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POSSIBILITIES OF INCREASING THE DURABILITY OF CHAIN WHEELS OF ARMOURED-FACE CONVEYORS

Summary. The main objective of the study was to demonstrate the possibility of replacing the materials of domestic and foreign production currently used for chain drums with alternative materials. ADIs were selected as materials that may replace the cast steels used so far. L35GSM cast steel, commonly used for mining chain wheels and austempered ductile iron, conforming with the requirements of EN-GJS-1400-1 quality grade were subjected to wear tests. On the basis of the experimental studies it has been observed that for almost all the combinations of destructive factors considered, the ADI in question was characterised by a wear resistance better than that in the case of the L35GSM cast steel used so far. In addition, it has been found that the ADI has favourable features predestining it for use in the production of chain drums for armoured-face conveyors.

1. INTRODUCTION

Armoured-face conveyors are machines used to transport mineral and energy raw materials, e.g., in coal-handling systems in power plants and combined heat and power plants, as well as in underground, surface and tunnel mining. An example view of an armoured-face conveyor with a chain wheel is shown in Fig. 1. The increase in the efficiency of the transmission system of the armoured-face conveyor entails the need for using solutions characterised by a high resistance to tribological wear. The chain drum is a component of an armoured-face conveyor that is particularly vulnerable to various forms of wear. It is used to transfer the torque from the drive to the scraper chain. Despite the fact that continuous changes in terms of technology and materials are made in the process of production of chain drums, there still occurs premature degradation as a result of the impact of the mining environment and intensified mining operations [1,2]. The factors intensifying the destruction processes affecting drive components of conveyors include the following:

- stone dust or stone-coal dust getting into the area of mating between drums and the chain,
- moisture contributing to corrosion on the surface of drums, which increases the susceptibility to abrasive wear,
- numerous successful and unsuccessful conveyor start-ups and
- overloads caused, inter alia, by overloading and blocking of the conveyors.

The impacts of the aforementioned factors include the following:

- significant abrasive wear of mating surfaces of drums and chains, which is intensified by the action of so-called third body, i.e., loose and hard abrasives,
- plastic deformations of mating surfaces of drums,
- significant chipping of the teeth of chain drums,
- teeth fractures of ad-hoc or fatigue nature at the base and
- combinations of operational factors.

Fig. 1. A view of an armoured-face conveyor

The nature of the action of abrasive grains on the material being worn depends on their movement relative to the surface of the material and on the nature and value of the loads transferred by the grains. Such damage may result in an incorrect position of chain links and, consequently, increase the dynamic forces in the conveyor [3].

In the course of the operation [1] of chain wheels of armoured-face conveyors, the following main destructive mechanisms can be distinguished:

– adhesive wear,
– abrasive wear and tribocorrosive wear,
– damage to the wheel as a result of plastic deformation and
– fatigue.

However, in the real operating conditions, there occurs the simultaneous action of two or more factors accelerating the destructive processes. These factors most commonly have a synergistic impact on the element operated and, thus, intensify each other [1], which results in an accelerated loss of the stability of that element. For example, abrasive wear processes play an essential role as factors accelerating the occurrence of other types of damage, e.g., tooth fracture or tribocorrosion.

The study [1] presents a summary of the share of individual types of operating damage to chain drums of armoured-face conveyors operated in the period 2007–2010. This summary shows that abrasive wear accounts for almost 45% of the main causes of damage, resulting in the withdrawal of chain drums of armoured-face conveyors from operation.

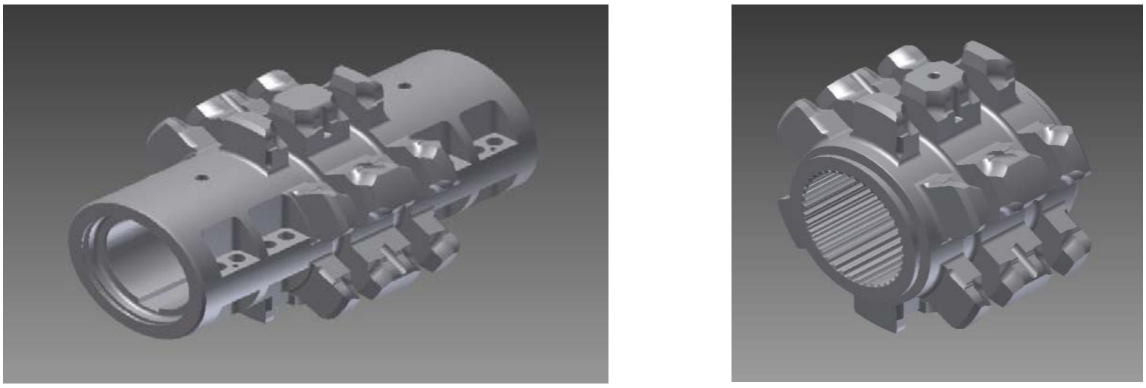
In the literature various noninvasive methods to diagnose different damages to machine components can be found [4 - 6].

2. CURRENT METHODS OF MANUFACTURING CHAIN WHEELS OF ARMOURED-FACE CONVEYORS

Split and non-split cast or forged drums (comparison of the both designs is shown in Fig. 2) are used for the construction of armoured-face conveyors characterised by highly efficient transportation of materials.

Different production technologies are used for individual manufacturing variants. Despite the differences in technology, the following main stages of production can be distinguished:

A. Preparation of casting made of cast steel with an increased resistance to abrasive wear or forging made of steel for quenching and tempering: this stage takes place essentially in foundries and forges; it includes operations associated with the preparation of the pre-shaped material in order to reduce the need for excessive material removal during processing; this stage, apart from forming the material, includes operations associated with the removal of the riser head or the scale layer, cleaning the surface, heat treatment (typically normalising, quenching and tempering) and quality control.



