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OPPORTUNITIES TO IMPROVE THE EFFICIENCY OF THE "GWAREK 1200" BELT CONVEYOR

Summary. The article presents the results of research of the Gwarek 1200 belt conveyor. The work aimed to determine the possible benefits of changing the type of rollers used. It was expected that the change of the rollers from N-type to C-type will reduce the costs of energy consumed by the conveyor drive system. This part of the research was carried out in a hard coalmine at the level of 665 m. The test was given the entire power unit in terms of the starting power demand and rated power in real time. Measurement works were carried out before and after the modernization of the conveyor for 5 years. Moreover, it was decided to extend the research to include vibroacoustic tests, aimed at determining the technical condition by measuring vibrations. It is expected that based on the analysis of vibration signals in the long term will allow to develop a method for diagnosing belt conveyor rollers and to quickly detect their malfunction under normal operating conditions.

1. INTRODUCTION

The belt conveyors are basic transport devices for the mining industry. The belt conveyor system of transportation is also used in many other industries, e.g. in mineral raw material treatment plants, a smelting industry, a cement industry, a paper-making industry, a building industry, and agriculture factories. An example of using a belt conveyor of a coalmine is shown in Fig. 1.

Fig. 1. An example of using a belt conveyor of a coalmine

The range of applications and differentiation resulting from the shape of mining activity requires a design and production of belt conveyor components with the highest care. The breaks or limitations in

the transported stream mass affected by individual elements of a belt conveyor simply lower the effectiveness of the whole technological system. Thus, already at the project stage of belt conveyors, optimization attempts are taken oriented, first, to reduce energy consumption [1]. It is achieved by lowering the main resistance of the belt conveyor. The savings of energy consumption may be expected in a sensible selection of rollers. Moreover, the influence of many construction parameters of the belt conveyor on the operation cost in a coalmine is very important. For example, elements of drive systems of the belt conveyor.

Numerous guidelines for designing belt conveyors can be found in the literature, e.g. in the works of Anath et al and Golka et al. [2, 3]. Some of them present the problem as a whole [2], taking belt speed, belt width, power absorber, gearbox, and drive roller shaft as design parameters. The paper also presents calculations of power consumed and simulated engine power.

The topic of energy efficiency of belt conveyors in underground and open-pit mining is discussed, among others, in the publication by Antoniak, J [4]. However, it is not a new topic in the world literature owing to the significance and importance of the problem, as it has been discussed in different terms for several decades.

In Wheeler et al [5] is present a combination of theoretical models and results of measurements to assist in the design of energy-efficient belt conveyors. Several theoretical models to predict the main resistances of belt conveyors have been discussed in the article with reference to standards. In the work by Lu [6], a developed two-dimensional model for rolling resistance is presented, which was then verified and used to determine the effect of various factors on rolling resistance. The indentation rolling resistance of spherically profiled rollers is presented in turn in the paper by Qui [7]. Different mathematical analytic models of indentation rolling resistance present in the work by Robinson and Wheeler [8].

The influence of the belt material on the energy efficiency of the conveyor operation is analyzed by the works of Bajda et al and Lodewijks [9, 10]. It was found that the application of aramid materials in a conveyor belt in conjunction with the application of a natural rubber/butadiene rubber drastically reduces the energy consumption of a belt conveyor. Discussion about ways to increase conveyor system capacity by using low rolling resistance roller cover rubber on conveyor belting is presented in the work by Steven [11].

Numerous works on belt conveyors concern the basis for selecting proper belt conveyor roller designs optimized for specific strength and operational criteria [12]. Preliminary concepts and results of energy efficiency labeling of conveyor belts and proposals for energy efficiency labels for conveyors operating in large transport systems are, in turn, the subject of the work by Kawalec and Woźniak [13]. The influence of the radial load of a roller on its resistance to rotation and a comparative evaluation of the quality of the rollers used in an underground mine, based on the results of research on the resistance to rotation under load, is presented in the article by Król and Kisielewski [14].

The research carried out in the Faculty of Transport and Aviation Engineering allowed to identify the effect of the construction of the rollers on energy consumption [15, 16]. In total movement resistance, for horizontal belt conveyors, the resistance of rolling on rollers placed belt conveyor route has the biggest contribution (ca. 50-60% of main resistance) [17].

Belt conveyors are the most common transportation systems used in underground mining. They efficiently and reliably transport materials over great distances. Despite their numerous advantages, belt conveyors use large amounts of electric energy to operating. In the case of an underground mine in which the belt conveyor is used for transportation, the energy consumption of conveyors accounts for approximately 20% of the total operating costs in the mine. At a time when companies strive to improve their economic efficiency and when global policies are implemented to reduce energy use and the resulting CO_2 emissions, numerous research centers have focused their efforts on reducing the energy consumption of the belt conveyors. One of the methods to reduce the energy consumption of the belt conveyor transportation systems is to decrease the belt conveyor resistance to motion.

