Casting alloys for agricultural tools operating under the harsh conditions of abrasive wear

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Summary. This paper addresses some issues related with the process of tribological wear, focusing on the phenomena that occur during the abrasive wear of parts. Mechanisms of this process were discussed, most important materials resistant to this type of wear were characterised and examples of castings designed for the agricultural sector, developed and manufactured by the Foundry Research Institute in Cracow in collaboration with the Research Institute of Agricultural Engineering in Poznań, were demonstrated. Then the leading methods used in the assessment of abrasive wear resistance of alloys, erosive wear included, were classified and described. The results of own research were quoted as an example. It has been proved that modern casting alloys can successfully compete with the wrought stock.
Key words: tribology, studies, castings, cast alloys, agricultural tools.

INTRODUCTION

Progress in many areas of the economy, the agricultural sector included, is dependent on the development trends in the art of designing machinery and equipment for operation under the increasingly difficult conditions. Technical progress in this area depends on the cooperation of specialists from a variety of industries, and on the close relations between the sphere of scientific research – on the one hand, and the producers of equipment and users of this equipment – on the other. Such interactions should form a type of closed loop. Materials of better performance durability enable the design of advanced structures. Advanced structures increase the efficiency of modern machinery and equipment, but require from materials engineering the development of better materials. Higher efficiency of equipment requires the use of materials more resistant to wear under the increasingly harsh operating conditions. This co-action must be supported by research work in the areas of fundamental theory, experimental trials and field testing of new products (Fig. 1).

Extreme operating conditions of machines and equipment mainly include corrosion with all its variations, the effect of high temperatures, often combined with the need to carry variable stress, and tribological wear. Abrasive wear, which is one of many types of tribological wear, is the subject of this study.

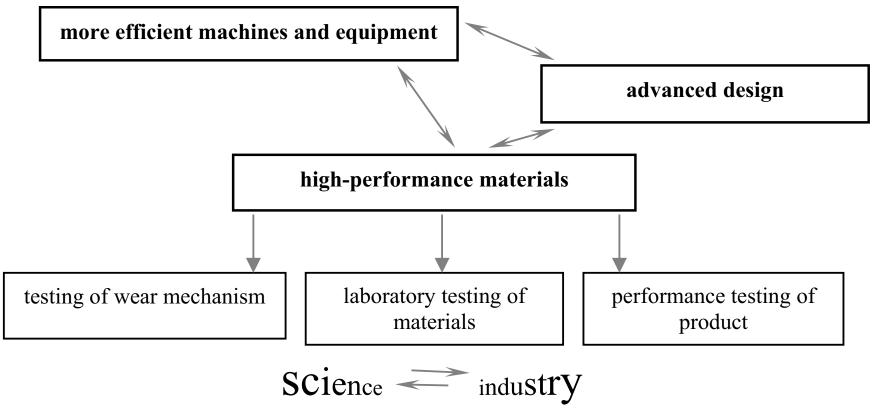


Fig. 1. The interaction of science and practice in improving the competitiveness of machinery and equipment

TRIBOLOGY

Tribology is the science of friction and of the processes accompanying this phenomenon. The name derives from the Greek words tribus – friction, logos – science. Tribology as a science deals with the description of physical, chemical, biological and other related phenomena occurring in the areas of friction. As a science, this field of knowledge was formally established in 1966. Previously, the individual issues of tribology were included in other disciplines.

Tribological wear is an important cause of failure of machinery and equipment. It is caused by the process of friction which leads to a change in weight, structure and properties of the surface layers of contacting bodies. The intensity of wear is a function of different types of interactions and of the resistance of these layers.

Generally speaking, there is no one single type of tribological wear that would have an exclusive influence on the whole process; the decisive effect has the leading mechanism. The elementary tribological processes are:

- loss of material (microcutting, detachment of surface irregularities, brittle cracking, peeling),
- transfer of material (ploughing, polishing, indentation),
- discontinuity of material (surface scratches, dimples)
- accretions (build ups, antibodies, oxide films, deposits),
- changes in geometric structure of the surface (deformation, directional shifting of
- structure, phase transformations),
- changes in chemical composition (new components, surface oxides).

Among the types of tribological wear, the following ones can be identified: abrasive wear, adhesive wear, scuffing, oxidation wear, fatigue wear by spalling (flaking wear), fatigue wear by pitting, fretting. All these types of wear are described in technical publications dealing specifically with the tribological wear [1, 2, 3, 4, 5, 6, 7, 8]. Here only the abrasive wear will be discussed.