A B

Fig. 2. Comparison of designs of chain wheels; A: split design, B: non-split design

B. Preliminary treatment: this step includes the treatment of the drum-parting surface as well as drilling holes for connecting bolts (only for the split drum variant), machining of the inner hole, outer faces and cylindrical surfaces.

C. Milling tooth spaces: this process involves the machining operations aimed at giving a proper shape to the chain wheel tooth spaces (Fig. 3) that will be mating with the chain (in the case of the cast variant this applies only to the area of mating between the chain and the wheel).

D. Making the surfaces of key joints: this stage involves chiselling keys or splines in the inner hole of the chain wheel.

E. Surface hardening of the area of mating between the wheel and the chain: this process takes place with the use of induction- or flame-hardening methods.

F. Final quality control: this stage includes the operations of dimensional control of the chain wheel, the shape of tooth spaces, as well as an ultrasonic examination of the surface aimed at detecting pores and shorts.

The study [7] presents a summary of the types and grades of materials and their mechanical properties (Table 1). The most commonly used materials are alloy steels or cast steels (after quenching and tempering) with the hardness H = 28–31 HRC. In order to increase the wear resistance, surface hardening is performed, as mentioned above, by which the surface layers are hardened to the hardness H = 50–56 HRC.

After surface hardening, a relatively thin layer (5–10 mm) below the surface obtains a high hardness (an example of the hardness distribution depending on the distance from the surface is shown in Fig. 4). Figure 5 shows an example of a horizontal cross section through the area of mating between the wheel and the chain after etching with a 10% aqueous solution of HNO_3 in order to reveal the location of the hardened layer (darker layer).

Taking into account the plot of hardness as a function of the distance from the surface (shown in Figure 4), it should be expected that there will be a reduction in the wear resistance of the chain wheels subjected to surface hardening along with the progress of the wear of these wheels. Such a dependence significantly reduces the service life of chain wheels. An alternative solution is to use a material with the same high wear resistance regardless of the distance from the surface. Such materials include austempered ductile iron (ADI). ADIs [8,9,10] are formed from alloy nodular cast iron after the processes of austempering and isothermal quenching. As a result of the combination of both processes, ausferritic structure is formed. It consists of a mixture of lamellar carbide-free ferrite and austenite. Because of external mechanical impacts, e.g., the impact of the mating element, the austenite is strengthened as a result of the martensitic transformation (TRIP effect: Transformation Induced Plasticity). The formation of martensite as a hard phase can effectively increase the resistance of elements to abrasive wear [11 - 18]. As a result of the combination of the above-mentioned processes, there is formed a material characterised by a very good wear resistance and, at the same time, by good mechanical and plastic properties, which may predispose ADIs for the use in construction of chain wheels of armoured-face conveyors exposed to heavy loads as well as abrasive and tribocorrosive impacts.

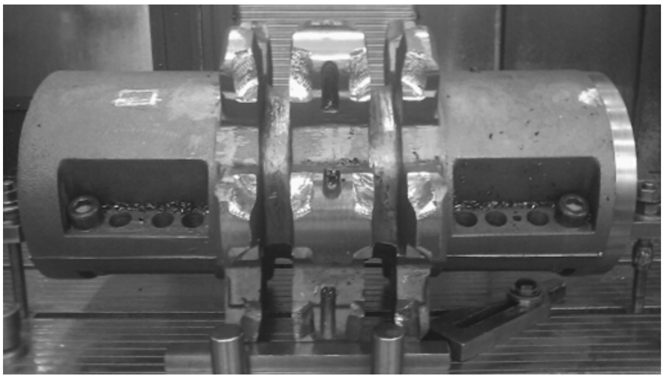


Fig. 3. A view of a split drum when milling the tooth space

Table 1

Properties of the materials in the quenched and tempered condition which are used for mining chain wheels [7]

Type of Fe alloy	The steel grade	Tensile Strength TS, MPa	Yield Strength YS, MPa	Elongation A5, %	Toughness K, J
Steel	36HMN	1030	830	10	70
Cast steel	L35GSM	1100	850	8	-
Cast steel	L35HM	750	550	14	27
Cast steel	GS42CrMo4	780÷930	650	14	35

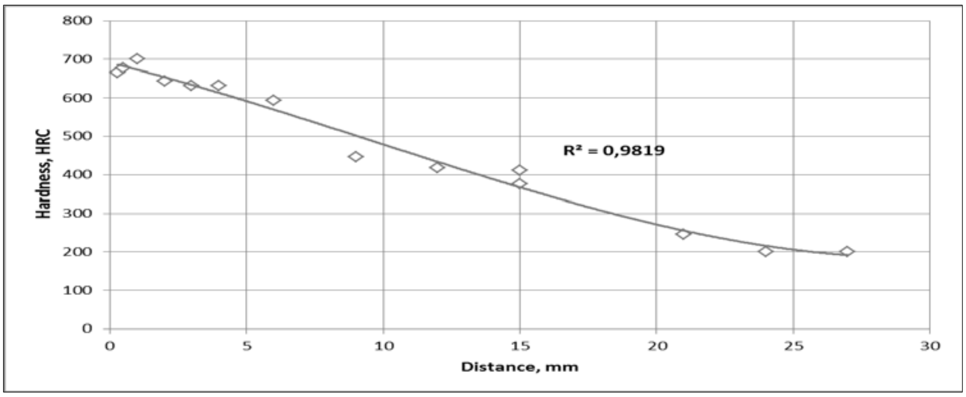


Fig. 4. Distribution of the hardness of the surface layer of the surface-hardened chain wheel 64x126 depending on the distance from the surface