Belt conveyor systems are widely used for continuous transport of dry bulk materials (i.e. coal and iron ore) over varying distances. However, the random failure of numerous rollers is of major concern

for conveyor operators. Failed rollers not only significantly increase energy consumption but may damage conveyor belts seriously. This consequently adds up downtime and maintenance costs for belt conveyor systems.

Rollers' failures can be divided into three phases: incipient failure, final failure, and catastrophic failure. The malfunction of inner bearings is the most common failure mode for rollers. The incipient failure phase refers to spalling on bearings reaching 6.25 mm^2 based on the research by Hager and Geesmann [18], define the final failure phase of rollers as the loss of suitability for further operation.

The catastrophic failure phase refers to seriously failed rolls that cannot operate properly and will cause high damage to conveyor belts. Up to date, rollers are still a challenge to be monitored efficiently owing to their large quantity and spatial distribution. The industry traditionally counts on person inspection to detect faulty rolls, which are labor intensive, inefficient, and costly. Recently, sensors have been introduced into roller inspection but are reported in a very limited number of publications. SKF has developed a roller sound monitoring kit to assist conveyor inspectors to spot roller that generates abnormal sound [19]. However, the representation of the technical condition of rollers by using the sound monitoring kit has not been reported. A fire detector was developed to monitor the temperature of rollers.

Based on the length of the conveyor, the kind of transported material, etc., several rollers can differ significantly, and the cost of their replacement can make up the different parts in the value of the whole conveyor. Whereas from several rollers depend on the losses of energy on rolling motion of the belt on the jacket of rollers , and the friction of the belt with the jacket of rollers for overcome turn resistances of rollers.

Based on the aforementioned, the aim of the presented study was a verification of the possibility of determining the technical state of rollers with the use of vibroacoustic methods. Authors make an assumption that the comparison of analyses results of vibration signals for new and wear rollers, after a specified time of exploitation, allows determining of limit levels of vibroacoustic phenomena, which exceeding qualify rollers to replacement.

For that purpose, on the presented stage of studies, the measurements of the jacket's vibrations of roller installed on the laboratory stand were conducted. Presented analyses had aimed at the creation of the basis of database symptoms of rollers' technical state.

Guidelines of evaluation of technical state of rollers can prevent the exchange of rollers whose condition allows further exploitation, as well be a basis for a possible replacement of worn rollers, which, according to the current evaluation criteria for such an exchange is not yet eligible. The development of a method of relatively easy diagnostics of cruisers during their operation should contribute to improving the energy consumption of the conveyor. The topic of belt conveyor diagnostics is extensively presented in the paper by Bartelmus [20].

2. RESEARCH OBJECT

The measurements of energy consumption were made on the supply energy of the belt conveyor Gwarek 1200-type. The coal was transported from the excavation to the mine shaft "Karol" at the level of 665 m. The research measurement was carried out in the CZU-10 Tr1 IT3Sb 400/6/1 transformer station. The conveyor drive comprises two electric motors with 90 kW power and rotational speed of 1477 rpm each. Network parameters are 1000 V, 50 Hz. The electrical diagram of the analyzed belt conveyor is shown in Fig. 2.

Parameters of the research object are listed in table 1. The distance between the rollers was 1.5 m. The rollers applied have a diameter of ϕ133 mm.

