Stanisław NOSAL
Politechnika Poznańska, Instytut Maszyn Roboczych i Pojazdów Samochodowych
ul. Piotrowo 3, 60-965 Poznań, Poland
e-mail: stanislaw.nosal@put.poznan.pl

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TRIBOLOGICAL ASPECT OF CREATING ABRASION RESISTANCE OF MACHINE ELEMENTS

Summary

The article presents the share of particular types of tribological wear and losses caused, with particular regard to abrasion. The wear on anchored grains and abrasion by grains between elements in frictional contact were characterized. General postulates regarding the limitation of abrasive wear depending on the conditions of its occurrence have been proposed.

***Key words**: abrasive wear, abrasion resistance on anchored grains, abrasion resistance in the presence of abrasive grains between elements*

ASPEKT TRIBOLOGICZNY KSZTAŁTOWANIA ODPORNOŚCI NA ŚCIERANIE ELEMENTÓW MASZYN

Streszczenie

Przedstawiono udział poszczególnych rodzajów zużywania tribologicznego i strat, które powodują, ze szczególnym uwzględnieniem ścierania. Scharakteryzowano zużywanie o ziarna umocowane i ścieranie przez ziarna obecne między trącymi się elementami. Zaproponowano ogólne postulaty dotyczące ograniczania zużywania ściernego w zależności od warunków jego występowania.

***Słowa kluczowe**: zużywanie ścierne, odporność na ścieranie o ziarna umocowane, odporność na ścieranie w obecności ziaren ściernych między elementami*

1. Introduction

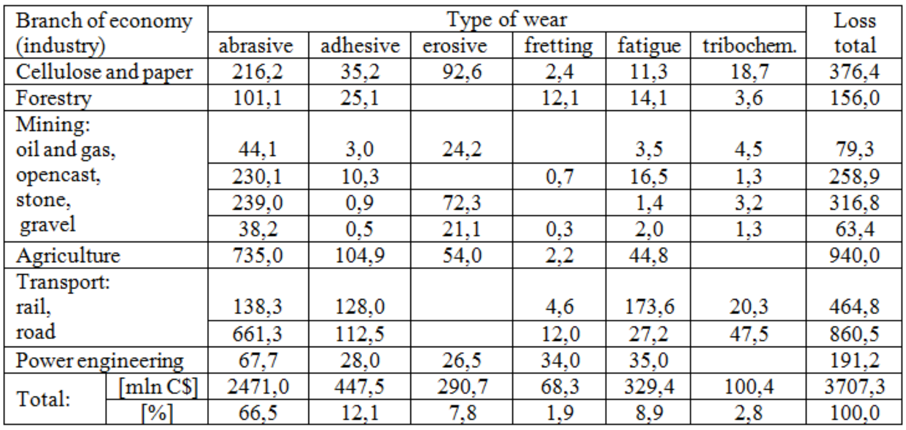
The task of tribology is, among others, to indicate what potential properties should be given to the elements in frictional contact in order to achieve the desired durability and energy effects under specific conditions of use. It is estimated that about one third of the world's energy production is lost to overcome frictional resistance. All those involved in machine research believe that their durability and reliability are largely determined by phenomena and processes occurring in kinematic nodes.

Tribological wear is the main cause (in about 80%) of the exploitation of the potential of machines and vehicles. According to Krim [9], a serious approach to the problem of friction and wear of materials could result in savings reaching 1.6% of GDP in developed countries, which is a considerable amount. Table 1 shows the losses caused by tribological wear on the example of the Canadian economy. Among the tribological processes destroying machine elements, abrasive wear is the most frequent and causes the greatest losses [3, 4]. As can be seen from Table 1, it causes the greatest losses in agriculture and road transport.

Simplified estimation of material losses generated by wear in soil in the example of Polish agriculture made by Talarczyk [16] showed that the total abrasive wear of the working elements of cultivation tools is about 7,840 tonnes of steel per year. Assuming that the consumption of these elements amounts to 40% on average, about 20,000 tonnes of steel need to be replaced annually, which accounts for several tenths of percentage of annual steel production in Poland.

The purpose of the article is to define general premises for creating the abrasive resistance of machine elements resulting from the analysis of the mechanism of this wear.