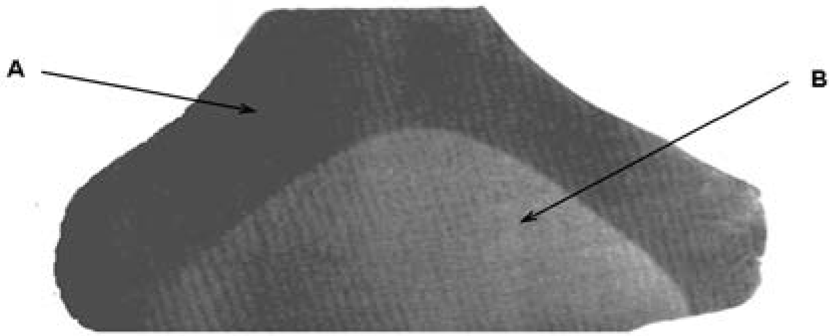


Fig. 5. Horizontal cross section through the area of mating between the chain wheel and the chain (after etching with 10% solution of nitric acid); A: hardened layer, B: the core [7]

3. THE OBJECTIVE AND METHOD OF THE WEAR TESTS

The main purpose of this study is to demonstrate the possibility of increasing the durability of chain wheels of armoured-face conveyors by changes in the materials. As a material constituting an alternative to the previously used cast steels, alloy austempered ductile iron of EN-GJS-1400-1 grade containing Ni, Cu and Mo (the mechanical properties of this ADI are shown in Table 2, whereas the chemical composition is presented in Table 3) was selected. Its wear properties were compared in relation to commonly used cast steel L35GSM (mechanical parameters of this cast steel are also summarised in Table 2).

Table 2

Mechanical properties of the materials examined

Material	Tensile Strength TS, MPa	Yield Strength YS, MPa	Elongation A5, %	Hardness, HB
L35GSM	1152±3,7	891±3,7	8,7±0,1	500±8
ADI (EN-GJS-1400-1)	1507±4,6	1072±4,4	3±1	415±4

Table 3

Chemical composition [mass%]

Material	C	Si	Mn	Cu	Ni	Mo
L35GSM	0,36	0,67	1,27	-	-	0,036
ADI (EN-GJS-1400-1)	3,50	2,54	0,16	0,5	1,40	0,24

The comparative tests of wear properties of both materials examined were carried out on a specially designed test rig that allows reproducing the real operating conditions of chain wheels. The details concerning the test rig as well as the method of determining the abrasive wear and the object of the tests are presented in [19].

In this study, the parameter $\delta_{i,N}$ was adopted as the main measure of wear. This parameter determines the measured difference (before and after the wear test) in the position of the i-th point of the route of the measuring head of the N-th tooth of the chain drum. The wear of a single measuring point $\delta_{i,N}$ is determined by equation (1):

$$\boldsymbol{\delta_{i,N}} = \sqrt{\left(\boldsymbol{x_{1\_i,N}} - \boldsymbol{x_{2\_i,N}}\right)^2 + \left(\boldsymbol{y_{1\_i,N}} - \boldsymbol{y_{2\_i,N}}\right)^2 + \left(\boldsymbol{z_{1\_i,N}} - \boldsymbol{z_{2\_i,N}}\right)^2} \tag{1}$$

where $x_{1\_i,N}$ is x coordinate of the i-th point of N-th teeth before the test, $x_{2\_i,N}$ is x coordinate of the i-th point of N-th teeth after the test, $y_{1\_i,N}$ is y coordinate of the i-th point of N-th teeth before the test, $y_{2\_i,N}$ is y coordinate of the i-th point of N-th teeth after the test, $z_{1\_i,N}$ is z coordinate of the i-th point of N-th teeth before the test, $z_{2\_i,N}$ is z coordinate of the i-th point of N-th teeth after the test, N is number of measured teeth.

On the basis of the value of wear of the i-th point of the measuring route $\delta_{i,N}$ determined for each N-th tooth, the values δ_{i_AVG} averaged in relation to all the measures of tooth surfaces of a given chain wheel were determined with the use of the following relationship:

$$\delta_{\mathrm{i\_AVG}} = \frac{\sum_1^n \delta_{\mathrm{i,N}}}{n} \tag{2}$$

where n is the number of seat surfaces of a given chain wheel (n = 24).

Using the determined values of the wear parameter $\delta_{i,N}$, a single-figure indicator of the maximum wear δ_{MAX} was determined using the following dependence:

$$\delta_{\mathrm{MAX}} = \frac{\sum_1^n \mathrm{Max}\{\delta_{\mathrm{i,N}}\}}{n} \tag{3}$$

During each of the test cycles, factors that intensify the destructive processes were applied. Quartz sand was added to intensify the abrasive wear (Variant 1), steel beaters were used to generate an additional dynamic load (Variant 2) and water (Variant 3) and technical salt (Variant 4) were added to accelerate corrosion processes. Table 4 summarises the factors inducing destructive processes for individual test cycles, whereas Fig. 6 illustrates the methods of generating individual variants of destructive processes on the test rig.