In the construction of the belt conveyor are used rollers with C4 class of seal in bearings as well as the labyrinth seal U4Exp 62/65 with cover 2LU4. In the rollers are applied bearings 6305ETN9/C4, with polyamide basket strengthened with glass fiber [19]. The construction of the roller is shown in Fig. 3.
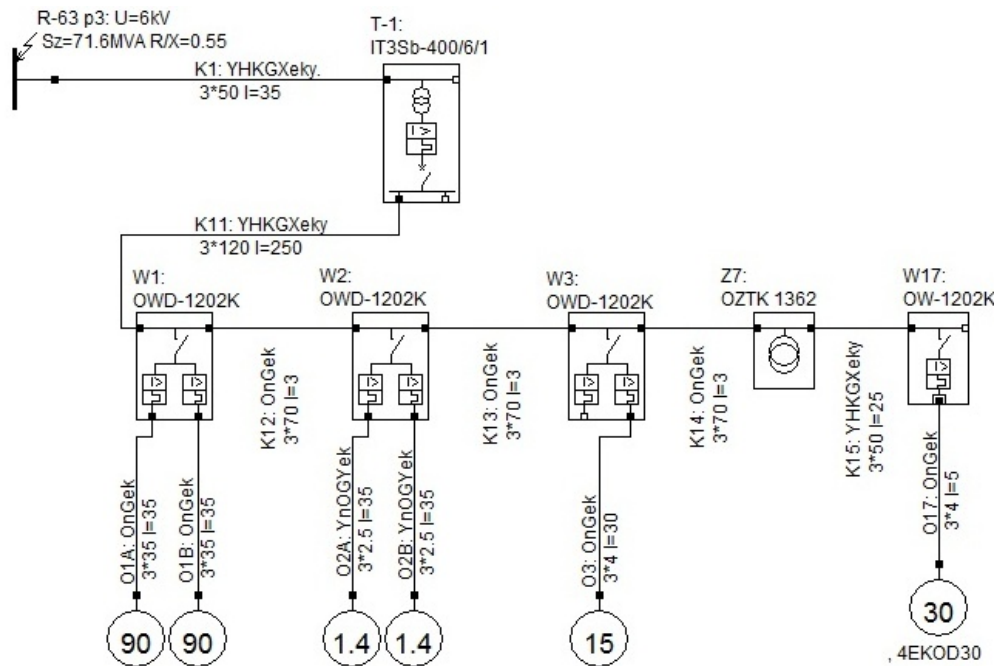
Fig. 2. Electrical diagram of the belt conveyor Gwarek 1200-type: two engines of 90kW, two brake-release units 1.4kW each, one idle engine 15kW, 30kW starter motor with *4EKOD30* soft start driver, *K1: YHKGXeky 3 * 50 I = 35* - power mining cable with 3 working conductors, 50mm^2 cross-section, individually shielded in PVC sheath with a copper tape top shield, flame retardant, *T-1: IT3Sb-400/6/1* - flame-proof transformer station, *W1: OWD-1202K* - mine switch, flame-proof, vacuum contactor switch, *O1A/B: OnGek 3 * 35 I = 35* - mine shielded sheathed power cable with copper cores, with ordinary insulating rubber insulation and rubber tire with improved mechanical properties and oil-resistant rubber, resistant to oxygen aging, and flame retardant, *O2A/B: YnOGYek 3 * 2.5 I = 35* - shielded mining cable with PVC insulation and sheath, *Z7: OZTK-1362* - OZTK type fireproof transformer assemblies

Table 1

Technical characteristics of the belt conveyor

Parameter	Value	Unit
Length of conveyor	~ 140	m
Average angle of inclination	9	o
Maximum efficiency of conveyor	1200	t/h
2-speed gear ratio	i_1=25.68 and i_2=46.96	-
Linear speed of the belt	v_1=3.15 and v_2=1.6	m/s
Power	P=2x90	kW
Tape width	B=1200	mm

The tests were carried out on new C-type rollers (Fig. 3) and C-type rollers disassembled from the conveyor belt operating in the mine and show visible signs of wear. Fig. 4 shows the condition of rollers delivered for testing after 3 years of operation on the conveyor in coalmine KWK Mysłowice-Wesoła. One of the rollers has clearly visible signs of shell surface wear.

With attention on the number of rollers, assurance of proper their technical state can contribute to lower consumption of necessary energy to drive the belt conveyor. The remaining rollers were installed successively on a laboratory stand, where, apart from the aforementioned tests, attempts were also made to determine static and dynamic rotational resistances. The tests were carried out according to the guidelines included in the PN-M-46606:2010 standard. However, this standard does not provide

for roller tests after a longer period of operation and does not specify the time after which the next test of roller technical condition should take place [21].
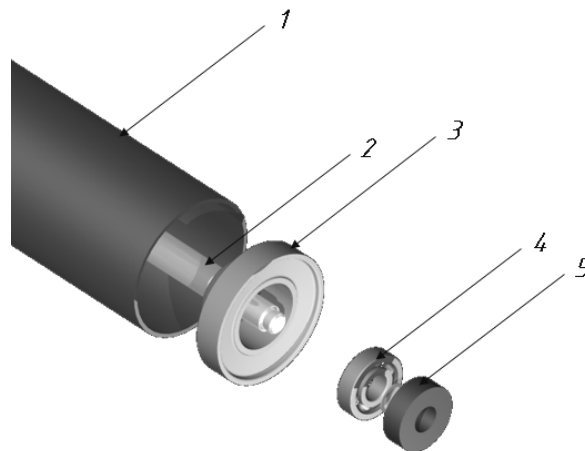

Fig. 3. The construction of belt roller: 1 – jacket, 2 – axle, 3 – cast iron hub, 4 – bearing, 5 – labyrinth seal

Fig. 4. Examined rollers with clearly visible marks of wear of jacket surface

According to the PN-M-46606:2010 standard, rollers are classified according to the working conditions in which they work. These include light work (marked with L-type), standard work (marked with N-type), and hard work (designated with C-type). These terms and conditions of work that divide rollers are specified in detail.

