_O = \frac{a_{1+2}}{a_1} \tag{1}$$

where: a_1 – the value of the property factor A obtained as a result of one component of the system, a_{1+2} – the value of property A obtained as a result of two system elements. It should be noted that $a_{1+2} \neq a_1 + a_2$.

The k_O coefficient can be greater than unity, equal to unity or less than unity. The numerical value of the coefficient of influence indicates the effectiveness of the influence. In the general case, the interaction of system elements can be constructive, neutral or destructive. It can increase the combined effect (synergism) without affecting the effect (neutralism) or decrease the combined effect (antagonism). Accordingly, depending on the value of the coefficient k_O, the paper **[L. 3]** proposed to assign names to it:

- synergy coefficient $k_S = k_O > 1$; the greater the numerical value of k_S – the greater the synergism (intensity of beneficial interaction),
- neutrality coefficient $k_N = k_O = 1$; that is, for $k_O = 1$, there is always a lack of interaction between factors – neutralism,
- antagonism coefficient $k_A = k_O < 1$; that is, for $k_O < 1$, there is always an oppositely directed action of the factors – antagonism; the smaller the numerical value of k_A – the greater the antagonism (intensity of adverse impact) is.

The synergism coefficient k_S is theoretically in the range of:

$$1 < k_S < \infty \tag{2}$$

The upper limit is usually at levels 2, 3, and 4 (value at the level of several) **[L. 3]**. The antagonism coefficient k_A, which is practically the inverse of the synergism coefficient, is theoretically in the range of:

$$0 < k_A < 1 \tag{3}$$

(with an upper limit $k_A = 1$).

The main goal of the study presented in the article is to add to the knowledge of the phenomena of the influence of various factors on the tribological properties of materials. In example one, the effect of performance additives on the anti-friction parameters of lubricating oils is shown. Moreover, the second example shows how different factors affect aggregate wear in the complex frictional, corrosive and abrasive interaction process.

ANALYSIS OF THE TYPES OF INTERACTION (AND THEIR INTENSITY) IN THE FOUR-BALL TEST OF LUBRICATING COMPOSITIONS

In earlier years at the Poznan University of Technology **[L. 4]**, tests on a 4-ball apparatus were carried out to evaluate the welding load of the domestically produced engine and gear oils with performance additives of the American company WYNN'S:

- HDC (Heavy Duty Concentrate for Diesel),
- SPF (Super Friction Proofing) – for engine oils,
- HPLS (High-Performance Lubricant Supplement) – for gear oils.

It was decided to cite the results of that study, despite the fact that older generation oils are no longer produced in the country, because of the fact that the analysis of the types of interaction (and their intensity) is a very useful methodological example for evaluating the results of lubricating compounding.

Labels:

- measured utility effect – weld load in 4-ball test,
- W – weld load using commercial oil composition with WYNN'S (corresponds to symbol a_{1+2} from equation 1).

W_{cz} – weld load in the test with "pure" commercial oil (corresponds to the symbol a_1 from equation 1).

As a result, the quotient W/W_{cz} is the impact factor, taking on different values for lubricating compositions of different compositions. The results of the study are shown in **Tables 1** and **2**.

Table 1. Overview of the effect of WYNN'S additives on the weld load of selected engine oils [L. 4]

Tabela 1. Zestawienie wpływu dodatków eksploatacyjnych firmy WYNN’S na obciążenie zespawania wybranych olejów silnikowych **[L. 4]**