Table 4

Variants of combinations of destructive processes

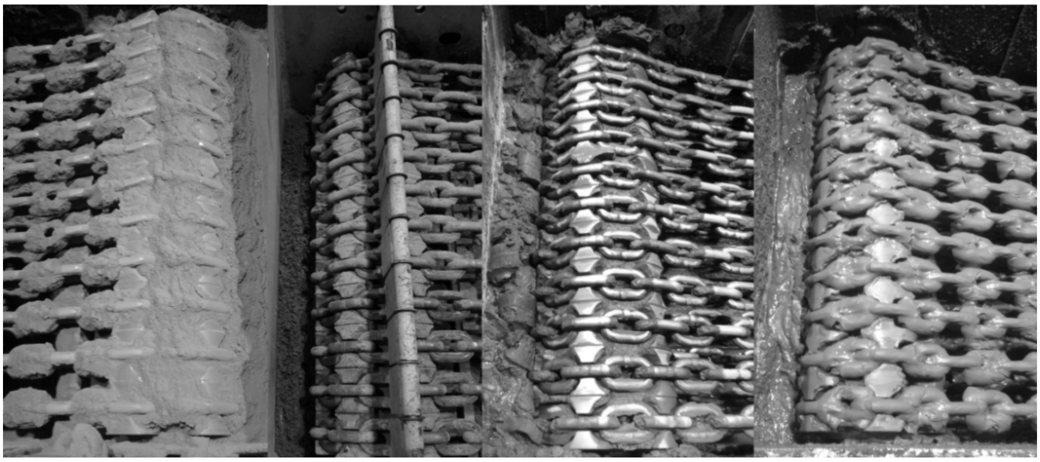
No. of the test variant	Factors accelerating the destructive processes	Simulated destructive processes
Variant 1	dry abrasive (quartz sand)	Abrasive wear
Variant 2	dry abrasive (quartz sand) and an external dynamic load	Abrasive wear and the action of dynamic forces
Variant 3	dry abrasive (quartz sand) and water	Abrasive wear and surface corrosion processes
Variant 4	dry abrasive (quartz sand), water and salt (1% NaCl)	Abrasive wear and intensified surface corrosion processes

4. TEST RESULTS AND DISCUSSION

After the completion of the wear tests, the test wheels were subjected to measurements in the area of wear using a coordinate measuring machine in order to determine the measure of abrasive wear.

On the basis of the measurements performed, courses of the parameter $\delta_{i,N}$ were determined along the measurement path for all five variants of the operation (Fig. 7–10). In addition, a single-figure indicator δ_{MAX} characterising the abrasive wear of the test chain drums was determined. Table 5 presents the values of the measure of abrasive wear δ_{MAX} of the chain wheels tested for different variants of predominating destructive processes. Figure 11 shows values of the relative difference in the wear of chain wheels made of L35GSM cast steel and ADI.

The indicator δ_{MAX} favours maximum values of the abrasive wear, whereas the parameter $\delta_{i,N}$ averages the values determined for all areas of mating. A different manner of determining both indicators implies that they are independent of each other and take different, incomparable values. The indicator δ_{MAX} was adopted as it is reliable for assessing the wear, whereas plots of the parameter $\delta_{i,N}$ constitute a graphical illustration of the wear area of the chain drums and the chain.



A B C D

Fig. 6. A view of the test rig during the wear tests for variants of destructive processes: A – Variant 1, B – Variant 2, C – Variant 3, D – Variant 4

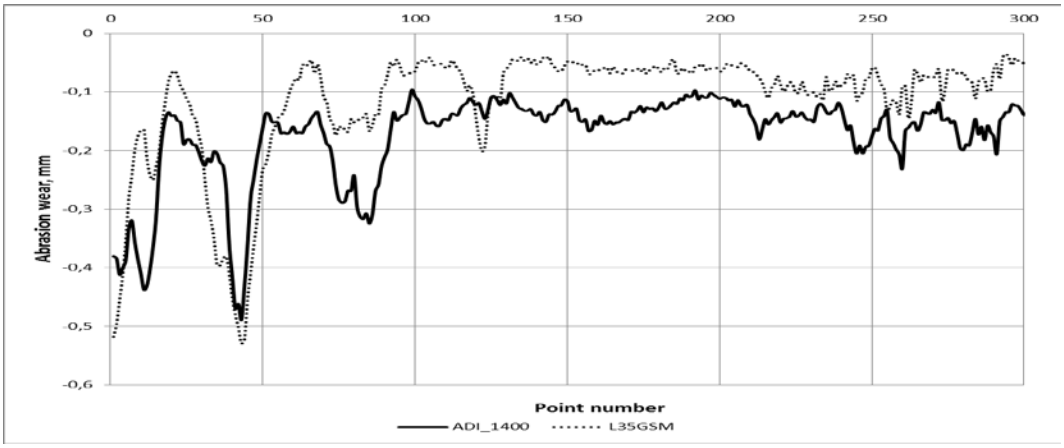


Fig. 7. Graphs of the parameter $\delta_{i,N}$ along the measurement route designated for Variant 1 of combinations of destructive processes

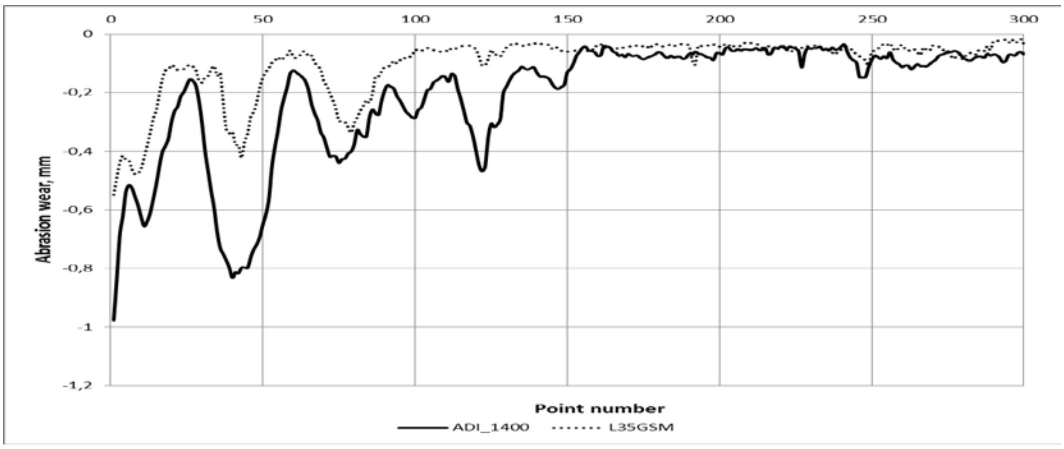


Fig. 8. Graphs of the parameter $\delta_{i,N}$ along the measurement route designated for Variant II of combinations of destructive processes