A light L-type roller is designed for conveyors for light conditions of work, at low intensity of work, and with low load. The bearings applied are 6204 2RS or 2Z. The bearing has one outside seal.

An N-type roller is designed for medium-duty conveyors, with the belt working in the medium of dust air conditions of work. A roller has a hub crowded-welded type bearing 6305 2RS or 2Z sealed from the outside with one seal. A roller of medium type is built similarly to an L-type roller. The only difference is the use of bearings with higher load capacity and labyrinth seals.

A heavy C-type roller is designed for heavy-duty conveyors working in very dusty conditions and load; these are the conditions that occur in coalmines. The roller has a hub cast-iron bearing type 6305 RS or Z. The bearing is sealed from the outside with three seals, labyrinth seals with a beater, or a special seal for heavy rollers.

3. PROCEDURE FOR THE ASSESSMENT OF THE TECHNICAL CONDITION OF A CONVEYOR BELT ROLLER

The sealing observations carried out show that all the seals fulfilled their function and secured the bearing from pollution coming from the atmosphere in which they worked. This is evidenced by the appearance of the lubricant in the bearing space (Fig. 5).

The lubricant after three years of work did not change its color and had the consistency of the lubricant placed at the time of the production of the roller. Lubricant also did not show signs of external pollution to the extent that it hindered work in the bearing node.
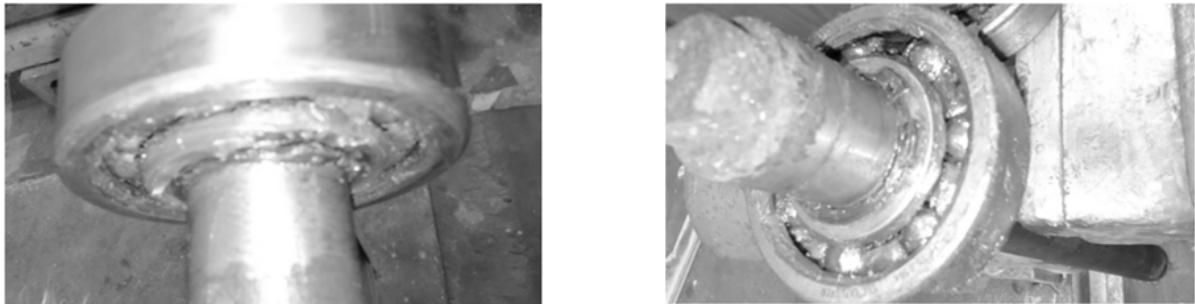
Fig. 5. The condition of the lubricant in the bearing space of the test rollers

The condition of the bearings directly affects the rolling resistance of the rollers. Diagnosing the technical condition of bearings is therefore justified and is the subject of numerous studies presented in the literature. In workshop practice, various methods of verifying the technical condition of bearings can be found, but some of them are subjective.

A symptom of bearing damage may also be excessive temperature increase. In its detection, you can use various probes for measuring temperature, including those that measure at a distance. Correctly mounted bearings do not exceed 70ºC in the vast majority of cases, and they emit a low and regular sound.

By analyzing vibroacoustic signals, in many situations it becomes possible to determine the type of bearing damage. This is especially the case for bearings mounted in simpler technical facilities. To obtain vibroacoustic signals, one can use, among others vibration acceleration transducers and / or laser vibrometers. Using transducers, vibration acceleration is measured. Vibrometers allow the measurement of vibration speed; in addition, using laser technology, non-contact measurement is also possible on the surface of rotating parts. However, they require much more expensive research equipment.

To assess the technical condition of bearings, due to the operating conditions of the conveyor, especially the noise accompanying its operation, as well as the adopted assumption that ultimately the determination of the condition of the rollers is to take place during their normal operation, it was assumed that a diagnostic test will be conducted solely based on the analysis of vibration signals. In many cases, the vibration signal is considered to be much more useful than an acoustic signal; the assumption is also a consequence of the inability to completely isolate the acoustic signal generated by the roller, especially by its bearings, from other sources of noise in the conditions of real operation of the conveyor. Basing research on a more modern bearing diagnosis method, which uses diagnostic devices to record the condition, recording residual processes resulting from the rotational movement of the roller allows eliminating the subjective nature of the assessment.

