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Krzysztof LIGIER*, Magdalena LEMECHA, Jerzy NAPIÓRKOWSKI*****

EFFECT OF CEREAL SEED CONTRIBUTION TO THE WEAR OF SELECTED MATERIALS USED TO PRODUCE SCREW CONVEYOR BLADES

WPŁYW ODDZIAŁYWANIA NASION ZBÓŻ NA ZUŻYCIE PIONOWYCH PRZENOŚNIKÓW ŚLIMAKOWYCH

Key words: wear, cereal seeds, screw conveyor, abrasion-resistant steel.

Abstract: This paper presents the analysis of the process of structural material wear by cereal seeds. Two steel grades were subjected to testing: C45 and low-alloy steel with a micro-addition of boron. The experiment was conducted under laboratory conditions by the "rotating bowl" method. Wheat and maize seeds were used as an abrasive. During the testing, analyses of specimen weight and volume loss as a function of the friction distance were carried out. An analysis of the test material surface was conducted as well.
The study results show that the C45 steel worn in maize grains exhibited a weight loss greater by 20% than that for the wear in wheat grains. For the abrasion-resistant steel, the difference was 22%. In both abrasive mediums, the C45 steel wore to a greater extent than the abrasion-resistant steel. For the maize grain abrasive, the weight loss value was approx. 1.5 times higher than that for the C45 steel. Similar correlations were noted for the wheat abrasive. The abrasion-resistant steel had a wear rate approx. 1.6 times lower than the C45 steel. The dominant wear types observed on the surfaces of the test steels include ridging and micro-cutting.

Słowa kluczowe: zużycie, nasiona zbóż, przenośnik ślimakowy, stal odporna na ścieranie.

Streszczenie: W pracy przedstawiono analizę procesu zużywania materiałów konstrukcyjnych przez nasiona zbóż. Badaniom poddano dwa gatunki stali: C45 i stal niskostopową z mikrododatkiem boru. Eksperyment przeprowadzono w warunkach laboratoryjnych metodą „wirującej misy". Jako ścierniwo użyto nasion pszenicy i kukurydzy. Podczas badań dokonywano analizy ubytku masy i objętości próbek w funkcji drogi tarcia. Wykonano również analizę powierzchni badanych materiałów. Wyniki przeprowadzonych badań wskazują, że stal C45 zużywana w ziarnach kukurydzy wykazywała o 20% większy ubytek masy niż w przypadku zużycia w pszenicy. Dla stali odpornej na zużycie ścierne różnica ta wynosiła 22%. W obu ośrodkach ściernych bardziej zużywała się stal C45 w porównaniu ze stalą odporną na zużycie ścierne. W przypadku ścierniwa, jakim były ziarna kukurydzy, wartość ubytku masy była wyższa o ok. 1.5 raza dla stali C45. Podobne zależności zaobserwowano w przypadku ścierniwa, jakim była pszenica. Stal odporna na zużycie ścierne zużyła się o ok. 1.6 razy mniej niż stal C45. Dominującym rodzajem zużycia, jaki zaobserwowano na powierzchni badanych stali jest bruzdowanie i mikroskrawanie.

** ORCID: 0000-0003-1348-7068. University of Warmia and Mazury in Olsztyn, Faculty of Technical Sciences, M. Oczapowskiego 11 Street, 10-719 Olsztyn, Poland, e-mail: krzysztof.ligier@uwm.edu.pl.
** ORCID: 0000-0003-3414-4099. University of Warmia and Mazury in Olsztyn, Faculty of Technical Sciences, M. Oczapowskiego 11 Street, 10-719 Olsztyn, Poland, Mailing address: e-mail: magdalena.lemecha@uwm.edu.pl
*** ORCID: 0000-0003-2953-7402. University of Warmia and Mazury in Olsztyn, Faculty of Technical Sciences, M. Oczapowskiego 11 Street, 10-719 Olsztyn, Poland.

