

Random Deterioration Process of Conveyor Belt Evaluated by Statistical Analysis of Core Failures Detected Along Belt Axis and Elapsed Time

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Abstract. Magnetic diagnostic methods are used for steel cord belt condition evaluation since the beginning of 1970s. Initially they generated an analogue signal for several tens of centimetres of conveyor belts scanned sequentially with one measuring head in several cycles or the whole width of the belt at one time thanks to the installation of many measuring heads across the entire cross section. This did not allow identification of single centimetre failures, but rather an aggregate assessment of the state of quite wide waist. Modern diagnostic devices, thanks to miniaturization, allow up to 200 heads per belt width to identify damage of individual cords. Instead of analogue signals, they generate a zero-one digital signal corresponding to a change in the magnetic field sign, which can illustrate damage on 2D images. This makes it easier to identify the location and size of the damage in the belt image. Statistical analysis of digital signals summed up for consecutive sections along the belt axis allows to present both the source signal and its aggregation for band of a given width to form aggregate measures of belt damage such as the damage density per 1 meter of belt. Observation of changes in these measurements at different times allows on evaluation of its rate of change over time, which can be used to forecast future belt condition and to select the proper moment of preventive belt replacement to another one to avoid emergency downtimes (egg in underground mines) or to recondition of belts (egg. in lignite surface mines). The paper presents the results of investigations of the damage condition of a core of a single belt segment working in one of the copper ore underground mines. Scanning of the belt condition was performed few times at intervals of several months. The paper presents the results of the analysis of the changes in core condition, showing the random character of the damage process along the axis and its change over time.

1. Introduction- a short history of application of magnetic scanners in Poland

In Poland, magnetic methods were used in the diagnostics of steel hoisting ropes in underground hard coal mines [15]. As flat steel-rubber ropes emerged, the measuring heads used in the measurements were adjusted so as the measuring circuit covered their width (up to 40 cm). The similarities in the structure of steel-rubber ropes and conveyor belts encouraged service providers to include conveyor belt inspections within the range of their services. However, due to narrow measuring circuit, the belt loops needed to be scanned several times. Such scanning services were offered in Poland as soon as steel-cord conveyor belts were introduced in underground mining. Even earlier, however, around the year 2000, the KWB “Turów” open-cast lignite mine introduced Dunlop’s EyeQ system designed to scan steel cords in much wider and stronger conveyor belts, which are operated in that mine. The



device was mobile and enabled scanning the belt over its full width (up to 2250 mm), as it was equipped with a measuring head in the form of a narrow bar with sensors providing simultaneous vision from 4 measuring circuits [5]. This system was used to scan belts installed on conveyors, but its main application was to classify belts for regeneration. Belts with excessively damaged core (disassembled from the conveyor after being operated for too long) typically did not lend themselves to repair. Extensive core damage (cut cords and corrosion) negatively affected adhesion between the rubber and the cords and as a result disqualified the belts from further operation, even if regenerated [10, 11]. Without a scanner, such condition was discovered only after the core was exposed or even after the regeneration, during the approval strength tests. Using non-destructive testing helped to avoid the costs related to the above problems, since the belt could be inspected and approved for regeneration immediately after being disassembled from the conveyor or on the premises of the regeneration facility, or even it could be qualified for replacement and regeneration when still operated on the conveyor [4, 14]. The device was successfully used in the mine for over ten years, until its wiring system was damaged. The task of modernizing the device was offered to specialists from the Faculty of Geoengineering, Mining and Geology, Wrocław University of Science and Technology. The examination of the device revealed that the number of sensors in the measuring head was greater than the number of measuring circuits, and signal aggregation resulted from the hardware limitation of analog signal processing. Upgrading the system with modern data acquisition devices dramatically increased its resolution (from 4 up to 9 measuring circuits), and writing a new data processing and interpreting application made the system significantly easier to use. The system has been since used in the mine to inspect the condition of belts installed on conveyors and to verify the quality of splices and repairs [6, 7]. It has also been used to inform decisions to disassemble belt sections for regeneration [3, 13].