Table 1. Losses of the Canadian economy [C $ million] caused by tribological wear in 1984 [3]
Tab. 1. Straty gospodarki kanadyjskiej [mln C$] spowodowane zużyciem tribologicznym w 1984 r. [3]



Branch of economy (industry)	Type of wear						Loss total
	abrasive	adhesive	erosive	fretting	fatigue	tribochem.	
Cellulose and paper	216,2	35,2	92,6	2,4	11,3	18,7	376,4
Forestry	101,1	25,1		12,1	14,1	3,6	156,0
Mining: oil and gas,	44,1	3,0	24,2		3,5	4,5	79,3
opencast,	230,1	10,3		0,7	16,5	1,3	258,9
stone,	239,0	0,9	72,3		1,4	3,2	316,8
gravel	38,2	0,5	21,1	0,3	2,0	1,3	63,4
Agriculture	735,0	104,9	54,0	2,2	44,8		940,0
Transport: rail,	138,3	128,0		4,6	173,6	20,3	464,8
road	661,3	112,5		12,0	27,2	47,5	860,5
Power engineering	67,7	28,0	26,5	34,0	35,0		191,2
Total: [mln C$]	2471,0	447,5	290,7	68,3	329,4	100,4	3707,3
Total: [%]	66,5	12,1	7,8	1,9	8,9	2,8	100,0

2. Characteristics of abrasion mechanism

Abrasive wear (abrasion) is the process of destroying the surface layer (SL) of bodies in frictional contact as a result of micro-cutting, micro-scratching and shearing effects of abrasive elements – abrasive particles, wear products, hard tops of roughness and hard structural components [11].

The specified definition does not take into account such elementary abrasion processes as micro-chasing, micro-crushing and coating of abrasive grains.

Abrasion can be carried out by anchored grains (sandpaper, included abrasive particles in the cooperating element, tops of roughness, hard structural components, etc.) and by loose grains.

The removal of a certain volume of material by a single abrasive element is possible when it penetrates the consumed surface to an appropriate depth with simultaneous displacement.

The conditions of the transition from elastic to plastic deformation and micro-cutting were primarily discussed by Kragielskij [8]. He determined these conditions depending on the h / R ratio, i.e. the penetration depth to the lip radius of the model inequality.

The ability of abrasive grains to penetrate into the consumed element mainly depends on the hardness ratio of abrasive Ha to the hardness of the abraded material Hm and their shape and dimensions. The importance of the ratio Ha / Hm (Fig. 1) for the intensity of abrasive wear was recognized by many authors, including Khrushchev, Babichev, Kragielskij, Zum-Gahr, Bern, Iwasaki and Peng [as cited in 5].

Fig. 1 shows that if Ha / Hm ≤ k1, then the hardness of abrasive grains is insufficient to penetrate deep into the worn element. In this area, the mechanism of wear is mechano-chemical (so-called mild abrasive wear) [6]. The plastic deformation is located at a small depth of SL, at the same time the stronger heat is the activating factor of the SL and intensifying its interaction with the active components of the atmosphere and the lubricant. As a result, thin reaction layers, e.g. oxide ones, are formed and then removed. If Ha / Hm ≥ k2 then abrasion is mechanical with dominant micro-cutting (Fig. 2).

The intensity of the mechano-chemical form of abrasive wear is 1-2 orders of magnitude greater than the accepted tribochemical (oxidative) wear, but also 4-5 orders of magnitude smaller than the mechanical form of abrasion [6]. Among the tribologists, there is no consensus on the critical values k1 and k2. According to Kałdoński [5] k1 values from 0.5-0.7 to 0.7-1.1, and k2 from 1.3-1.7 to 2 are adopted.