INTRODUCTION

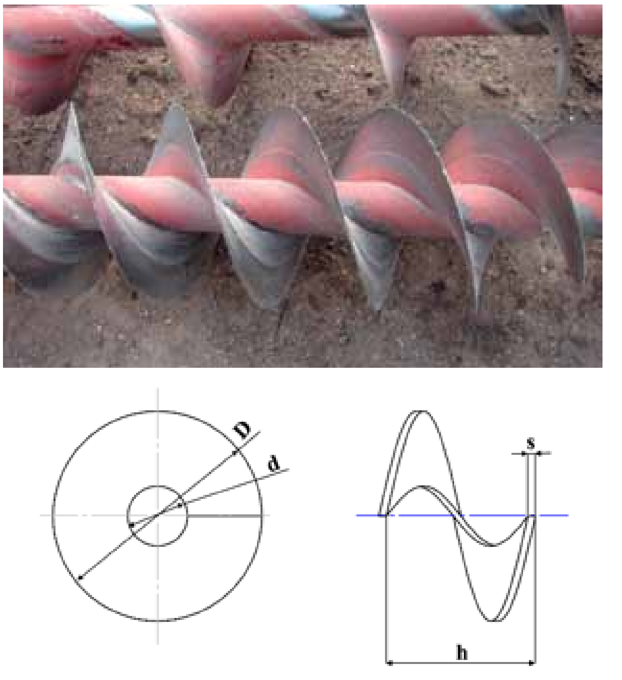
High-load lifting screw conveyors are primarily used for performing continuous operations in the process of leading machine feeding in various industry sectors. The main criteria for their correct functioning include the delivery of an adequate portion of the material in a set time and the elimination of damage to the products being transported. The fulfilment of the first criterion is determined by the chute filling coefficient, which is dependent on the product transported and the worm shaft pitch. Ensuring that the second criterion is met properly results from the condition of the coil surface and its geometry.

Conveyors of this type are integral to seed stores, dryers, and mixers **[L. 1, 2]**. The operating life of conveyor operating parts, primarily coils, results from the course of tribological processes, the method for performing the work process, and the type of material transported **[L. 3]**. Wear processes occur along the entire path of seed movement via both the transmission and discharge equipment **[L. 4]**. The effects of abrasive wear are material losses on the surface interacting with the plant material transported **[L. 5]**.

Research into the friction phenomena associated with moving crop seeds focuses on the determination of the external friction coefficient of seeds in combination with different structural materials **[L. 6, 7]** and the coefficient of internal friction in a grain mass **[L. 8]**. Based on the studies conducted to date, it can be concluded that the factors affecting the external friction coefficient of cereal grains include, e.g. the material type, roughness of the surface layer, and the grain moisture content **[L. 9, 10]**. These studies are limited to the determination of the friction coefficient value in the context of energy intensity of work processes **[L. 11, 12, 13]**, while ignoring the aspect of the wear of the parts interacting with seeds in relation to the raw material transported (processed) and the structural material used.

The problem of wear of the conveyor worm concerns virtually every structural and technological solution in which it is used **[L. 14]**. Both the replacement and renovation of a worn operating part are usually very expensive. Therefore, when designing conveyors, the wear resistance of the structural material used needs to be taken into account.

The operating part most exposed to wear in lifting conveyors is the worm blade housed in the body. This part is commonly made from welded constructional steel by welding the conveyor blades to the centrally positioned shaft (**Fig. 1a**). The blades themselves are made from strips of hot- or cold-formed steel sheet with the required dimensions (inner and outer diameter and the stroke – **Fig. 1b**) maintained.



D – outer diameter, d – inner diameter,
h – stroke, s – sheet thickness

Fig. 1. View of the conveyor worm
Rys. 1. Widok ślimaka przenośnika

For the production of conveyor operating parts, weldable unalloyed steels types S235, S355, and C45 are commonly used. As regards conveyors designed for transporting raw materials with a considerable wear impact, manufacturers offer blades made from abrasion-resistant steels such as Hardox, Cresaubro, Thyssen, and Raex.

The correct choice of material for conveyor blades should be determined by the type of the material to be transported. As far as plant seeds are concerned, the specificity of their wear impact is not considered. This fact, combined with the use of unalloyed steels for the production of conveyors, results in intense wear of the conveyor operating part. **Figure 2a** shows a section of a lifting conveyor worm in a seed drying room after being in use for 100 hours during maize grain drying. In this case, the wear of the conveyor blade operating surface is concentrated around the outer edge (**Fig. 2a**), thus resulting in a reduction in the blade diameter and its deformation. An increase in the gap between the blade and the transmission pipe and its deformed surface result in damage to grains (**Fig. 2b**).

a)

b)