The next system developed on the basis of the BeltGuard measuring head manufactured by Beltscan is the DiagBelt system. Its primary advantages include high resolution (the measuring circuit of one sensor is approx. 2.5 cm) and reduced digital signal which indicates magnetic field changes from -1 to +1 and neutral 0. Such mode of record allows the visualization of damage on a plane, as a set of areas of different colour which correspond to magnetic fields (2D image). Grey colour indicates no damage (neutral 0), yellow colour indicates the negative field (-1) and blue colour indicates positive field (+1) (Figure. 1).

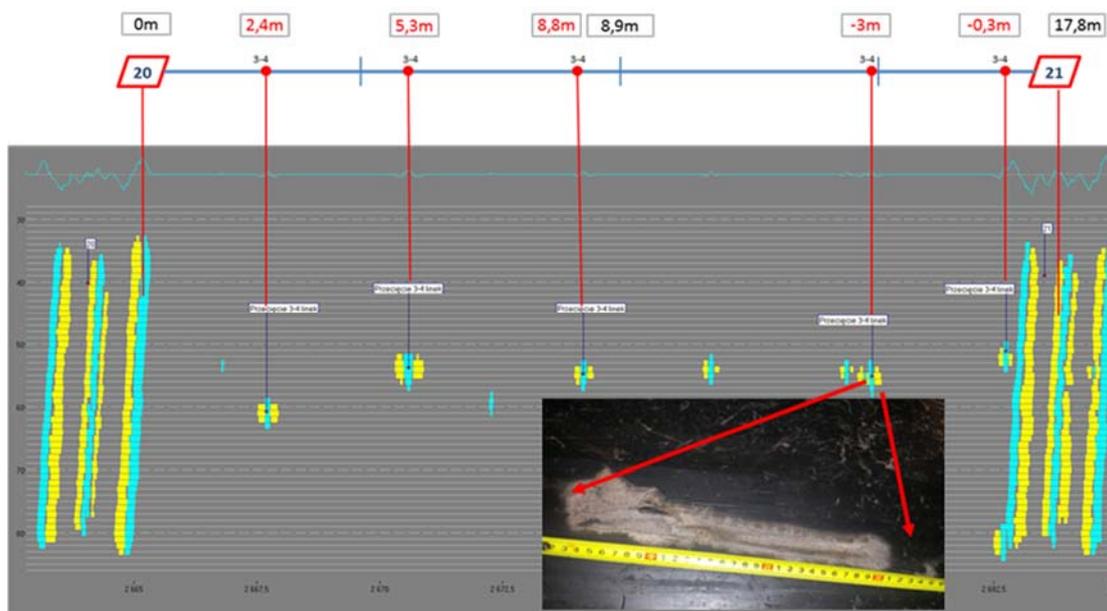


Figure. 1. A view of one of the belt's segments with a real defect indicated (internal record)

The change of magnetic field from negative to positive corresponds to the location where discontinuity in the cord's structure starts, and the change from positive to negative indicates the location where it ends. Therefore, the blue area corresponds to the defective area of the core. Hence, of the compressed digital record (without the neutral zeros which do not indicate any change), only positive cells (+1) can be subjected to statistical analysis, since they represent defects.

The system's high resolution and the possibility to use the system to investigate magnetic field changes on different levels of sensitivity allow a 3 D representation of damage (Figure 2 right side), while their aggregation to 10 cm x 10 cm squares allows a 2.5 D representation, in which the background colour corresponds to mean intensity level of the signal, and the central point is indicated by colours corresponding to maximum values for the area (Figure 2 left side).

The system has sufficient resolution to allow a precise inventory of defects and the representation of aggregated damage level measures, such as for example damage density per running meter and the damage histogram on the belt section for a particular belt fragment or for the complete belt section from splice to splice. Aggregating numerous defects into a synthetic measure is necessary to evaluate the general condition of a belt section, which is coded with colours (Figure 3) enabling the user to instantly evaluate the degree of wear and tear in each of the segments in the loop. Green colour corresponds to no damage and red colour indicates a significant number of defects which may pose a threat to the functioning of a transportation system (Figure. 3).