During studies were measured accelerations of vibration of rollers' jackets in two points as shown in Fig. 6. The research aimed to obtain information on the effects of vibration caused by rolling bearings mounted in the roller. Their condition directly affects resistance during rotations.

For vibration measurement was used accelerometers (ICP standard). Acceleration transducers allow registration of vibrations with frequencies in range 1 Hz to 10 kHz. Accelerometers were

connected to 8–channel data acquisition card EC VibDAQ 8+, which allows to record signals on hard disc of laptop. Card uses 24–bit/105 kHz A/D converters and offers synchronous sampling for all channels. During the study, simultaneous measurements of linear accelerations of jacket on the hub bearing were made. The signals are sampled at a frequency of 31.25 kHz, which is allowed by the Nyquist criterion for the registration of whole range of vibration acceleration measured by sensors.
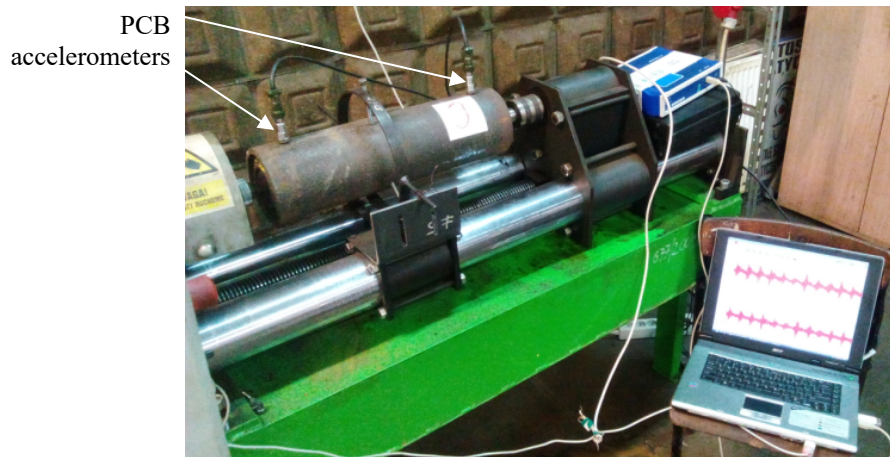

Fig. 6. The test stand with mounted roller and vibration acceleration transducers during measurements of one of the rollers of the belt conveyor

Rolling bearings are diagnosed in many ways. In laboratories is possible a simple method based on the evaluation of sounds generated during operation of the bearing. The testing method uses traditional or electronic stethoscopes. The method of listening is an important drawback – the sense of hearing, and the ability of its perception tends to get used to the processes that occur gradually. Because of that, the method is subjective and does not always allow for the proper diagnosis.

Regardless of used equipment, the organoleptic methods are effective only when a specialized person performs a diagnosis. For the elimination of the subjective character, studies were based on more modern methods of bearings' diagnosis. They use for evaluation diagnostic equipment, which records residual processes resulting from the operation of the machine. In consequence of the impossibility of full isolation of the acoustic signal generated by a roller, in particular by its bearings from other noise sources, in the test, the authors resigned from measurements of this residual process – changes in sound pressure. This results from the conveyor's work environment. It is characterized by too high noise, besides many external interferences from other devices nearby. The study on presented stage of research took place in laboratory environment, with the reverse method of driving the roller. During operation in normal conditions, that is to say in belt conveyor, axle of roller remains stationary while the jacket rotates. During the measurements, jacket was attached in a manner preventing its rotation, while the drive is adjusted to the axle direct from motor rotating at a speed of ~600 rpm.

Owing to the working conditions of the conveyor, especially the noise accompanying its operation, it was assumed that any attempt of diagnose will be carried out only based on vibration signals. In many cases, the vibration signal is considered to be much more useful than the acoustic signal, and the assumption made is also a consequence of the inability to fully isolate the acoustic signal generated by the roller, especially its bearings, from other noise sources under real conveyor operation conditions.

The rollers were mounted on a laboratory test stand which enabled the drive to be brought to the axle, and their shell was fixed with a special clamp. Contrary to the working conditions in the mine, during which the conveyor's axis remains stationary and its jacket rotates, on the test stand, the roller' axis was driven directly by the induction motor of the laboratory stand with a rotational speed of 650 rpm. The method of measurement is shown in Fig. 7.

During the measurements, the following measurements were realized simultaneously:
- acceleration of linear vibrations of the roller shell in places located above the bearing nodes - 2 points, approximately 50 mm from the roller edge; and

- time courses of the marker of the angular position of the roller axis.