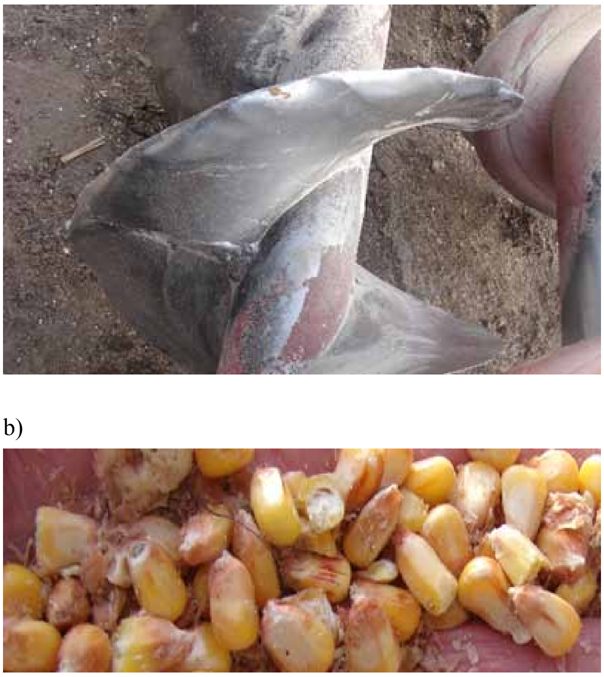


Fig. 2. View of the conveyor worm operating screw (a) and damaged maize grains (b)

Rys. 2. Widok śruby roboczej ślimaka przenośnika (a) i uszkodzone ziarna kukurydzy (b)

The wear marks visible on the blade surface indicate different wear processes depending on the operating zone of the blade (**Fig. 3a**). In the zone located near the shaft, scratch marks are visible with clear marks of spot material losses having a character of erosion wear (**Fig. 3b**), while in the zone located near the edge, scratching processes are dominant (**Fig. 3c**).

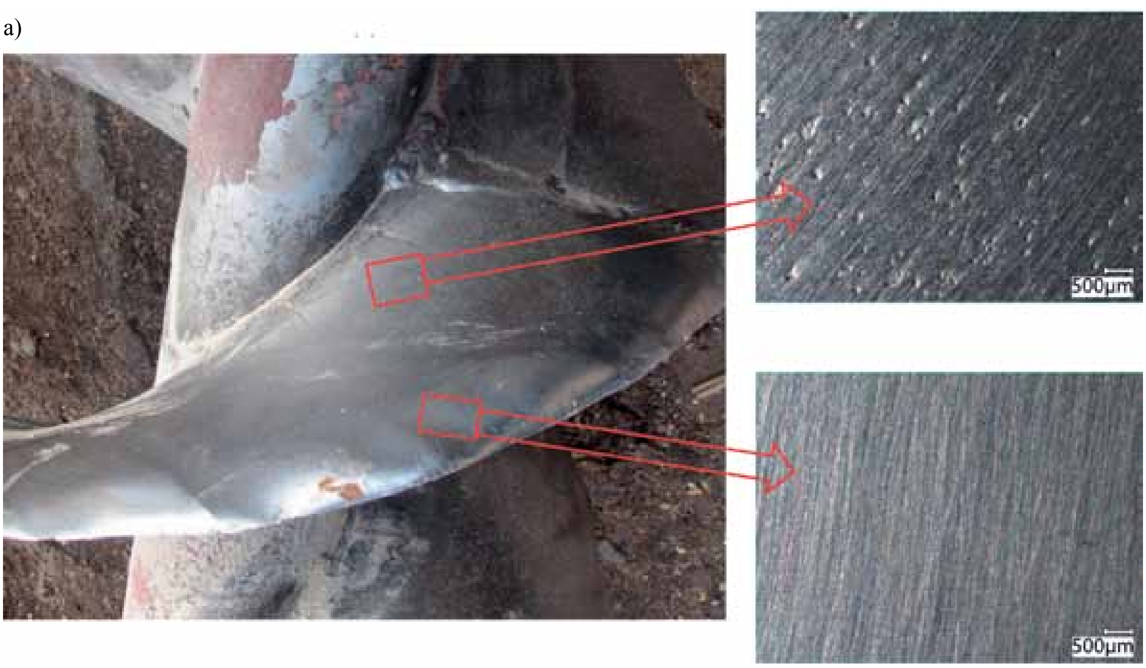
In the case described, intense wear of the blades occurred following a short period of conveyor use (100 h). The basic way to increase the operating life of conveyors and mixers is to adapt the properties of structural materials to the type of raw materials transported.