ABRASIVE WEAR

Abrasive wear is the most common tribological process of destruction. It arises when the loss of material in the surface layer is caused by the particle detachment due to *microcutting, scratching or ploughing*. This process occurs when within the areas of friction between the mating parts there are loose or fixed abrasive particles or protruding asperities of harder material, which play the role of local micro-edges. In a similar way oxidised products of wear operate within the friction area [1, 2, 3, 4, 5, 6, 7, 8].

Figure 2 presents a dynamic model of the elementary processes of the wear due to abrasion.

As a criterion distinguishing the type of wear, a quotient of the surface area of the cross-sections of the scratch recess (F_2) and swelling of material around the scratch (F_1) was adopted. This is illustrated in Figure 3.

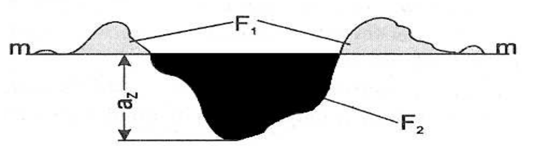


Fig. 3. Criterion distinguishing the types of wear [7]
az – depth of recess, ***m-m*** – reference level

If $F_1/F_2 = 1$, it means that only plastic deformation in the contact areas, or ploughing, occurs. The material indented by protruding asperity or abrasive grain is "pushed" outside the surface (swelling of material on both sides of the scratch).

If $F_1/F_2 = 0$, that is, cross-sectional area of the swollen material is equal to zero ($F_1 = 0$), it means that only microcutting occurs.

If $0 \leq 1 \leq F_1/F_2$, it means that microcutting, plastic deformation and scratching occur.

During scratching, the material within the region of abrasive wear is crushed, upset and cut (chips, other products of wear).

The resistance to abrasive wear depends on many factors such as:

- chemical and fractional composition of loose or fixed abrasive particles,
- relative hardness of abrasive particles compared with hardness of the material exposed to wear,
- specific pressure,
- frequency of the replacement of products in the areas of friction (blowing out, rinsing),
- slip velocity.

Abrasion can take place through:

- grains fixed in mating surfaces,
- single loose abrasive grains,
- abrasive layer that occurs between mating surfaces,
- abrasive jet,
- abrasive environment.

In the case of mating machine parts, due to the impact of mating surfaces, the rubbing grains can execute:

- a translatory motion in direction parallel to the abraded surface,
- a rotary motion in respect of their own axis (rolling).

ploughing *cutting of asperities* *cutting of irregularities with abrasive through protruding asperity* *plastic deformation of material*

Fig. 2. Dynamic model of the elementary wear process types [7]

In the case of grinding, especially crushing of hard materials, the abrasion is characterised by:
- larger dynamics of the effect of forces acting between the abraded surface and grains,
- greater irregularity in the motion of these grains,
- higher proportional share of components normal to the surface, resulting in a dynamic crushing.

Abrasion in an abrasive jet (erosion) means the impact of a jet of fluid or gas, in which the abrasive particles are suspended (e.g. abrasion by sand blasting, abrasive wear by particles suspended in water or other liquids).

Abrasion of metals in an abrasive environment (e.g. caterpillars of vehicles) is characterised by large kinetic energy of the abrasive grains. The grain contact with the abraded surface occurs under the effect of forces performing the work of abrasive wear and crushing of the material. In many cases, the abrasive agent is soil in which there are mineral grains (mainly silica), causing the abrasive effect.

Experimental relationships were obtained between the relative abrasive wear resistance and hardness of metals (Fig. 4).

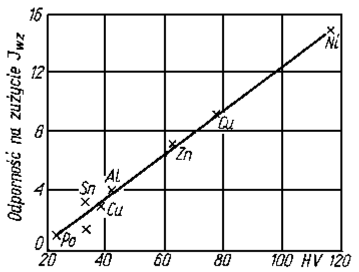


Fig. 4. Relationship between relative abrasive wear resistance (**J**$_{wz}$) and Vickers hardness (**HV**) of metals [1]

As follows from this chart, there is a linear relationship between the increase in the relative abrasive wear resistance of metals and hardness (in the case when hardness of the abrasive material is much higher than the hardness of the abraded metal).

Obviously, the relative abrasive wear resistance of steels of different types (steels hardened, tempered, carbon-containing, alloyed, etc.) is also different, but in each case (alloy grade) this resistance is proportional to the hardness of the abraded material. The quotient of the relative abrasive wear resistance of metal (J_{wz}) and its hardness (HV) is for a given family of metals (alloys) constant, that is:

$$J_{wz} / HV = const.$$

Penetration of abrasive particles into the top layer of the abraded metal often causes serious anomalies in the intensity and mechanism of abrasive wear.