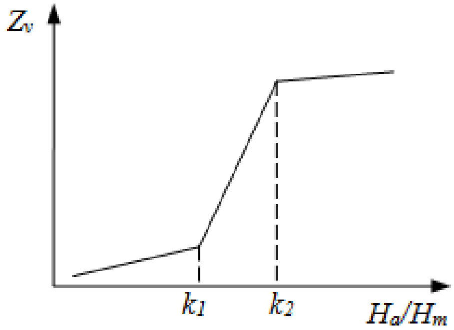


Fig. 1. Schematic effect of the hardness ratio of Ha abrasive grains to the Hm material hardness for Zv wear [3]
Rys. 1. Schematyczny wpływ stosunku twardości ziaren ściernych H_a *do twardości materiału* H_m *na zużywanie* Z_v *[3]*

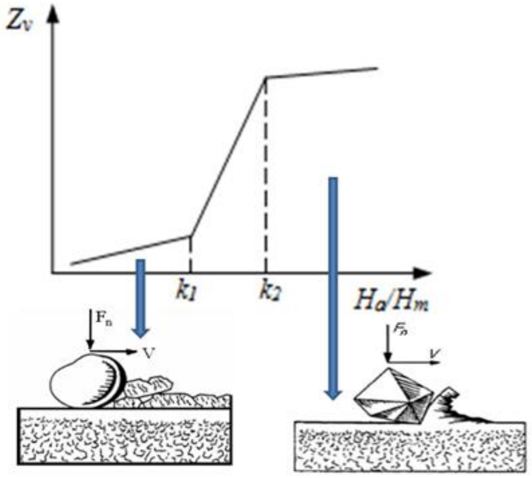


Fig. 2. Schematic effect on wear Zv of the hardness ratio of Ha abrasive grains to the hardness of the Hm material [12]
Rys. 2. Schematyczny wpływ na zużywanie Z_v *stosunku twardości ziaren ściernych* H_a *do twardości materiału* H_m *[12]*

Extensive testing of wear resistance of the most commonly used materials in the 1980s was conducted by Zum Gahr [18, 19]. The results of these tests are presented in Fig. 3. It shows a high compatibility with the results obtained much earlier by Khrushchev [2].

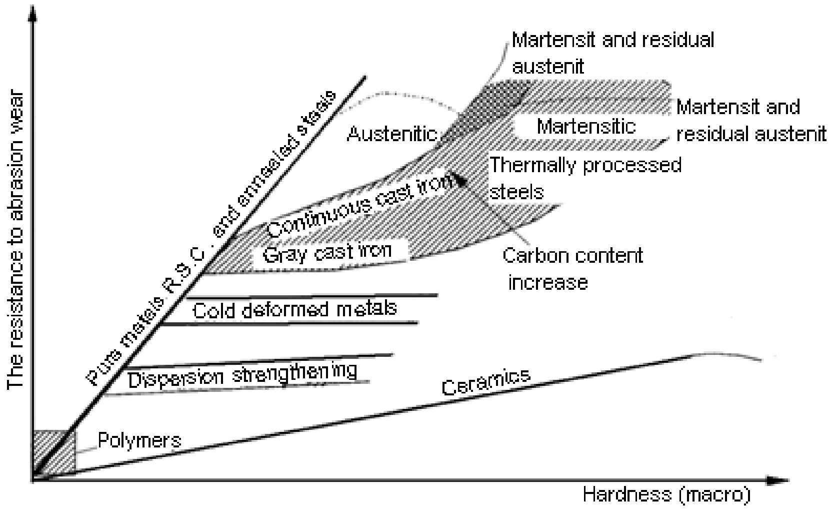


Fig. 3. The dependence of the abrasion resistance of various materials on their hardness, as determined by Zum Gahr [19]
Rys. 3. Zależność odporności na ścieranie różnych materiałów od ich twardości, ustalona przez Zum Gahra [19]

Zum Gahr included many new materials in his research, e.g. polymers and ceramics. He points out that ceramics with high hardness are not proportionally high in abrasion resistance. This is explained by the fact that the abrasive wear of brittle ceramics depends not only on the hardness, but also on the break strength.

At this point, it is worth discussing the relationship between the roughness of one friction pair and the abrasive wear of the other. It is convenient to do this for the metal-polymer combination, because the difference in the hardness of these materials is considerable. The dependence of polymer wear on the roughness (Ra parameter) of the spigot can be interpreted as the effect of the summation of three types of wear: abrasive, adhesive and fatigue (Fig. 4).