The aim of the study is to investigate the wear of selected steel types used to produce screw conveyor blades when exposed to the impact of wheat and maize seeds.

STUDY MATERIAL

Two steels were selected for the study: a quality unalloyed toughening steel C45 (PN-EN ISO 683-1:2018-09) and a low-alloy abrasion-resistant steel. Cuboid-shaped specimens with dimensions of 30 × 25 × 10 mm were cut out from a steel sheet. In order to prevent changes to the material microstructure, steel specimens were cut out using a high-energy waterjet cutting technology. They were then processed on a surface grinder to give them the form of a cuboid. In the next step, the specimens were polished on a grinding and polishing machine to ensure uniform roughness at a level Ra = 0.3 µm.

a)



b)

c)

Fig. 3. Worn surface of a lifting conveyor blade

Rys. 3. Zużyta powierzchnia pióra przenośnika unoszącego

The C45 steel in a normalised state is characterised by a pearlitic-ferritic microstructure (**Fig. 4**). It is one of the constructional materials commonly used, e.g. to produce operating parts of screw conveyors.

The microstructure of abrasion-resistant (AR) steel is characterised by a homogenous lath-tempering martensite structure (**Fig. 5**). Steel of this type has a wide range of general applications. It performs particularly well under conditions where impact resistance is as important as abrasion resistance. This steel is characterised by a lower carbon content and an increased content of manganese, silicon, chromium, molybdenum, and boron compared to the C45 steel (**Table 1**).

A dried biological material in the form of wheat and maize seeds was used as an abrasive. The measurement of seed moisture content was conducted by the capacitive method using a TwistGrain pro moisture meter with a measurement accuracy of +/- 0.5%. The instrument is equipped with options for automatic temperature compensation and automatic calculation of the mean value of the four most recent measurements. The average moisture content of the seeds ranged from 12% for maize to 13% for wheat.

TESTING METHODOLOGY

Grains are visco-elastic materials whose strength properties, which describe their behaviour under loading conditions, mainly depend on the grain size and shape, internal structure as well as the impact of external factors, i.e. storage time, moisture content, and temperature. The hardness of abrasive grains was determined using a Mecmesin Multi Test 1-i testing machine (Mecmesin Limited, UK) by means of determining the maximum value of the compressive force at which grain fracture occurred. The experiment was conducted at a constant compression head travelling speed of 5 mm·min^{-1}. The maximum loading force was 1,000 N. The compression process was carried out at constant specimen deformation of 10% of the height for wheat and 20% for maize. A total of 50 grains of each material were tested. The results are provided in **Table 2**.

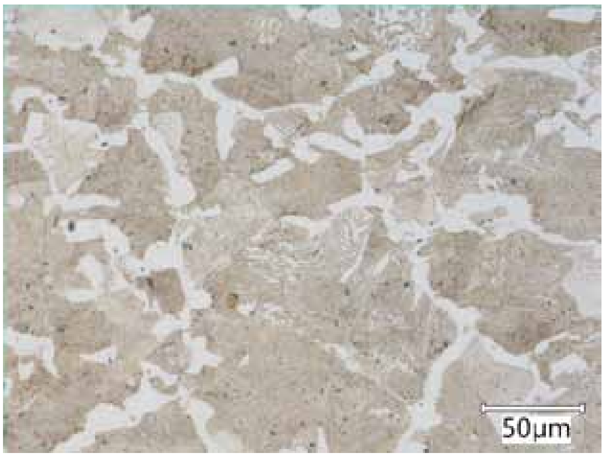


Fig. 4. C45 steel microstructure
Rys. 4. Mikrostruktura stali C45

Fig. 5. AR steel microstructure
Rys. 5. Mikrostruktura stali trudnościeralnej

Table 1. Chemical composition of the test steels
Tabela 1. Skład chemiczny badanych stali

Material type	Selected chemical element [%]									
	C	Mn	Si	Cr	Mo	Ni	Cu	P	S	B
C 45 (according to PN-EN ISO 683-1:2018-09)	0.42	0.50	0.10	0.30	0.10	0.30	0.30	0.04	0.04	–
AR steel (manufacturer's data)	0.28	1.40	0.35	0.50	0.25	0.30	–	0.03	0.03	0.004

Table 2. Hardness of test grains
Tabela 2. Twarodość badanych ziaren

Material	Maize	Wheat
Hardness [N]	261.73	90.60

The measurements of steel hardness were carried out by the Vickers method in accordance with the PN EN ISO 6507-1 standard, using a Wilson VH1150-type hardness tester. The hardness measurement results are provided in **Table 3**.