With significant differences in the hardness of mating parts, eventually it is the harder metal that can suffer a more intensive wear. This is due to penetration of a large number of abrasive grains into a softer metal. Due to this, the friction surfaces get coated with a specific kind of abrasive "brush", composed of hard abrasive particles and soft metal layers binding them together.

As a result of this phenomenon, the softer metal becomes a kind of grinding wheel, which causes intense cutting of hard metal.

THE ABRASIVE WEAR OF IRON ALLOYS

In the examination of carbon steel, the results were obtained from which the following general conclusions were drawn:
- pearlitic structures with lamellar pearlite are slightly more resistant to abrasion than structures with spheroidal pearlite (Fig. 5),

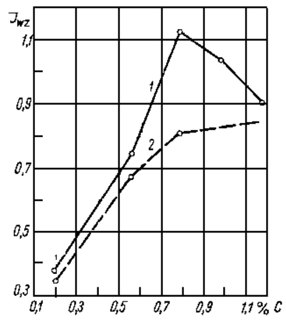


Fig. 5. Effect of pearlite structure on changes in the relationship between hardness and abrasive wear resistance [1];
1 – steel with lamellar pearlite,
2 – steel with spheroidal pearlite

- the wear resistance of hardened steel increases with the increasing carbon content, but starting with 0.8% this increase is gradually becoming less intense, to disappear almost completely at 1% C (Fig. 6).

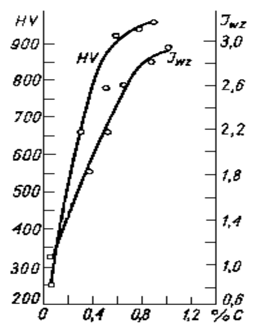


Fig. 6. Relationship between hardness (**HV**) and abrasive wear resistance (**J**$_{wz}$) of hardened steels as a function of the carbon content [1]

- in steels quenched and tempered, the abrasive wear resistance decreases with increasing temperature of tempering, but to a lesser extent than the hardness (Fig. 7),
- most abrasion-resistant are non-tempered martensitic structures,
- the increasing content of retained austenite in the structure of martensitic tool steels makes their abrasive wear resistance decrease,
- in hypoeutectoid, annealed, ferritic-pearlitic steels, when the increase in hardness with the increase in carbon content is due only to the increasing content of pearlite of

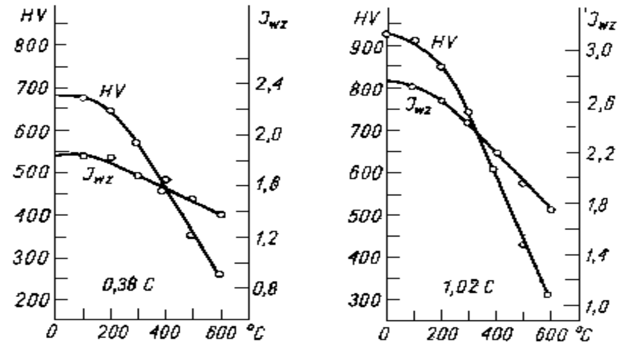


Fig. 7. Relationship between hardness (**HV**) and abrasive wear resistance ($\mathbf{J}_{wz}$) of steel as a function of the tempering temperature [1]

the same structure, i.e. to the change in the phase content ratio without any change in the essential characteristics of the structure, the resistance to abrasion is strongly dependent on the hardness,
- as soon as the eutectoid point is exceeded (according to some studies even a little earlier), and the microstructure of the steel changes quite significantly, the relationship between these parameters, valid for the hypoeutectoid steels, now loses its validity,
- changes in the structure of pearlite also change in both ranges the relationship between hardness and abrasive wear resistance (Fig. 5),
- the relationship between hardness and abrasive wear resistance seems to be valid only for structures of the same type,
- the increase in "natural" hardness, i.e. in hardness of pure metals and annealed steels, is accompanied by much more pronounced increase in the abrasive wear resistance than the increase obtained by quenching and tempering,
- the increase in hardness as a result of cold work, which does not cause any phase transformations in the hardened layer, such as e.g. the transformation of austenite into martensite, gives practically no improvement in the abrasive wear resistance,
- the aforementioned relationships confirm the thesis given previously that only structural changes caused by the heat treatment, mechanical treatment, etc. determine changes in the abrasive wear resistance of a material, and not the associated increase in hardness.