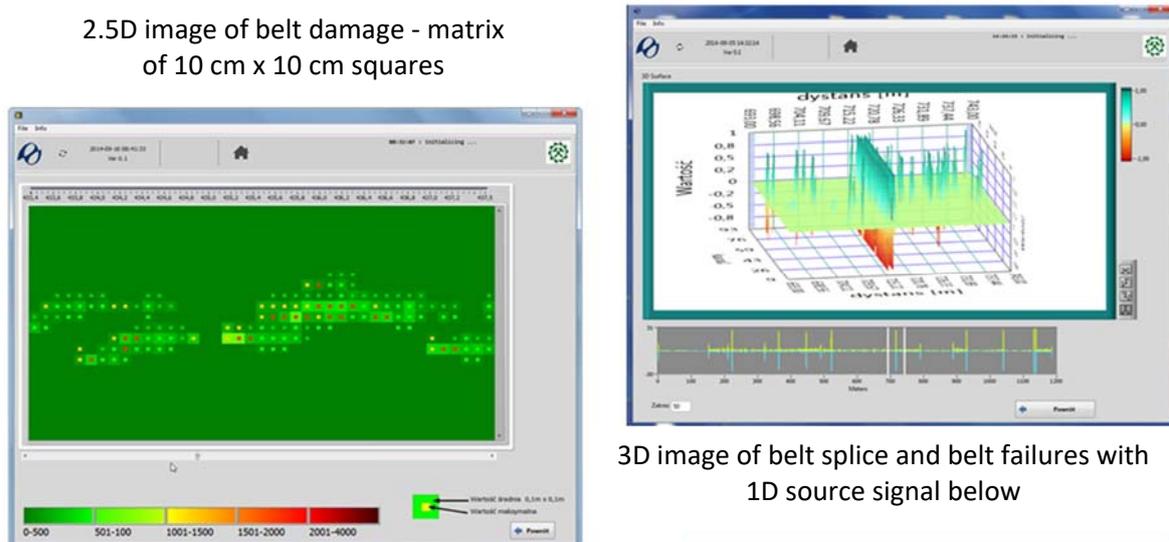


Figure. 2. A view of one of the belt's segments with a real defect [16]

Visual representation of belt sections and their fragments allows the evaluation of the scope of each defect and the identification of locations in need of repair (Figures 1-3). Owing to the system's resolution, the size of each defect can be estimated and tracked over time.

2. Measurements using the Diagbelt diagnostic system in an underground mine

The diagnostics of the loop of steel cord belt operated in a Polish underground copper mine on a conveyor having length of 2200 m performed in order to evaluate the condition of its core provided results which served to demonstrate random belt degradation process and its change over time. The first inspection of belt St 3150 was performed in March 2016, when the belt had been operated in the mine for 55 months. The inspection was repeated after 6 months (in September 2016) and after 9 months (in December 2016) to identify changes. The evaluation covered the technical condition of the core of steel-cord belt used in the transportation of copper ore.