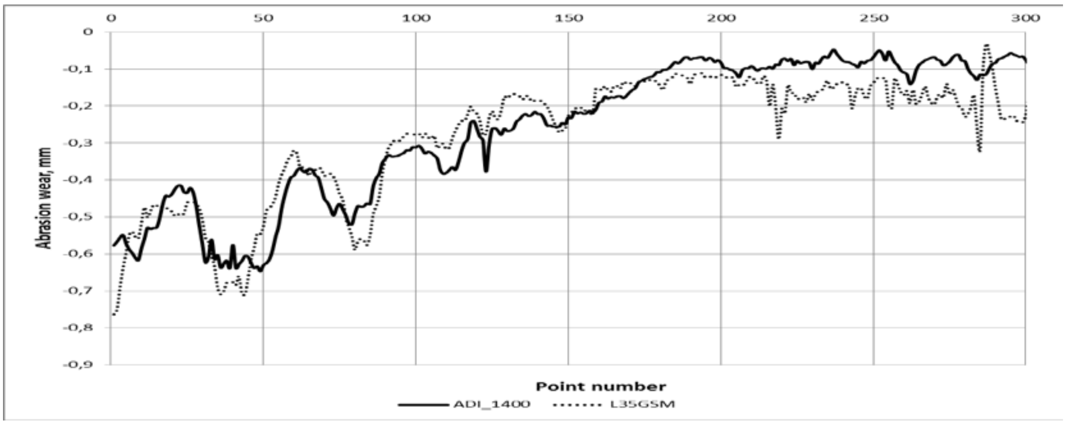


Fig. 9. Graphs of the parameter $\delta_{i,N}$ along the measurement route designated for Variant III of combinations of destructive processes

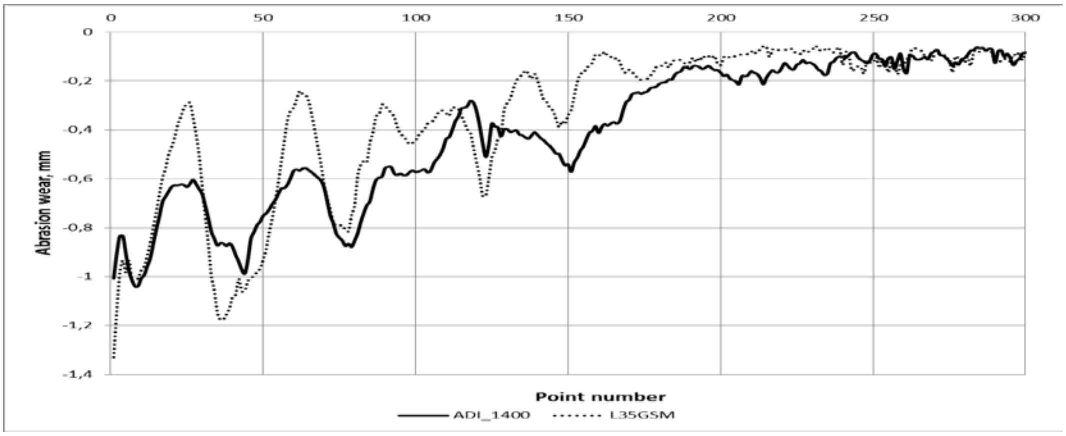


Fig. 10. Graphs of the parameter $\delta_{i,N}$ along the measurement route designated for Variant IV of combinations of destructive processes

Table 5

The wear values δ_{MAX} determined for the variants of combinations of destructive processes

Material	Variant 1	Variant 2	Variant 3	Variant 4
L35GSM	0,809	0,939	1,288	1,194
ADI (EN-GJS-1400-1)	0,707	0,993	0,754	1,056

Figure 7 shows values of the relative difference in the wear of chain wheels made of L35GSM cast steel and ADI.

On the basis of Table 5 and Figures 7, 9, 10 and 11, it can be easily noticed that more favourable wear properties has the ADI with the strength class of 1400 MPa during operation in the quartz abrasive (Variant I), in the presence of the corrosive agent (Variant III) and in the presence of an additional dynamic force (Variant IV). It should be noted that the initial hardness of ADI_1400 cast iron was lower than that of 35GSM cast steel. The reason for the favourable tribological properties of the cast iron tested is the transition of metastable austenite occurring in the microstructure of the ADI cast iron (Fig. 12) into martensite as a result of the action of the load and the abrasive grains. This is clearly proved by the HV 0.1 hardness distribution determined in the area of mating between the chain drum and the chain (Fig. 13). As a result of mating, there occurred a distinct increase in the hardness of the near-surface layer (0–0.2 mm) compared with the hardness of the core (Table 2).