The abrasive wear resistance of cast iron as an alloy of complex multi-phase structure is characterised by the structural features, properties, and percent content of individual phases, the width and shape of the grains and their mutual distribution. One of the characteristics typical of the cast iron abrasive wear is the fact that the constituent undergoing the most intense wear is graphite.

The product of the wear is the graphite powder, which acts as a *lubricant* reducing the coefficient of friction and improving the abrasive wear resistance, especially under the conditions of dry friction. In the mixed mode of friction, the cavities and crevices created by the loss of graphite play the role of "storage tanks" for the lubricant. In those cavities are also accumulated the products of wear, thus reducing the abrasive effect.

On the other hand, graphite inclusions in cast iron act as lubricants of very low resistance, breaking the continuity of the metallic matrix, which can lead to the detachment of metal particles and the related *notch effect*.

The effect of microstructure on the abrasive wear resistance of cast iron depends on:
- content and structure of the metallic layer,
- content, shape and dispersion of graphite inclusions,
- content and shape of the phosphorus eutectic.

The above mentioned microstructural factors are obviously dependent on:
- chemical composition of cast iron,
- the conditions of the casting solidification and cooling,
- possible heat treatment.

The latest generation of casting alloys characterised by high abrasive wear resistance includes ADI and high-alloyed cast steel hardened with nitrogen added as an alloying element. At the Foundry Research Institute in Cracow, for many years, research and implementation works have been conducted on the aforementioned alloys, mainly to explore the possibility of using them for agricultural tools working in the soil [9, 10, 11, 12, 13, 14, 21, 22, 23, 24]. Some examples of castings made for the agricultural sector are shown in the photographs below (Figs. 8 and 9):

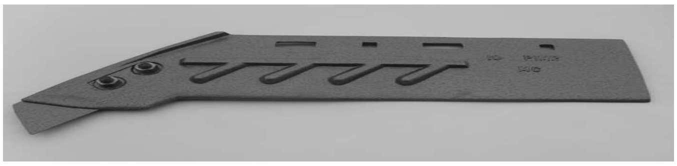
WEAR RESISTANCE TESTING

Among various methods to test the tribological wear resistance, three main groups are distinguished:
- field testing,
- bench testing,
- laboratory testing.

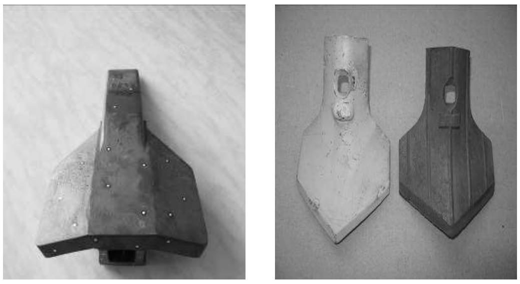
High complexity of tribological damage imposes the need to reproduce during testing, as exactly as possible, all conditions under which the wear takes place, and so to ensure exact mapping of the operating conditions of the tested mechanism, machine part or material.

FIELD TESTING

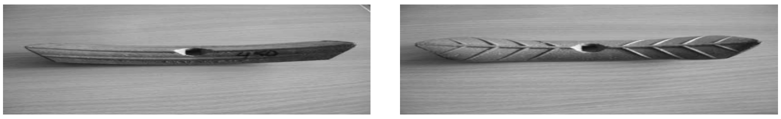
Field tests are carried out on machines or equipment under conditions of their actual operation. The purpose of these tests is, among others, to detect weak parts suffering frequent damage and determine the intensity of their use. Field tests may be carried out as part of research to determine the wear rate of specific components included in a new design and / or made of a new (tested) material.



Ploughshare with cutting blade for the reversible and single-sided plough (ADI)



Cast subsoiler coulter. Cast duckfoot for the flexible cultivator teeth



Cast coulters for the flexible cultivator teeth (two types)

Fig. 8. Examples of parts resistant to abrasive wear cast from ADI (own designs)

Casting of rake (left) and part of combine to make compost (right)

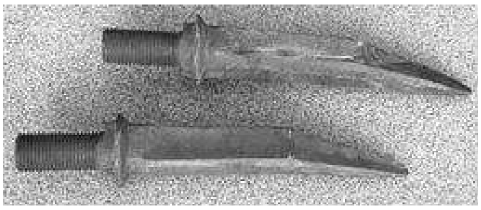


Fig. 9. Examples of parts resistant to abrasive wear made from high-alloyed cast steel with nitrogen

These tests reproduce most fully and faithfully actual operating conditions of parts of the machines and equipment to be evaluated. Since these are usually long-term studies, often, when they are running, narrower operating parameters than under normal operating conditions are applied. However, application of these experimental conditions should not cause changes in the abrasive wear mechanism.