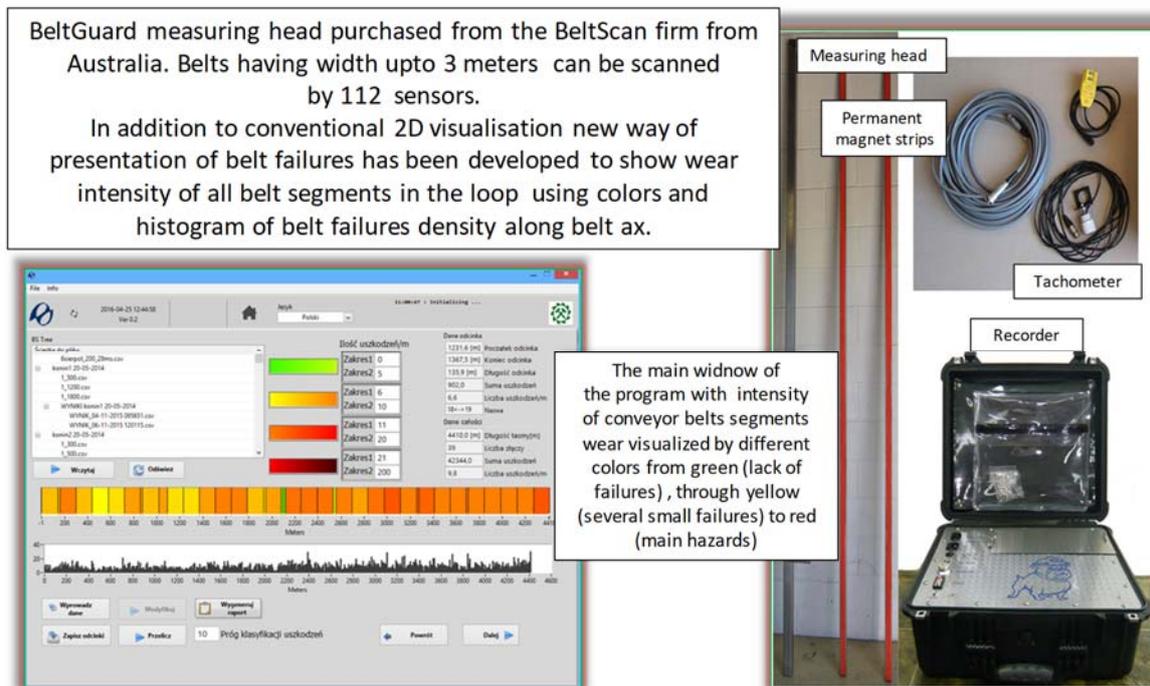


Figure. 3. The view of the magnetic module's main window with a graphic representation of the degree of wear and tear for the segments in the belt loop [16]

The diagnostic system was located in the vicinity of the conveyor's head station, on the belt's flat section. Two magnet heads and a measurement head were installed at a distance of 30 mm above belt cover. For the duration of the complete test, the belt's speed, as measured with a tachometer, was approx. 2.5 m/s. The measurement data were exported to separate .CSV (Comma-separated Values) files to facilitate their further processing and the statistical analysis of defects. The exported digital data regarding the belt's condition and damage were aggregated by calculating the total number of defects per successive running meters of the inspected belt section. Thus, aggregated belt condition measure was obtained – damage density. Damage density can be used as a basis to evaluate the condition of a complete section or of its parts – in this case of successive 1-meter fragments of the inspected section. The analysis covered both the changes in the belt's condition over time as observed during successive inspections and the differences of the belt's condition along its axis.

3. Inspection results of the condition of a belt section over time and along belt axis

The graph in Figure 4 shows the change of damage density over time in successive measurements from March, September and December 2016. Importantly, all cells with the positive magnetic field value of +1 were added. One cell corresponds to the size of one measuring circuit (approx. 2.5 cm) in the section, and therefore the total number of cells in cross sections represents total damage length in a given section rather than an actual number of defects, since these may occur next to each other in the adjacent sensor circuits, suggesting a larger defect and not a number of smaller but separate defects. Therefore, evaluation should be based not only on the basis of damage density statics but also on the basis of the 2D belt condition image. A single but large defect is more severe than many smaller separate defects, especially if it is located on the edge of the belt. This is because such a defect may interrupt the system's continuous operation. The negative influence of defects on belt strength is described with a special factor – safety index, which is calculated as a relative, adaptive measure of the belt section's reduced strength in relation to maximum stress values allowed on a particular belt conveyor [3].