In the case of Variant IV, it has been found that anti-wear properties of ADI_1400 cast iron were worse compared with L35GSM cast steel. This could be caused by a relatively low-impact resistance of this cast iron (Table 2), which led to high-volume chipping in the surface layer. An example of such chipping is shown in Fig. 14. With respect to L35GSM cast steel, the predominating wear process was the process of abrasive wear, but in the area of mating there were noticed deformations zones (Fig. 15) typical for materials with relatively high plastic properties.

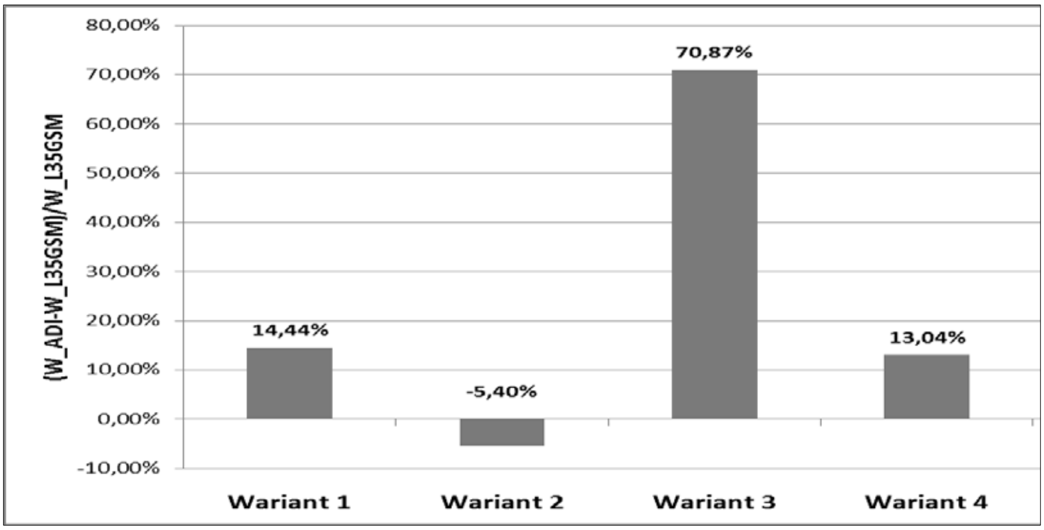


Fig. 11. The relative difference in the wear between ADI_1400 and L35GSM cast steel determined for the variants of destructive processes

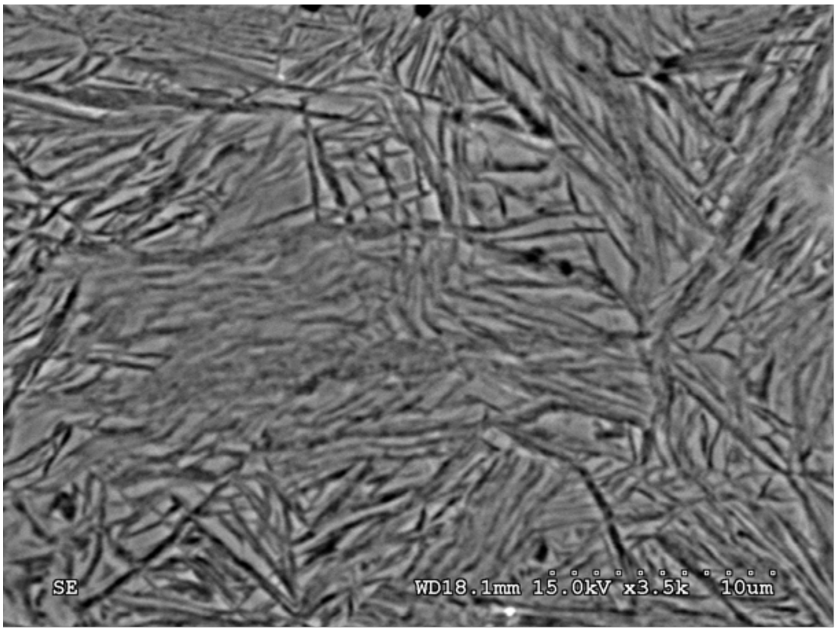


Fig. 12. Microstructure of cast iron ADI_1400 (SEM, magnification x3500)

5. SUMMARY

The main objective of the study was to demonstrate the possibility of replacing the materials of domestic and foreign production currently used for chain drums with alternative materials. ADIs were selected as materials that may replace the cast steels used so far. It turned out that in order to achieve the objective of the study it was necessary to use a new test rig of own design, which allows reproducing the process of the actual operation. L35GSM cast steel commonly used for mining chain wheels and austempered ductile iron conforming to the requirements of EN-GJS-1400-1 quality grade were subjected to wear tests.