No.	Oil type	Oil name	Concentrations of the additive [%]		$k_o=W/W_{cz}$	
			1	2	1	2
			SFP	HDC	SFP	HDC
1	C	SUPER FALCO CD SAE 15W/40	0 6 8 10	0 6 8 10	1 1.25 1.25 1	1 1 1.25 1.25
2	C	SUPER MILVUS CC SAE 15W/40	0 6 8 10	0 6 8 10	1 2 2 2	1 2 2 1.6
3	C	ALANDA CB/SC SAE 15W/40	0 6 8 10	0 6 8 10	1 0.78 0.78 1	1 1 1 1
4	S	GRAND BETA SAE SG/CD 15W/40	0 6 8 10	0 6 8 10	1 0.8 0.8 0.8	1 0.8 0.8 1
5	S	ANTUS SF/CC SAE 15W/40	0 6 8 10		1 0.8 0.8 1.26	
6	S	APUS SF/CC SAE 15W/40	0 6 8 10	0 6 8 10	1 1.25 1.25 1.25	1 1.57 1.57 1.25
7	S	GRAND ALFA SF/CC SAE 15W/40	0 6 8 10	0 6 8 10	1 1 1.26 1.26	1 1 1.26 1.26
8	S	LOTOS SG/CD SAE 15W/40	0 6 8 10	0 6 8 10	1 1.58 1.58 1.58	1 1.26 1.26 1.26
9	S	AQUILA SG/CD SAE 15W/40	0 6 8 10	0 6 8 10	1 1 1 1	1 1 1 1

Unambiguous synergism was found for gear oil-based compositions (**Table 2**) – the variation in the synergy coefficient k_S was found to range from 1.26 to 1.75. In the case of compositions of additives with engine oils, three types of interactions can be distinguished between pure oils and their compositions with additives:

- Synergism k_S (=W/W_{cz}) for position 1 (in **Table 1**), 2, 6, 7, 8 more than 1 (neutralism k_S = 2 – position 2),
- Neutral interaction k_N=1 (position 9, position 3 with HDC),
- Antagonism k_A<1 (position 3-5 in **Table 1**).

The obtained results may indicate that the performance additives (DE) mixed with the first group of oils were more active than the lubricity additives introduced at the production stage (technological additives – DT) or interacted with them to produce a synergetic effect. In the second case (no change), the introduced additive was probably weaker than the technological additives, while in the third case, it weakened the effect of the basic additive (antagonistic effect).

ANALYSIS OF SYNERGIES IN THE ASSUMED WEAR PROCESS

Some machine kinematic nodes operate in corrosive environments and are then subject to a complex process of corrosion-mechanical (or mechanical-corrosion) wear **[L. 5–15]**. Often there are even more complex operating conditions when mechanical interactions in friction and electrochemical corrosion are accompanied by abrasive wear **[L. 16-21]**. The research and results of the evaluation of the simultaneous corrosion and erosion process are included in the **[L. 22, 23]**. The complex state of wear is characteristic of sugar industry equipment machines.

The theoretical and experimental analysis of the system of individual components (mechanical, corrosive and abrasive) and the evaluation of the interaction between them was undertaken by P. Tyczewski **[L. 24]**. On the basis of the work of earlier researchers of complex wear processes, dealing mainly with two-component processes **[L. 5-23]**, he formulated his own model taking into account the total (resultant) wear also the abrasive wear component **[L. 24]**:

$$I_C^T = I_M + I_K + I_Ś + I_Δ \tag{4}$$

where:

I_M, I_K, $I_Ś$ – mechanical, corrosion and abrasive components of total wear.

The $I_Δ$ component is an interaction component, which in the general case, can be presented as the sum of components resulting from binary destructive processes like abrasive-mechanical ($I_{ΔŚM}$), corrosion-mechanical ($I_{ΔKM}$), abrasive-corrosion ($I_{ΔŚK}$) and the simultaneous influence of abrasive-corrosion-mechanical processes ($I_{ΔŚKM}$).

In order to simplify the analysis further, the separation of the unit impacts of abrasive-mechanical ($I_{ΔŚM}$), corrosion-mechanical ($I_{ΔKM}$) and abrasive-corrosion ($I_{ΔŚK}$) were abandoned. Then a simplified model of total wear with simultaneous abrasive, corrosive and mechanical processes takes the form **[L. 24]**:

$$I_C^T = I_M + I_K + I_{CŚ} + I_{ΔKM} + I_{CŚKM} \tag{5}$$

A graphical interpretation of this simplified relationship is shown in **Figure 1b**, while **Figure 1a** highlights all possible interactions between the components under $I_Δ$ conditions.