Table 3. Hardness of test materials
Tabela 3. Twardość badanych materiałów

Material	Hardness [HV 10]	Std. Dev. [HV 10]
C45	188	19.8
AR steel	483	35.4

The tribological experiment was conducted using a "rotating bowl"-type wear machine (**Fig. 6a**). The specimen was mounted in such a manner that the angle of attack of grains on the specimen surface was 45° (**Fig. 6b**).

The following testing parameters were applied:

- linear velocity – 1.40 m · s^{-1},
- total friction distance – 20 000 m.

Weight wear was adopted as the wear measure. Weight wear was measured every 4000 m using a laboratory balance with an accuracy of 0.0001 g.

Weight wear was calculated according to the following relationship:

$$Z_w = m_p - m_k \qquad (1)$$

where:
Z_w – specimen weight wear [g];
m_p – initial specimen weight before the wear testing [g];
m_k – specimen weight after covering a specified friction distance [g].

The images showing the microstructures, surfaces subjected to abrasive wear testing, and the specimen roughness profile following friction tests were taken using a KEYENCE VHX 7000 digital microscope.

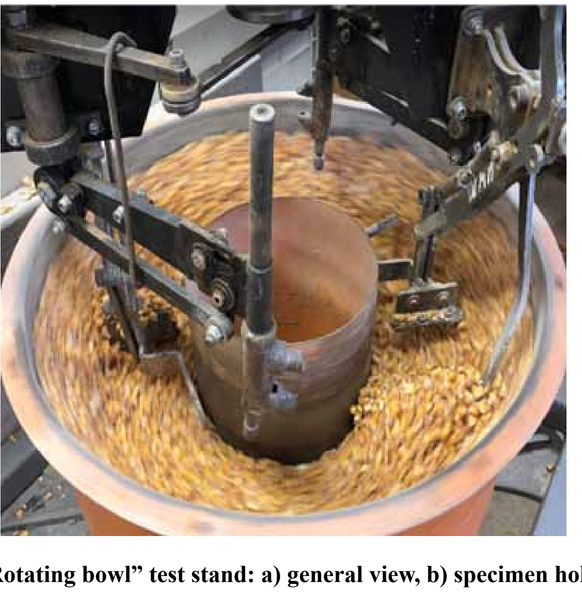
TEST RESULTS

The results of the test material mass loss are provided in **Figure 7**.

Based on the test material mass loss results obtained, it can be concluded that the material which wore more intensely in both abrasive mediums tested is the C45 steel. The wear value for this material was approx. 1.6 times higher in both maize and wheat grains.

The maize grain shape is described as flattened and wedge-like, with the apex being considerably

a)



b)

Fig. 6. "Rotating bowl" test stand: a) general view, b) specimen holder
Rys. 6. Stanowisko „wirująca misa": a) widok ogólny, b) uchwyt próbki

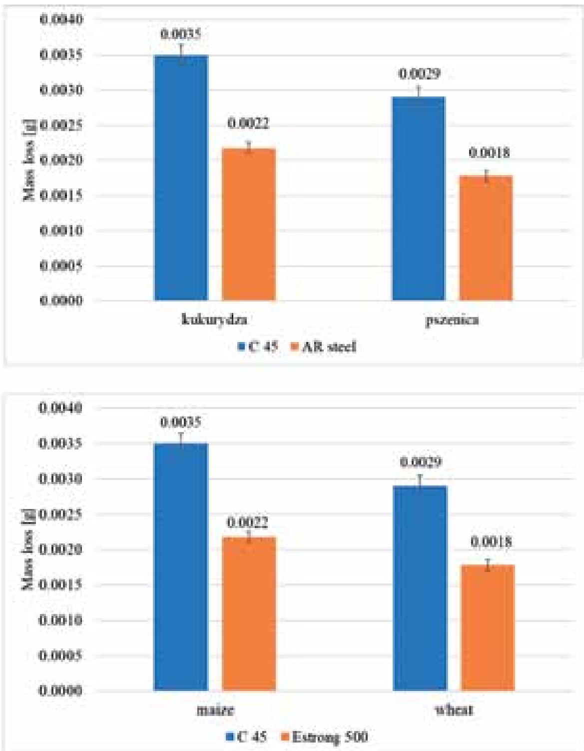


Fig. 7. Summary of the test material wear results after 20 000 m of friction distance