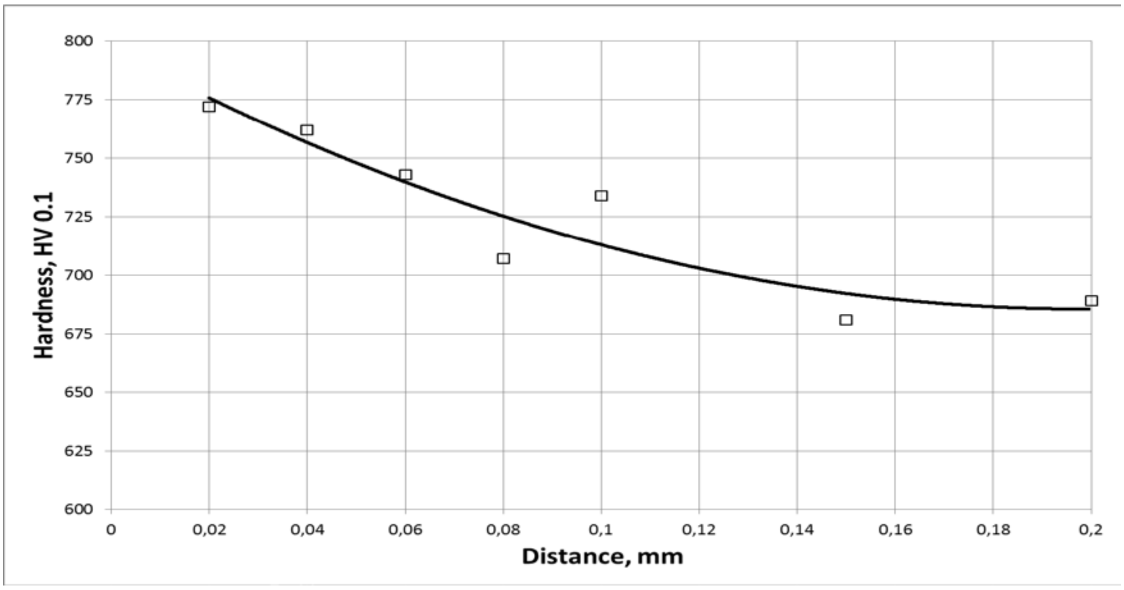


Fig. 13. Hardness HV0.1 of surface ADI_1400

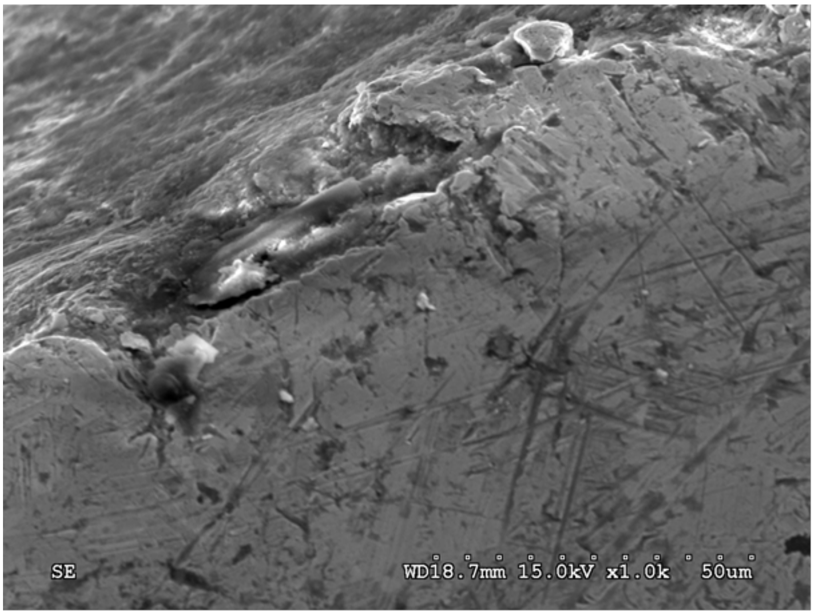


Fig. 14. A view of the surface crushing of cast iron ADI_1400 (SEM, magnification x3500)

On the basis of the experimental studies on the wear properties it has been observed that for almost all the combinations of the destructive factors considered (apart from Variant 2) the ADI in question was characterised by a wear resistance better than that in the case of the L35GSM cast steel used so far. The fact that the ADI's resistance to the abrasive wear in the presence of external forces was lower than that in the case of the cast steel in question can be explained by a reduced impact resistance, which, in turn, determines the fracture toughness.

The results prove that there is a high potential in using austempered ductile irons to make the chain wheels exposed to the combined action of operating factors and that the ADI has favourable features predestining it for the use in the production of such wheels. It should be mentioned that in the case of surface-hardened cast steels, the highest hardness, and, thereby, the expected wear resistance, occurs in the near-surface layer. Along with the progressing wear, the layer with a higher hardness is removed, whereas the surface layer areas with a lower hardness and a lower expected wear resistance are exposed. A critical situation is the wear of the entire hardened layer and the mating between the non-hardened core of the material and the chain, which results in an intensive surface destruction process. In the case of ADIs, a different situation is expected. They are also subject to wear, but under a load, a thin layer of martensite, formed as a result of the transition from austenite, is restored, which causes ADIs to maintain their high tribological properties in the entire cross-section. The TRIP process occurring in ADIs predestines them for operation in conditions with heavy loads and the action of an abrasive. However, it is necessary to optimise further the chemical composition and the process conditions in order to ensure better plastic properties of austempered ductile irons for the production of chain drums. The first thing that should be considered is increasing the amount of austenite in the microstructure, which may increase the impact resistance of this material at the cost of its strength properties. It is also necessary to carry out strength analyses to confirm the possibility of using the proposed cast irons in construction of chain drums.