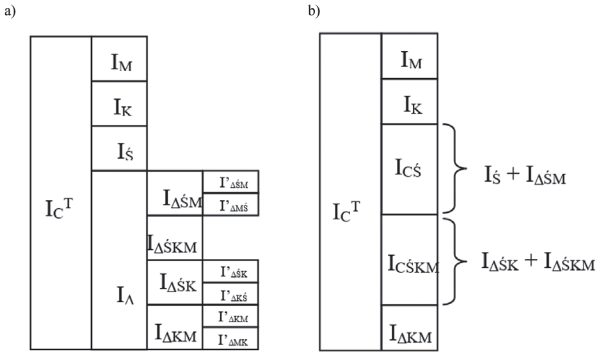

Fig. 1. Theoretical components of the abrasive-corrosion-mechanical process interaction: a) distribution of individual components, b) simplified distribution of components [L. 24]

Rys. 1. Składowe teoretyczne wzajemnego oddziaływania procesów ścierno-korozyjno-mechanicznych: a) rozkład poszczególnych składowych, b) uproszczony rozkład składowych **[L. 24]**

In the work **[L. 24]**, a series of factorial experiments were planned and carried out to determine the components of total wear described by equation 2 as factor variables in the experiments were, among others, the concentration of the electrolyte and the size of the abrasive particles. The results of the experiments: calculations of the components of total wear are presented in the form of percentages in **Figures 2** and **3**.

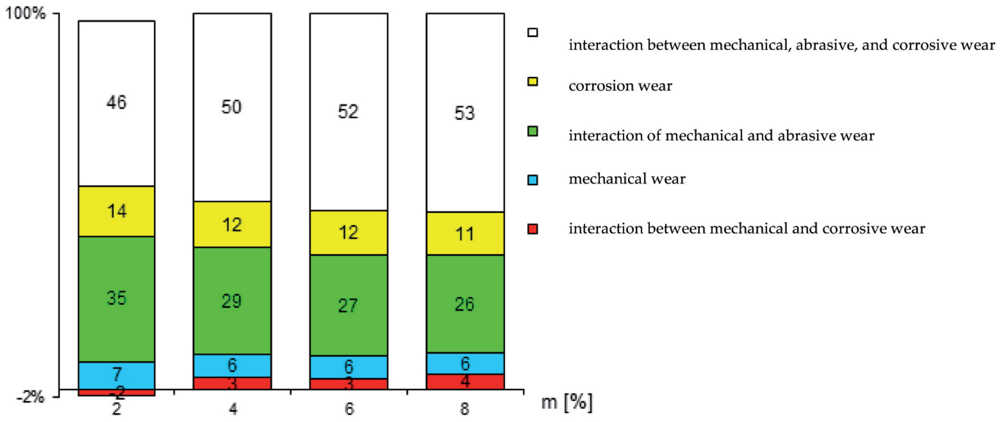

Fig. 2. Values of wear components for the wear process under varying corrosion forcing caused by varying content of the corrosive agent

Rys. 2. Wartości składowych zużycia dla procesu zużywania przy zmiennych wymuszeniach korozyjnych spowodowanych zróżnicowaniem zawartości czynnika korozyjnego