Rys. 7. Zestawienie wyników zużycia badanych materiałów po 20 000 m drogi tarcia

wider than the point of setting on the cob. A grain kernel is surrounded by the seed coat and fruit wall with a thickness of up to 135 µm. The thickness of the seed coat and fruit wall decreases with maturity. This change, however, is accompanied by an increase in hardness **[L. 15]**. Wheat grains are oblong in shape, with one side flattened and a visible furrow running along the entire length of the ventral side of the kernel. Their shape is described as flattened and wedge-like, with the apex being considerably wider than the setting point. The hardness of wheat provides information on its suitability for processing. In addition to the hardness of the wearing grains, the actual friction surface is of considerable importance in the wear impact. Visually, the friction surface of the wheat is greater than the friction surface of the maize, which is due to the differences in the shape of the two grains.

When relating the wear values to the hardness of the test materials, it can be noted that the material that wore less intensely exhibited greater hardness.

To identify homogeneous groups and determine significant differences in weight losses of the test materials in the particular types of abrasive material, a statistical analysis was conducted using the Statistica 13.3 program (StatSoft). The significance of the effect of the use of the material used on the wear value was determined using the variance analysis. For each abrasive material type, a null hypothesis of the lack of significant differences between the weight loss values after covering the distance of 20 000 m, and an alternative hypothesis of the occurrence of significant differences depending on the test material used, were adopted. Where the null hypothesis must be rejected in favour of the alternative one, the Duncan test was applied to distinguish homogeneous groups. The statistical analysis results are provided in **Table 4**.

Based on the statistical analysis results, it can be concluded that for the abrasive material in the form of both maize grains and wheat grains, statistically significant differences were noted in the weight losses of the structural materials tested. This fact may be evidenced by the hardness of the biological material tested, which contributes to the destructive impact on the structural material.

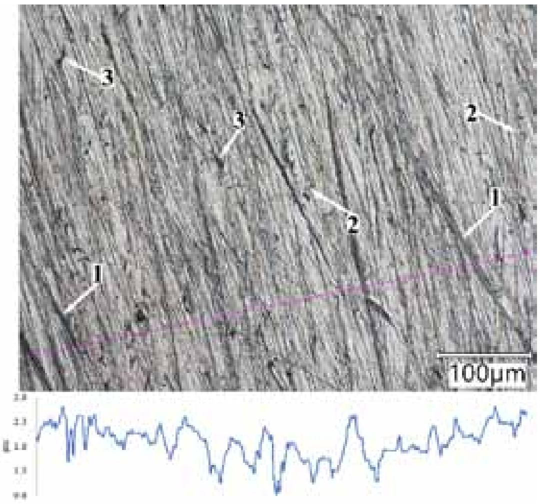
After tribological tests, an analysis of the wear processes was conducted based on the images of the test material surfaces (**Fig. 8, Fig. 9**). The metallographic analysis of the test materials was supplemented to include tests of the surface geometry, conducted using a KEYENCE VHX 7000 digital microscope.

Table 4. Variance analysis results

Tabela 4. Wyniki analizy wariancji

Duncan test; variable C45, AR steel Homogeneous groups, alpha = .05000 Error: Intergroup MS = .00000, df = 8.0000						
	C45 Mean values	***1***	***2***	***AR steel Mean values***	***1***	***2***
wheat	0.0029	****		0.0018	****	
maize	0.0035		****	0.0022		****

a)



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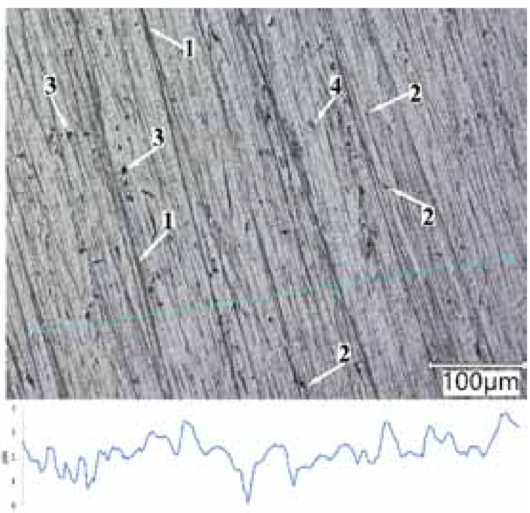