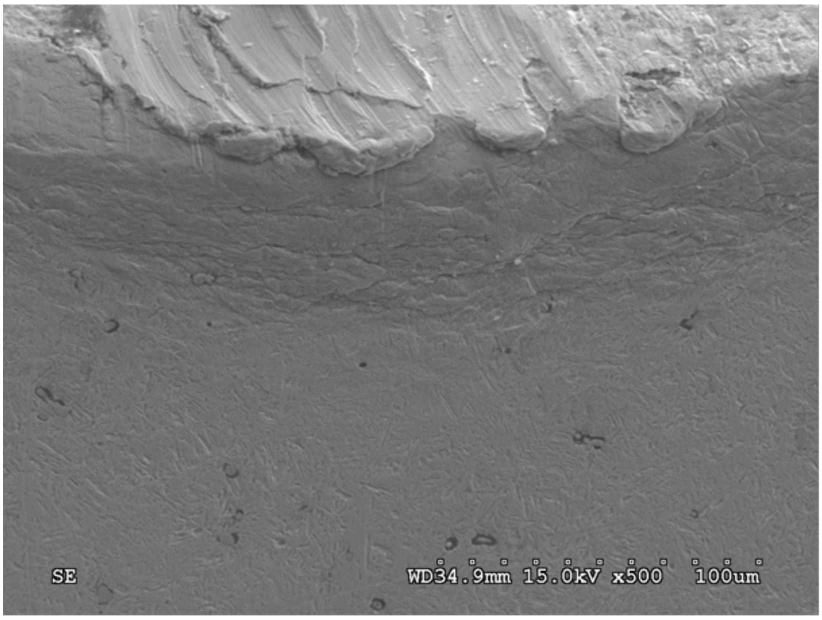


Fig. 15. A view of the deformation zone of the surface of cast steel L35GSM (SEM, magnification x1000)

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References

1. Dolipski, M. & Giza, T. & Mikuła, S. & et al. Eksploatacyjne uszkodzenia bębnów łańcuchowych górniczych przenośników zgrzebłowych. *Bezpieczeństwo Pracy i Ochrona Środowiska w Górnictwie.* 2011. Vol. 12. P. 3-8. [In Polish: Exploitation damaging of chain drums of mining scraper conveyors. *Work Safety and Environmental Protection in Mining*].

2. Burdzik, R. & Folęga, P. & Łazarz, B. & et al. Analysis of the impact of surface layer parameters on wear intensity of frictional couples. *Archives of Metallurgy and Materials*. 2012. Vol. 57. No. 4. P. 987-993.
3. Suchoń, J. *Górnicze przenośniki zgrzebłowe. Budowa i zastosowanie*. Gliwice: Instytut Techniki Górniczej KOMAG. 2012. 331 p. [In Polish: *Mining scraper conveyors. The construction and use*. Gliwice: Institute of Mining KOMAG].
4. Wieczorek, A.N. Analysis of the possibility of integrating a mining right-angle planetary gearbox with technical diagnostics systems. *Scientific Journal of Silesian University of Technology. Series Transport*. 2016. Vol. 93. P. 149-163. DOI: https://doi.org/10.20858/sjsutst.2016.93.16.
5. Czech, P. Identification of Leakages in the Inlet System of an Internal Combustion Engine with the Use of Wigner-Ville Transform and RBF Neural Networks. In: *Telematics in the Transport Environment. Book Series: Communications in Computer and Information Science*. 12th International Conference on Transport Systems Telematics. Springer. 2012. Vol. 329. P. 414-422.
6. Madej, H. & Czech, P. Discrete wavelet transform and probabilistic neural network in IC engine fault diagnosis. *Eksploatacja i Niezawodność - Maintenance and Reliability*. 2010. No. 4. P. 47-54.
7. Wieczorek, A.N. Możliwości zastosowania nowych materiałów na bębny łańcuchowe górniczych przenośników zgrzebłowych o zwiększonej odporności na zużycie. *Tribologia*. 2013. No. 1. P. 135-148. [In Polish: Potential use of new materials on the drums chain of mining scraper conveyors with increased wear resistance].
8. Hayrynen, K.L. & Keough, J.R. Wear Properties of Austempered Ductile Cast Irons. *AFS Transactions*. 2005. Vol. 187. P. 1-10.
9. Hayrynen, K.L. & Keough, J.R. & Pioszak, G. L. Designing with Austempered Ductile Iron. *AFS Transactions*. 2010. P. 1-15.
10. Grech, M. & Young, J.M. Impact properties of a Cu-Ni Austempered Ductile Iron. *Cast Metals*. 1987. Vol. 8. P. 98-103.
11. Ahmadabadi Nili, M. & Ghasemi, H.M. & Osia, M. Effect of successive austempering on the tribological behaviour of ductile iron. *Wear*. 1999. Vol. 231. P. 293-300.
12. Ahmadabadi, Nili, M. & Nategh, S. & Davami P. Wear behaviour of austempered ductile iron. *Cast Metals.* 1992. Vol. 4. P. 188-193.
13. Boutorabi, S.M.A. & Young, J.M. & Kondic, V. The tribological behavior of austempered spheroidal graphite aluminium cast iron. 1993. *Wear.* Vol. 175. P. 19-24.
14. Fordyce, E.P. & Allen, C. The dry sliding wear behaviour of an austempered spheroidal cast iron, *Wear*. 1990. Vol. 135. P. 265–278.
15. Schissler, J.M. & Brenot, P. & Chobaut, J.P. Abrasive Wear Resistance of Austempered Ductile Iron at Room Temperature. *Mater. Sci. Tech.* 1987. Vol. 5. P. 71–77.
16. Owhadi, A. & Hedjazi, J. & Davami, P. Wear Behavior of 1.5Mn Austempered Ductile Iron, *Mater. Sci. Tech*. 1998. Vol. 14. P. 245-250.
17. Haseeb, A.S.M.A. & Aminul Islam Md., Tribological Behavior of Quenched and Tempered, and Austempered Ductile Iron at the Same Hardness Level. 2000. *Wear*. Vol. 244. P. 15-19.
18. Prasanna, N.D. & Muralidhara, M.K. Studies of Wear Resistance of Austempered Ductile Iron (ADI) Using Wet Grinding Type of Wear Test, Proc. *World Conference on ADI*. 1991. P. 456-467.
19. Wieczorek, A.N. & Polis, W. Operation-oriented method for testing the abrasive wear of mining chain wheels in the conditions of the combined action of destructive factors. *Management Systems in Production Engineering*. 2015. Vol. 19. P. 175-178.

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