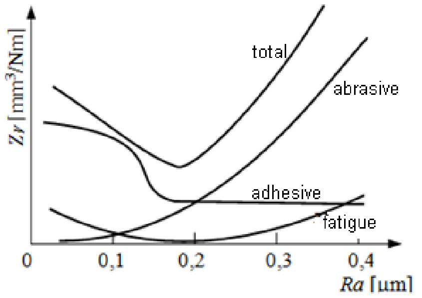


Fig. 4. Summation of the different types of wear of the polymer depending on the roughness of the steel [15]
Rys. 4. Sumowanie się różnych rodzajów zużywania polimeru w zależności od chropowatości elementu stalowego [15]

With low roughness, the greatest impact on wear is caused by the formation and destruction of strong adhesion welds between surfaces. With the increase of the roughness of the metal element, the share of micro-cutting increases and abrasive wear prevails. There is an optimum range of roughness, which corresponds to the minimum wear [15]. The abrasive elements may also take the form of the edges of hard, crushed carbide inclusions or phosphor eutectics contained in the cast iron. Fig. 5a shows the upper part of the ship's cylinder liner, the wall thickness of which increased as the power obtained from the cylinder increased. Thickening of the liner wall changed the solidification conditions of the cast iron, which resulted in the precipitation of thick inclusions of phosphorus eutectics. During the liner production, the inclusions were broken and their sharp edges (Fig. 5b) intensively abraded the piston rings.

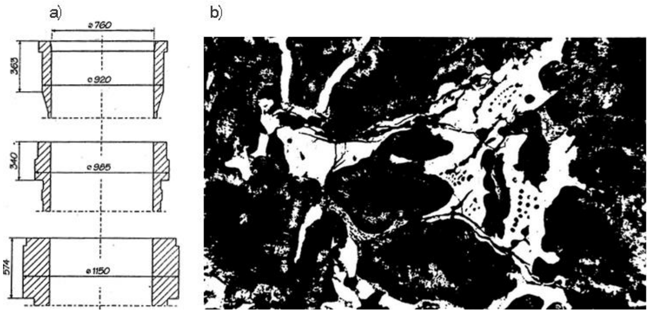


Fig. 5. The upper part of the cylinder liner in ship's engine (a) and the microstructure of the most thickened wall (b) [11]
Rys. 5. Górna część tulei cylindrowej silnika okrętowego (a) i mikrostruktura najbardziej pogrubionej ścianki (b) [11]

In operational practice, abrasion often occurs in the presence of abrasive. Abrasive grains get between the co-operating surfaces together with the working medium (fuel, lubricant, hydraulic fluid, etc.), constituting its impurity. They can also occur in dry-running nodes, getting inside from the environment.

In this case, the wear mechanism is much more complex and less recognized than in the case of abrasion with anchored grains.

The effect of abrasive grain between two surfaces in frictional contact (Fig. 6) depends on:

a) its size,
b) its hardness, shape and compressive strength,
c) hardness of elements in frictional contact,
d) clearance values,
e) normal load.

There is no consensus on the dominant process that causes wear in this case. Although it is most often believed that this is due to micro-cutting, it is not at all an isolated opinion that SL micro-crushing is predominant due to fatigue caused by coating of abrasive grains (Fig. 6d). Such an opinion is expressed, inter alia, by authors of the publication [10]. They treat micro-cutting as an extreme process, estimating its share in the wear of only about 15%.