Fig. 7. Roller number 15 with visible transducers mounted above the bearing nodes during the measurement of vibration accelerations

According to Bartelmus [20], diagnostics based on the registration of broad-band vibration levels of bearing nodes uses the trend of changes in vibration levels to assess the condition. Increasing the vibration level by more than 10-times leads to a change in the technical condition of the device from good to unacceptable. A sensor directly coupled to the roller axis was used to generate the marker. Vibration accelerations were measured using EC Systems acceleration transducers screwed into specially prepared M6x1 holes on the rollers. Transducers were used to measure vibrations in the range from 0.5 to 10 000 Hz and a resonance frequency of 25 kHz.

4. RESEARCH RESULTS

Power measurement was carried out with the help of Ditch tongs in the voltage box of the supply transformer. Power measurement was carried out during the start of the conveyor without spoil, and after a few seconds, it was flooded from the hopper, to achieve full backfilling at the entire length. The obtained measurement results are shown in Table 2.

The study was conducted for several months every 7 days for 60 minutes. In total, the study was carried out for 1260 minutes during the normal work of the tested belt conveyor. The actual performance of the winning transported was measured by hopper with the possibility of measuring the instantaneous value of the tested conveyor belt performance [8].

The difference in the level of generated vibrations is visible, which is reflected in many measures determined from the signals recorded for each roller. In particular, this applies to a few of all tested rollers; the condition of the others did not cause any significant differentiation compared with the new roller. The best-known methods of determining the technical condition of bearings with the use of vibroacoustic methods include the determination of the values of various measures. These can be RMS value, peak-to-peak value, or dimensionless discriminants. For this reason, after carrying out the measurements for all tested objects, signal analyses were performed using simple amplitude measures. The analyses were carried out on averaged and non-averaged signals subjected to low-pass filtration, following the measuring ranges of the converters, separately for each side (left and right) of the roller. The dimensionless discriminants commonly used in diagnostics include crest factor, waveform factor, clearance factor, and impulsivity factor. The basic information on the changes in the vibration signal caused by the operational wear of rollers delivers RMS value of vibration accelerations. Apart from a few rollers, the level of the RMS value of vibration acceleration is comparable to that of a new roller. The results after start-up and a few minutes of operation are similar.

Changes of the RMS value of vibration accelerations of jacket rollers after nine months of operation $a_{RMS(wear\ roller)}$ related to the values obtained for the new roller $a_{RMS(new\ roller)}$ are presented in Fig. 8a. In Fig. 8b are, however, presented changes of variance values of jacket vibration acceleration

related to the values obtained for the new roller. The results only for 3 rollers in the worst condition of all tested were presented.

<div align="right">Table 2</div>

<div align="center">Average values of the power of the conveyor belt for the analyzed group of rollers</div>

No.	Rollers used in the belt conveyor Gwarek 1200-type	Time of work	Type of conveyor work	Power P [kW]
1.	Conveyor work with N-type rollers	after 12 months of work	Transit work -start	139,3
2.			Working in set motion	102,0
3.	Conveyor work with C-type rollers	3 days after mounting on the conveyor	Transit work -start	129,4
4.			Working in set motion	97,5
5.	Conveyor work with C-type rollers	30 days after installation	Transit work -start	96,7
6.			Working in set motion	94,8
7.	Conveyor work with C-type rollers	10 months after installation	Transit work -start	96,0
8.			Working in set motion	93,7

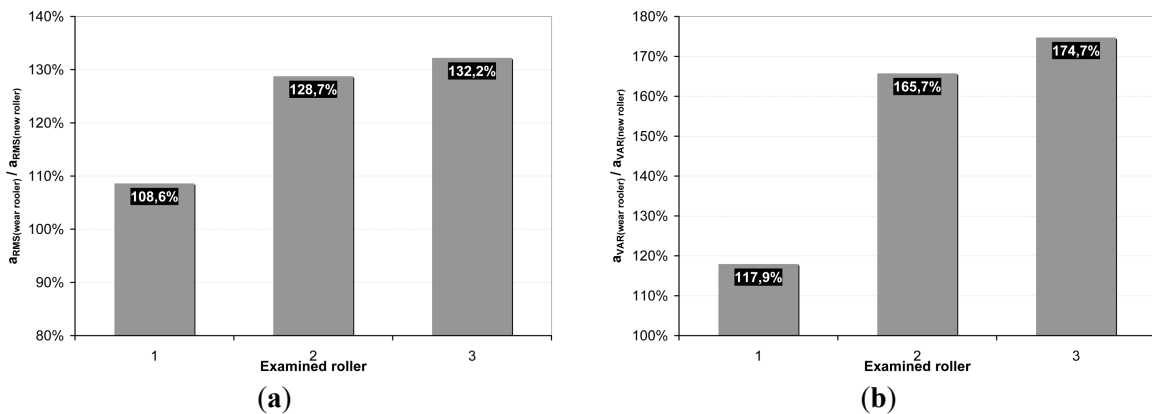<div align="center">(a)   (b)</div>

Fig. 8. Changes of RMS and variance values of vibration acceleration of jacket of all examined rollers in relation to the acceleration measured for a new roller