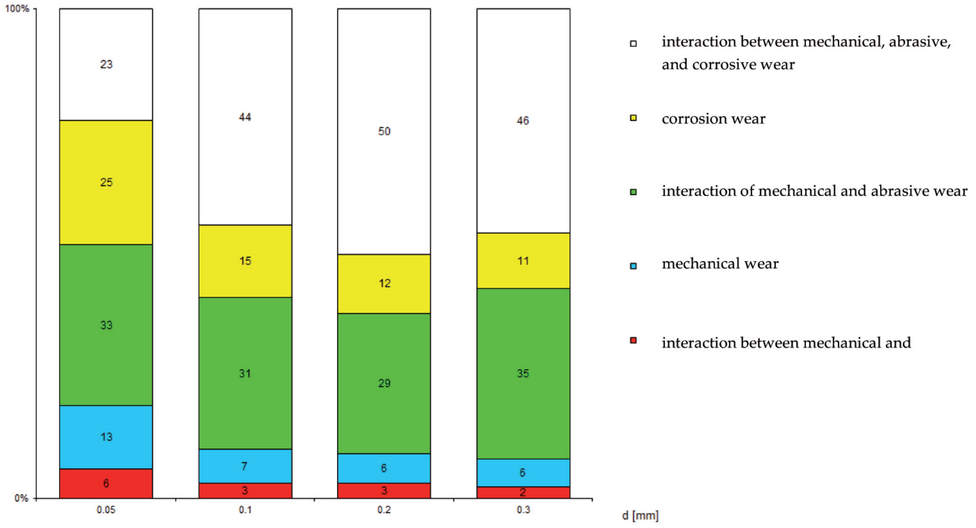

Fig. 3. Wear component values for the wear process with variable abrasive interactions

Rys. 3. Wartości składowych zużycia dla procesu zużywania przy zmiennych oddziaływaniach ścierniwa

The following conclusions can be drawn from the models presented in **Figures 2 and 3**:

1. In aggregate wear, the component resulting only from mechanical interactions (friction), is at the level of a few to several per cent;
2. At a slightly higher level of several per cent (on average), the values of the corrosion component are formed;
3. Wear values resulting from mechanical and corrosive interaction are at the level of a few per cent. In one variant of the study, an effect not of a synergistic nature (-2%) but of an antagonistic nature was recorded;
4. The contribution of the component resulting from the simultaneous mechanical and abrasive action is about 1/3 of the global wear;
5. In most cases, the sum component of mechanical-friction-corrosion interactions is 40–50%.

By taking into account the last two observations, it can be concluded that abrasion and the interaction processes caused by it (abrasive-mechanical, abrasive-corrosion and abrasive-corrosion-mechanical) play a dominant role in mechanical-corrosion wear.

The issues of complex mechanical corrosion wear processes were also considered in the works

[L. 25–29]. The sum component of mechanical-abrasive-corrosion interactions was determined to be up to 50%. This means that the total wear that occurred as a result of all three destructive processes simultaneously (with interactions) doubles the baseline wear (without interactions). The maximum coefficient of synergism can be estimated at $k_S \approx 2$. This is a strong synergistic relationship, and it should not be forgotten that it involves a complex destructive process (wear expressed in terms of weight loss).

CONCLUSIONS

The authors of this article express the belief that its content can be an interesting contribution to the knowledge of the phenomenon of synergism in tribology systems. The first example analysed the effect of additives to commercial oils (engine and gear oils) on the strength of the boundary layer measured on a 4-ball apparatus. This is a two-factor system in which the property is desired at the highest possible load value in the 4-ball apparatus. The base factor "a_1" was the result of testing with commercial (pure) oil, designated in Tables 1 and 2 as W_{cz} – the operation of only one component of the system. In the second experiment, two elements of the "a_{1+2}" system (commercial oil in a composition with an operating additive) were already operating at the same time – the result was marked as "W" in Tables 1 and 2.

The calculated interaction coefficients $k=W/W_{cz}$ allowed us to assess the type of interaction (synergism, neutrality, antagonism) and its strength. Strong synergism $k_S=2$ occurred for the composition for the oil composition of item 2 in **Table 1**. The obtained results allow us to select the optimal concentration for compositions showing synergism and eliminate from the "pool of interest" compositions with antagonism ($k_A<1$) or neutral interaction ($k_N=1$).

The second example describes the results of testing a three-factor system. The resultant value was the total mass wear of components subjected to mechanical corrosion abrasive wear. In specially proposed experiments, the components of wear from mechanical, corrosion, and abrasive and their interactions were determined. The results of the experiments (and calculations) are presented in the form of diagrams and present the percentages of total wear from the "base" and interaction components. The sum component of mechanical-abrasive-corrosion interactions was in the range of 40-50% of total wear.

If the value of 50% is taken, the synergy coefficient $k_S \approx 2$, which means a strong synergy (4). Unfortunately, this applies to an undesirable property of the three-factor system: the amount of wear on the component.

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