Fig. 8. Surface of the C45 steel worn in (a) maize and (b) wheat

Rys. 8. Powierzchnia stali C45 zużywanej w (a) kukurydzy, (b) pszenicy

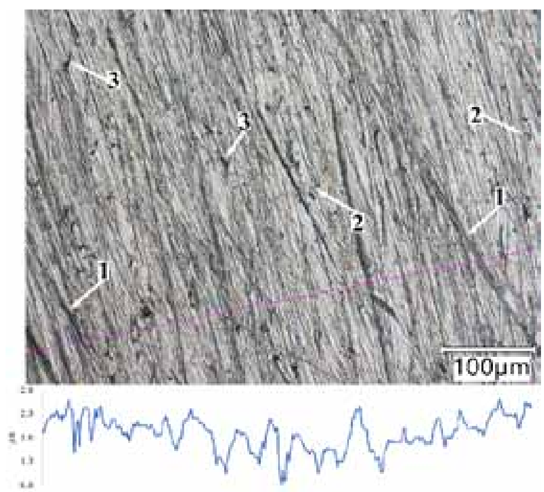
On the surface of the C45 steel worn in maize, grooves (**Fig. 8a** (1)), numerous small pit spots that have a character of micro-cutting (**Fig. 8a** (2)), and material tear-ups (**Fig. 8a** (3)) caused by impacts of the hard tip of the grain are visible. In addition, small scratches can be noted that are oriented obliquely to the direction of the corn grain impact. Maize grain is composed of the pedicel, seed coat and fruit wall, embryo and endosperm. The pedicel is a hard and fibrous remnant of the tissue connecting the grain with the cob, and it is its impact on the friction surface that contributes to the emergence of mechanical wear modes.

As regards the wear-resistant steel surface, wear marks similar to those for the C45 steel are visible. Due to the higher hardness value of this material, the ridging (**Fig. 8b** (1)), micro-cutting (**Fig. 8b** (2)), and material tear-up marks (**Fig. 8b** (3)) are shallower and found in smaller numbers. Moreover, plastic deformations (**Fig. 8b** (4)) and scratches oriented obliquely to the direction of friction are visible (**Fig. 3**).

The analysis of the worn surfaces demonstrated clear differences in the degree of surface deformation between the materials worn in maize and in wheat. Based on the surface profiles, it can be concluded that the surface of the specimen worn in wheat is smoother than the surface worn in maize. On the surface of the C45 steel worn in maize, there are more deep grooves than on the surface of this steel worn in wheat.

Similar changes can be observed on the surface of the abrasion-resistant steel. In this case, grooves (**Fig. 9** (1)), micro-cutting (**Fig. 9** (2)), and material tear-up marks **(Fig. 9** (3)) are also visible, with these marks being more numerous on the surface worn in maize.

a)



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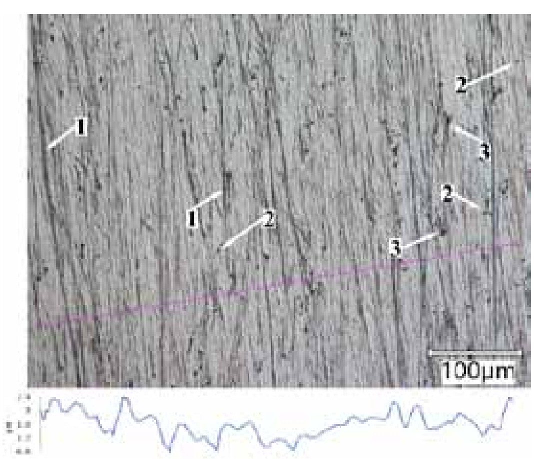