In field testing, the main methods of the measurement of the degree of wear include the measurement of dimensional changes, the method of artificial bases, and isotopic method. Gravimetric method, due to the large mass of the components under inspection, is less useful. Sometimes the weight of the products of wear is determined.

Due to the fact that the operating parameters (load value, ambient temperature, humidity, etc.) under normal conditions vary at random, it is necessary to provide a statistical approach to the results of experiments, which considerably increases both the time and cost of studies.

BENCH TESTING

Bench tests are carried out on entire machines or individual components. They have a control or experimental character. The construction of a stand has to provide conditions similar to the real ones. Compared with field testing, these studies enable wider programming of operating conditions, their exact recording, increasing the number and accuracy of measurements, and high reproducibility of the results. This allows using smaller number of repetitions, which reduces the cost of the experiment.

LABORATORY TESTING

Laboratory tests are carried out for the mating parts of machinery or equipment, or for the mating materials. It is difficult to reproduce in laboratory equipment the real operating conditions such as e.g. the stiffness of structure, the precision of assembly, vibrations, etc.

Therefore, laboratory testing of material wear is most often done for comparative purposes only. These tests are designed to compare the wear resistance of the examined materials with the wear resistance of the adopted reference standard. The studies do not refer to the conditions under which the tested material will be operating, but adopt a simple mechanism of wear for which the comparison is carried out.

Within the framework of materials testing of the developed and implemented casting alloys of a new generation to be used for agricultural tools working in the soil, numerous tests to assess the resistance to abrasive wear have been carried out [15, 16, 17, 18, 19]. For example, Figure 10 compares the erosive wear rate of ADI castings with other selected casting alloys.

Owing to a high content of residual austenite in the matrix, ADI hardens under pressure in a way similar to Hadfield cast steel, offering also similar resistance to erosive wear.

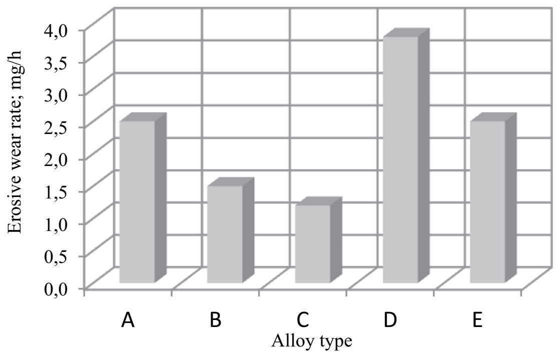


Fig. 10. Erosive wear rate tested in silica sand – water slurry for different ferrous alloys (own studies)
A – Hadfield alloy, B – chromium-nickel cast steel, C – chromium-nickel cast steel with addition of nitrogen, D – ductile iron, E – austempered ductile iron (ADI)

Even more resistant to this type of wear is the high-alloyed, chromium-nickel cast steel, in particular with the addition of nitrogen. High resistance of this alloy to tribological wear was confirmed by comparative bench tests carried out on harrow teeth, shown in Figure 11. Despite a significant increase in the life of harrow teeth cast from the high-alloyed, chromium-nickel steel, compared with forged steel teeth, the rationale of their use must be decided against the background of economic reasons (the cost of production).

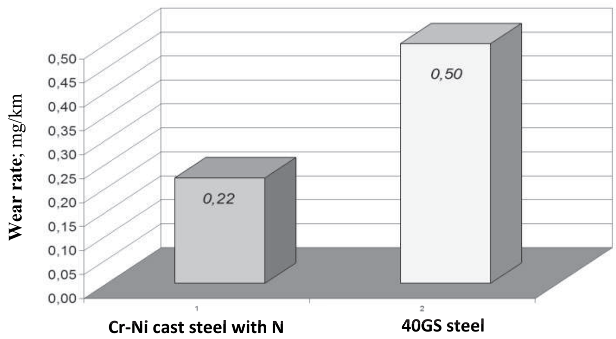


Fig. 11. Abrasive wear rate compared for harrow teeth made from different alloys

In cooperation with the Research Institute of Agricultural Engineering in Poznań, the Foundry Research Institute in Cracow has developed a series of innovative agricultural tools made from the austempered ductile iron (ADI); the developed castings were subjected to a series of laboratory and field tests. Examples of the obtained results are given in Figures 12-15.