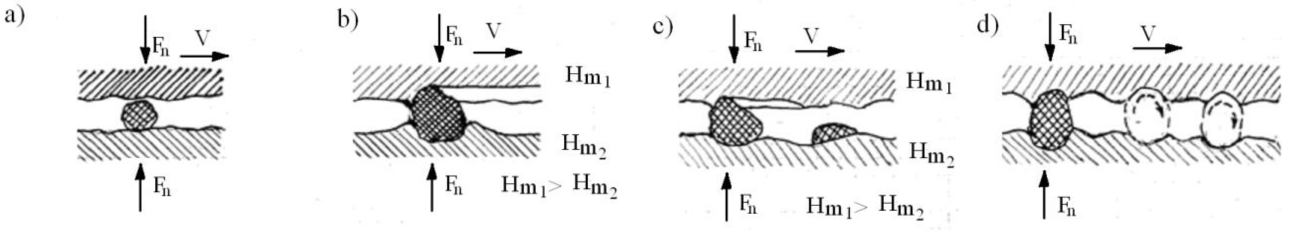


Fig. 6. Examples of the impact of abrasive grains between surfaces in frictional contact [12]: a) grain with a size smaller than the clearance is removed from the friction area without damaging the surface; grains larger than clearance: b) the grain has been included in a softer material and causes micro-cutting or micro-scratching of the harder element, c) the grain has been crushed, the fragment with a size larger than the clearance has been pressed into a softer material and behaves like an anchored grain, d) grain gets coated, deforms plastically the top layer of bodies in frictional contact
Rys. 6. Przykłady oddziaływania ziaren ściernych występujących między trącymi się powierzchniami [12]: a) ziarno o rozmiarze mniejszym niż luz zostaje usunięte z obszaru tarcia bez uszkadzania powierzchni; ziarna większe niż luz: b) ziarno zostało zainkludowane w bardziej miękkim materiale i powoduje mikroskrawanie lub mikrorysowanie twardszego elementu, c) ziarno zostało rozkruszone, fragment o rozmiarze większym niż luz został wgnieciony w bardziej miękki materiał i zachowuje się jak ziarno umocowane, d) ziarno obtacza się, odkształcając plastycznie warstwę wierzchnią trących się ciał

3. Postulates for shaping ability of abrasion resistance of components and friction pairs from mechanism of abrasive wear

When talking about shaping resistance to abrasive wear, the conditions in which it occurs should be taken into account. If wear is due to friction on anchored grains or friction in the abrasive mass, the graph (Fig. 2) showing the dependence will be very useful in formulating its postulates $Z_v = f(H_a/H_m)$.

Significant, even by a few orders of magnitude, increase in abrasion resistance of the surface layer can be obtained by shaping its hardness to obtain a ratio $H_a/H_m < k_1$. Then the abrasion will have a mild, mechanochemical form, as the hardness of abrasive grains will be insufficient to penetrate the used element. Increasing the hardness of the surface layer to the extent that the condition is met $k_1 < H_a/H_m < k_2$, will also make it difficult to penetrate abrasive grains, the more so the ratio H_a/H_m will be closer to k_1.

As previously stated, the tops of the roughness of the hard element can act in a similar way like the anchored grains. Therefore, the second important premise concerns forming the roughness of a harder element of combination with the sliding cooperation with a softer element. Its value should be as close as possible to the operational roughness, that is, the one that will be formed as a result of lapping.

The abrasive effect of the sharp edges of crushed hard structural components, e.g. phosphorus eutectic inclusions in cast iron, can be reduced by using additional treatment (glazing) that will remove the crushed grains.

The formation of WW elements of friction pairs between which there are abrasive grains is more complex. In this case, the intensity of abrasive wear combination is determined by the ratio of the abrasive hardness to the harder element and the hardness ratio of both elements.

Extensive research in this respect was carried out by the authors of the work [17]. The tests were based on a roller-bearing combination lubricated with oil containing abrasive particles (4 types) differing in hardness. Steel rollers with three hardness values cooperated with brass, aluminum and steel bearings.

From these tests it appears that for the same materials of the sliding pair, its wear decreases with the decrease of the hardness ratio of the abrasive to the hardness of the harder component, i.e. the plug along with the decrease in the ratio between the hardness of the bearing to the hardness of the plug (Fig. 7).

In light of the above results, it is understandable to use a significant difference in hardness between the sliding friction elements pairs. The shaft should be harder: three times according to Barwell [1], 4-5 times according to Milowitz [7] and 5 times according to Rabinowicz [14].

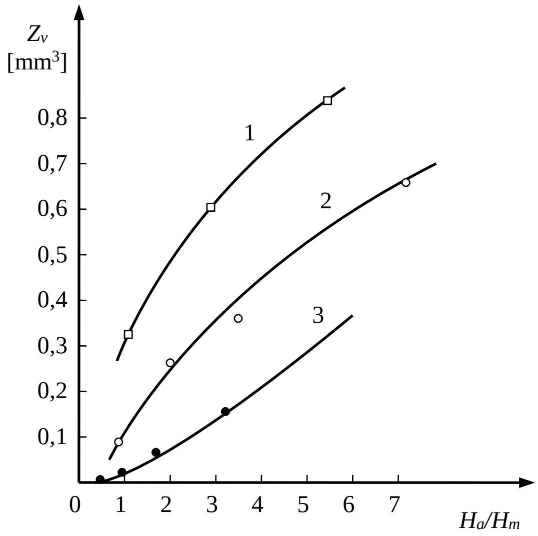


Fig. 7. The influence of the hardness ratio of abrasive grains to the plug hardness H_a/H_m and the ratio of the hardness of the plug to the hardness of the bearing H_m/H_b on volume wear Z_v of combination (based on [17]); 1 – H_m/H_b = 1,33, 2 – H_m/H_b = 1,70, 3 – H_m/H_b = 3,30