The largest increase of RMS value of jacket vibration acceleration of used rollers in relation to the new roller (about 32%) was observed for the third examined roller. The smallest difference (about 8%) occurred for the first roller. Approximately 24% difference of values was obtained for the rollers with the same operation time due, inter alia, from a different place of roller installation on the conveyor. Analogous changes were observed for variance and peak-to-peak values. Fig. 9 presents these changes in peak-to-peak values for tested rollers.
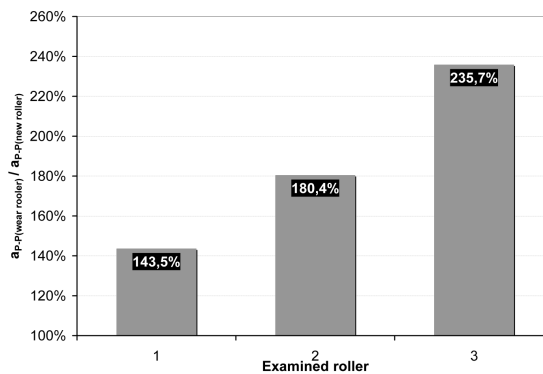

Fig. 9. Changes of peak-to-peak values of vibration acceleration of jacket of all examined rollers in relation to the acceleration measured for a new roller

Figs. 10a to 10d show changes of alues of dimensionless factors: crest factor (C), waveform factor (K), clearance factor (L), and impulsivity factor (I).
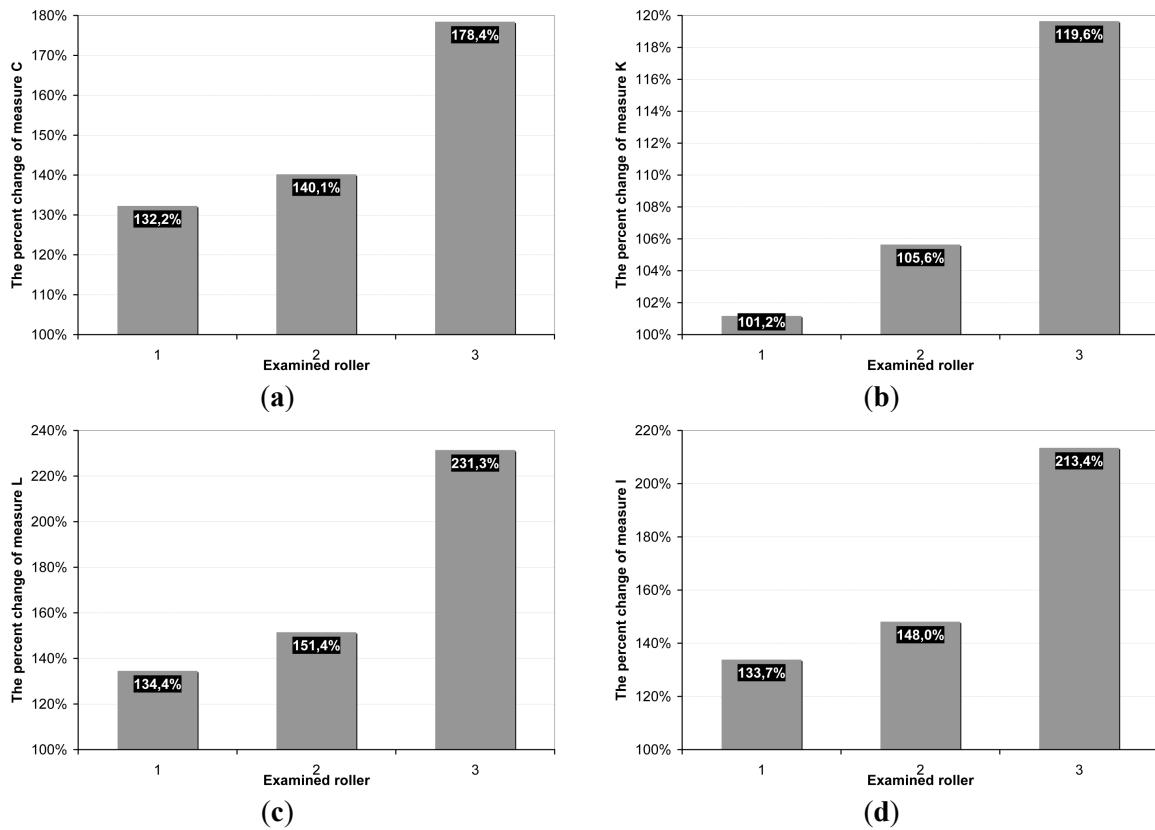
Fig. 10. Changes of dimensionless discriminants values of vibration acceleration of jacket of all examined rollers in relation to the acceleration measured for a new roller