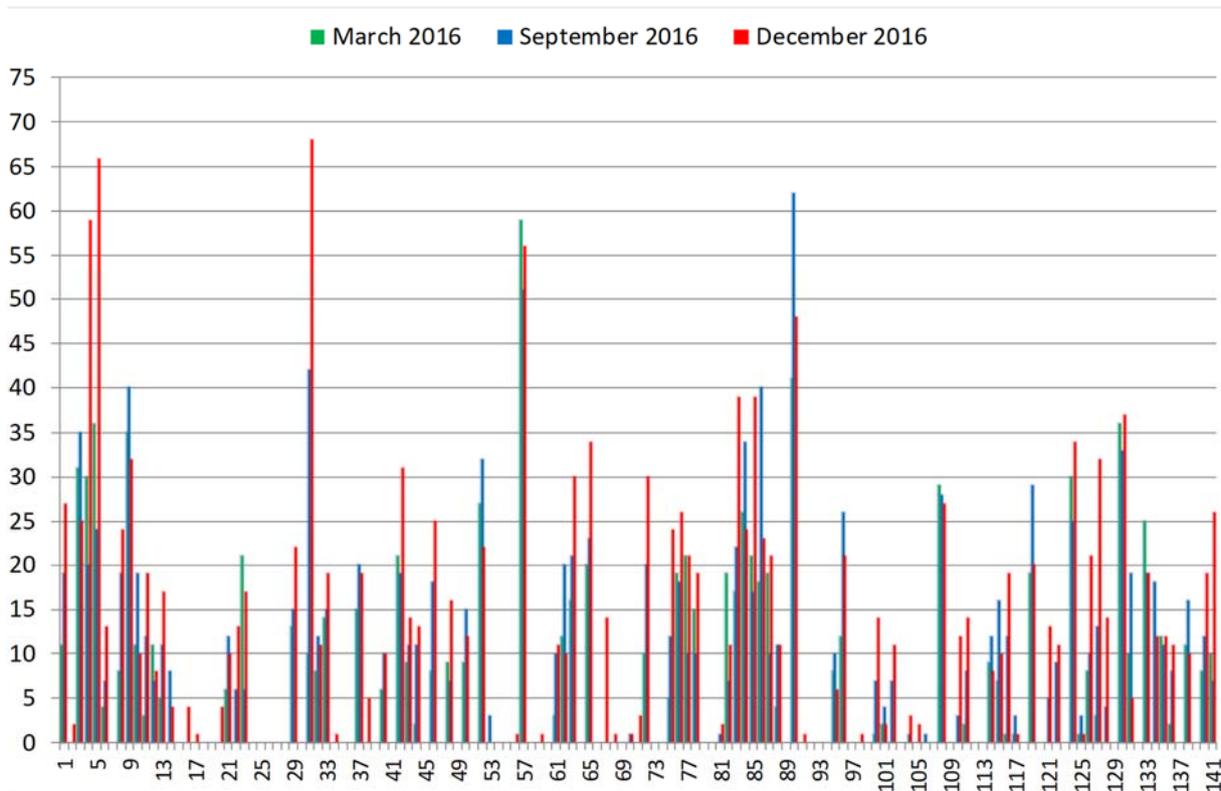


Figure 4. Histogram of belt failures density along x axis of the analyzed belt segment 7-8

The histogram of damage density shows that damage is random. Even after many years in operation, some 1-meter belt sections still show no trace of damage. Some other fragments, on the other hand, have over 65 defects per 1 running meter. Importantly, successive inspections reveal that the number of defects increases significantly from 6.8 defects per 1 running meter, through 8.9 (2.1 increment) , until 11.3 (2.4 increment) (Figure 5). This fact, however, is not clearly visible when all of the 1-meter sections are considered jointly, since local variations are much greater (Figure 6 left side). The differences between the successive inspections show clearly in the quantile plot (Figure 6 right side).