Rys. 7. Wpływ stosunku twardości ziaren ściernych do twardości czopa H_a/H_m i stosunku twardości czopa do twardości panewki H_m/H_b na zużycie objętościowe Z_v skojarzenia (na podstawie [17]); 1 – H_m/H_b = 1,33, 2 – H_m/H_b = 1,70, 3 – H_m/H_b = 3,30

The wear of sliding parts exposed to the presence of abrasive between them can, in general, be limited in three ways, namely:

a) protection against the ingress of abrasive particles to the friction nodes (the use of seals and filters of air, fuel and oil);

b) such hardening of the cooperating elements (maintaining their good strength properties) that instead of including, the abrasive grains were crushed and removed from the contact zone;

c) providing one of the elements with a high capacity to "absorb" abrasive particles and at the same time a high fatigue resistance of the surface layer due to multiple plastic deformation by abrasive grains; this method can be only applied if there is a very small amount of abrasive grains in the friction zone.

4. Summary

When summarizing the subject of technological development of the surface layer exposed to abrasive wear, a differentiated approach to this problem should be clearly recommended, depending on the conditions in which abrasion occurs. This is schematically shown in Fig. 8.

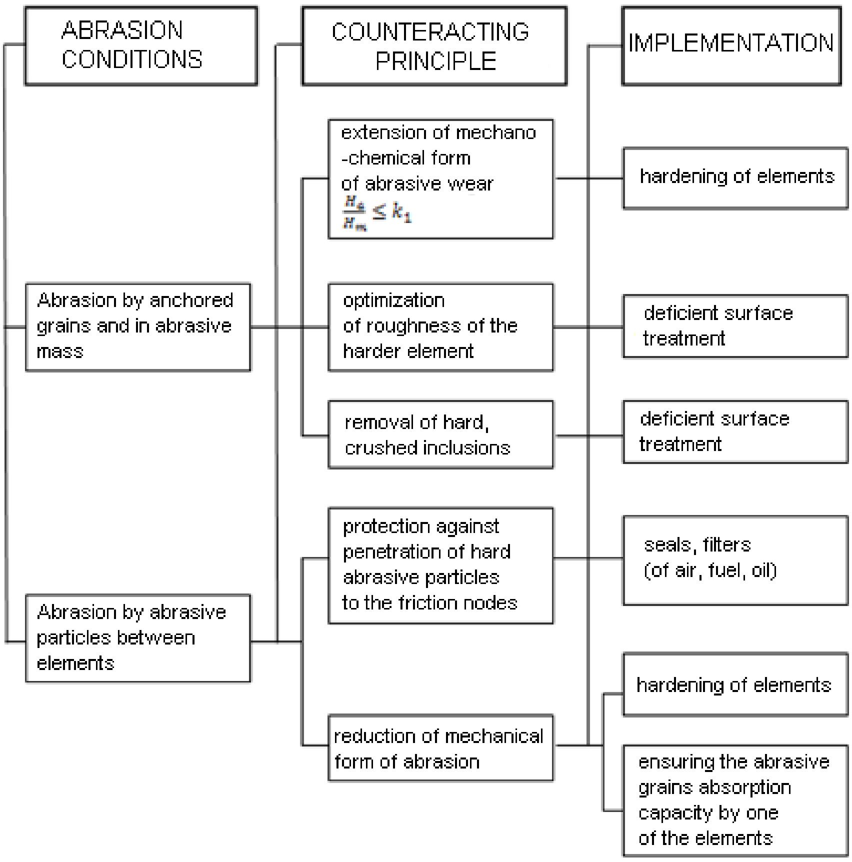


Fig. 8. Principles of counteracting abrasive wear depending on the conditions of its occurrence [12]
Rys. 8. Zasady przeciwdziałania zużywaniu ściernemu w zależności od warunków jego wystąpienia [12]

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