From all dimensionless factors, which are presented, the least sensitivity for wear has a waveform factor (K). For the first of the tested roller, the change amount only to 1.2%. The best results were received for the clearance factor (L) and impulsivity factor (I).

The frequency spectra obtained using the Fourier analysis, presented in Fig. 11, concerns two rollers, one of which was in a new state and the second showed the highest wear among of all the tested units. In the case of the new roller, the most frequency components occurred in the frequency range below 1 kHz. The spectrum of the damaged roller was more broad-band.
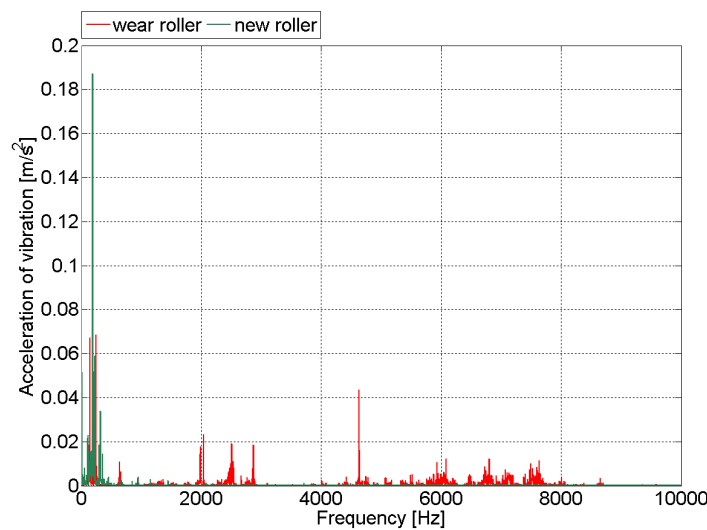

Fig. 11. Frequency spectra obtained for the roller in the worst technical condition from rollers classified for vibroacoustic tests (red) and the new roller (green)

Wear after 9 months of exploitation in mine for each roller caused the appearance in the spectrum of high–amplitude components in the range 6÷8 kHz. This is most evident in the case of a third of the examined belt roller. For the first roller, in the range 2÷3 kHz of the spectrum are also clearly visible frequency components. A significant difference is visible for low frequencies part of the spectrum. For new roller is characteristic component 189 Hz, which has maximal amplitude. For the first used examined roller, maximal amplitudes have components with frequencies 145 Hz and 244 Hz.

5. CONCLUSIONS

Wear caused by exploitation affect visible changes in vibration. Changes are visible both in values of simple measures, like RMS value, and dimensionless factors. Only the waveform factor has too small sensitivity for wear. With the use of these measures, the service of conveyor can detect and control the degree of wear.

A more complete picture of changes in the vibration signal provides time-frequency analysis. From the diagnostic point of view, the most useful frequency ranges for the examined rollers are $2 \div 3$ kHz and $6 \div 8$ kHz, wherein in each examined case the differences were seen. Further studies are aimed at building measures, which are sensitive to wear of rollers' bearings, based on the results of the vibration signal analysis.

Despite obtained results, additional laboratory tests carried out on all used rollers have shown that, despite the significant differences seen in the vibration signal caused by the occurrence of wear, they still have a low static and dynamic resistance to rotation. Small values of resistance were also confirmed by measurements of the energy consumption of the conveyor drive carried out at each stage of the research.

The aforementioned research and analysis shows that the rollers using the C-type power unit declined (for the test conveyor) by 6.6% compared with the N-type rollers.

The determination of the ratio of energy consumption at 100% of the conveyor utilization and its use of the real level of 62.5% of the nominal (assumed by designers) is as follows:

- for N-type rollers, changing the power demand per unit decreased by 9.3%, and
- for C-type rollers, changing the power demand per unit decreased by 15.3%.

It can therefore be concluded that by using C-type rollers, the unit power consumption is reduced by 6%.

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