Fig. 9. Surface of AR steel worn in (a) maize and (b) wheat

Rys. 9. Powierzchnia stali AR steel zużywanej w (a) kukurydzy, (b) pszenicy

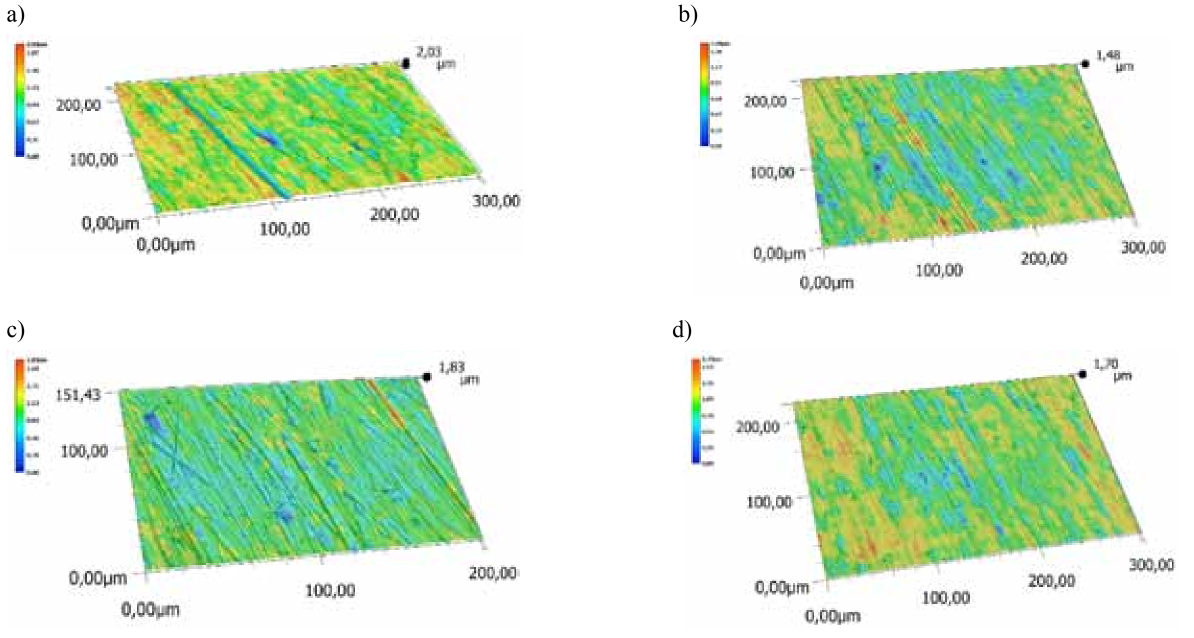

Fig. 10. Surface after wear: a) C45 in maize, b) C45 in wheat, c) AR steel in maize, d) AR steel in wheat
Rys. 10. Powierzchnia po zużyciu: a) C45 w kukurydzy, b) C45 w pszenicy, c) AR steel w kukurydzy, d) AR steel w pszenicy

For the assessment of the roughness of the surfaces presented in **Fig. 10**, the parameters Sa, Sq were used, which exhibited a significant functional relationship with the surface wear (**Table 5**) **[L. 16]**.

Table 5. Roughness parameters for the test materials
Tabela 5. Parametry chropowatości dla badanych materiałów

	Maize		Wheat	
	Sa	Sq	Sa	Sq
C45	0.44	0.56	0.35	0.43
AR steel	0.33	0.42	0.12	0.16

The analysis of the Sa and Sq parameter value for the test surfaces revealed pronounced differences in the surface roughness. Mean arithmetic deviations of the height of surface irregularities from the reference plane for the surfaces worn in maize are higher than those for the surface worn in wheat. The Sq roughness parameter values show that the surfaces of the test steels worn in maize have higher irregularities and the highest peak density per unit of area than those for the surfaces worn in wheat. This may be due to the higher (by approx. 2.9 times) hardness value of maize grains than that of wheat grains. As indicated in the literature **[L. 17]**, maize grains are less susceptible to impact loads while exhibiting high resistance to abrasive wear. This characteristic translates into a higher degree of destruction of the surface impacted by these grains.

SUMMARY

Based on the analysis of the study results, it can be concluded that the tribological impact of maize and wheat seeds varies. The values of the test material weight loss in maize were approx. 20% higher than those for the test material weight loss in wheat. In both abrasive mediums, the C45 steel, as compared to the abrasion-resistant steel, was characterised by higher weight loss values. For the abrasive of maize seeds, this value was approx. 1.5 times higher. Similar correlations were noted for the wheat abrasive. The abrasion-resistant had a wear rate approx. 1.6 times lower than the C45 steel.

On the surfaces of both tested materials, similar wear patterns were observed, regardless of the abrasive medium, yet they were more numerous and more intense for maize grains. This relationship can also be noted when interpreting the roughness profiles and parameters for the test steels, which are considerably higher for the materials worn in maize.

The roughness parameter values measured indicate that for both test steel grades, the surfaces worn in maize have a higher value of the irregularity height and the peak density per unit of area than the surfaces worn in wheat.

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