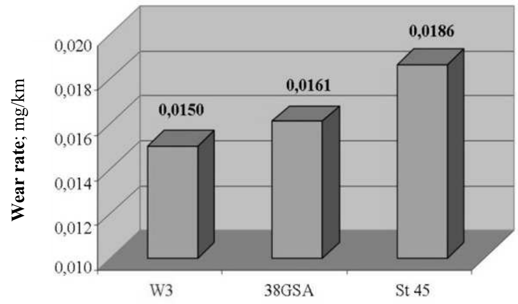


Fig. 12. Wear behaviour of investigated alloys under the conditions of dry friction [own studies]

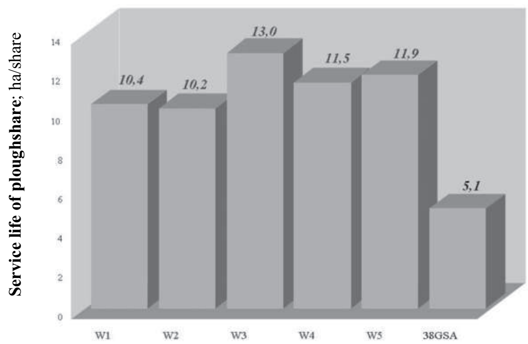


Fig. 13. Service life of ploughshares cast from ADI (designated with symbols W1 – W5) and ploughshares forged from 38GSA steel [own studies]

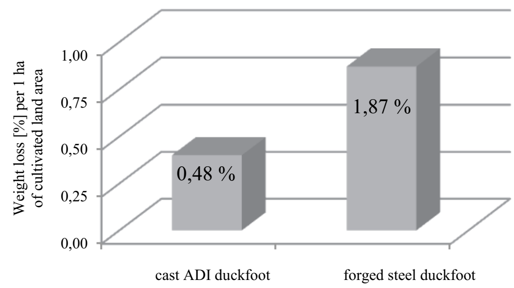


Fig. 14. Weight loss in cultivator duckfoot cast (own studies) and forged [20] calculated per 1ha of the cultivated land area

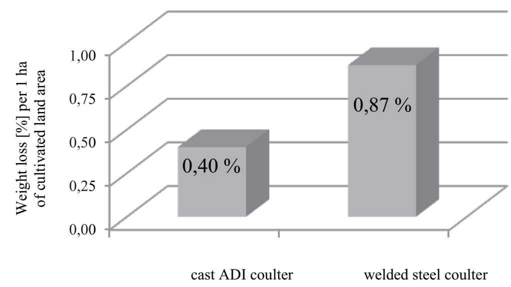


Fig. 15. Weight loss in three-tooth subsoiler coulters cast and welded calculated per 1ha of the cultivated land area (preliminary studies)

CONCLUSIONS

The tests and studies carried out have shown that modern casting materials can in many cases successfully replace the traditional wrought alloys. Sometimes, redesigning of the replaced components is necessary due to changes in production technology, while their introduction to common use requires wide-scale dissemination of innovative solutions wherever it is economically justified.

ACKNOWLEDGMENTS

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STOPY ODLEWNICZE PRACUJĄCE W TRUDNYCH WARUNKACH ZUŻYCIA ŚCIERNEGO PRZEZNACZONE NA NARZĘDZIA ROLNICZE

Streszczenie. W artykule omówiono wybrane zagadnienia związane z procesami zużycia trybologicznego, koncentrując się na zjawiskach zachodzących w trakcie zużywania się detali w trakcie ścierania. Omówiono mechanizmy takiego procesu,

scharakteryzowano ważniejsze materiały odporne na ten rodzaj zużycia i pokazano przykładowe odlewy przeznaczone dla sektora rolniczego opracowane i wykonane w Instytucie Odlewnictwa w Krakowie we współpracy z Przemysłowym Instytutem Maszyn Rolniczych w Poznaniu. Następnie sklasyfikowano i opisano ważniejsze metody oceny odporności stopów na zużycie ścierne, w tym zużycie erozyjne. Przytoczono przykładowe własne wyniki takich badań. Wykazano, że nowoczesne stopy odlewnicze mogą z powodzeniem konkurować z tradycyjnymi tworzywami przerabianymi plastycznie.
Słowa kluczowe: trybologia, badania, odlewy, stopy odlewnicze, narzędzia rolnicze