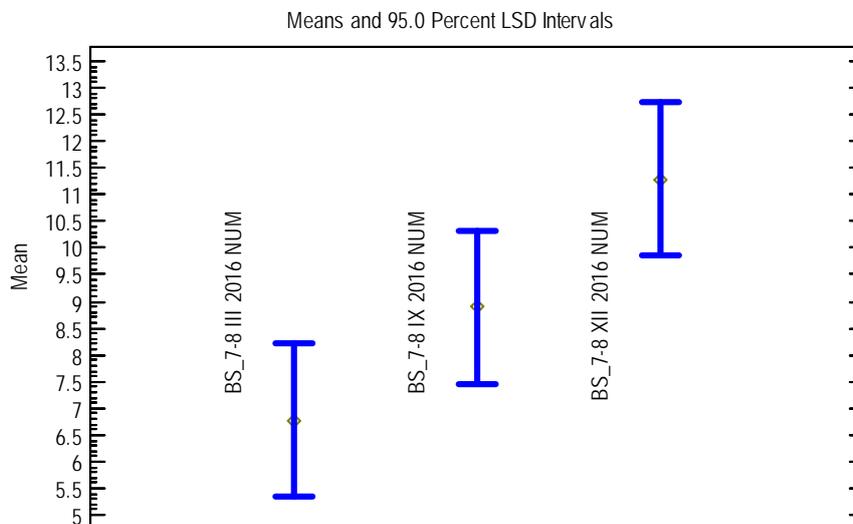


Figure 5. Means and 95 % LSD intervals for belt failures density

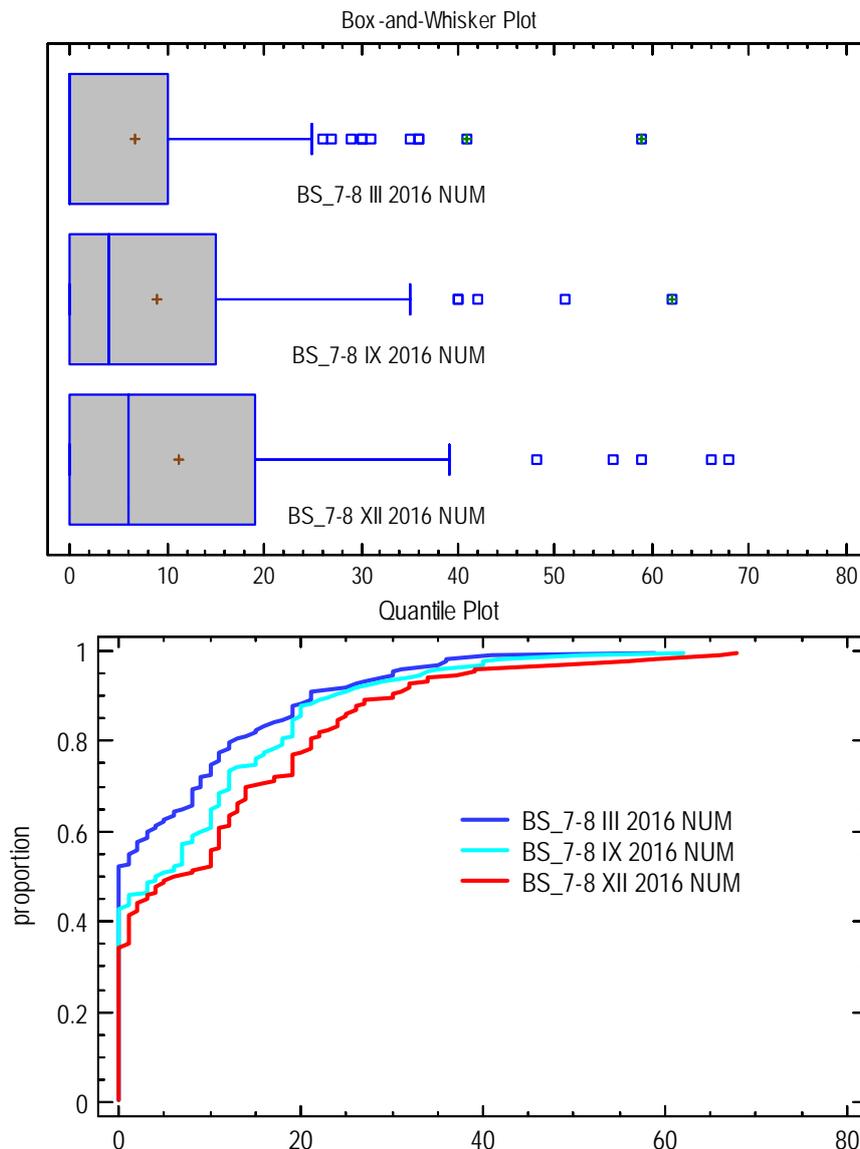


Figure 6. Box and whisker and quantile plots for 141 failures densities calculated for 1 meter belt segments in March, September and December 2016.

Significant local changes suggest that the whole 141-meter belt section has some fragments with several tens of defects. Such areas may pose a risk, since belt strength is significantly lower there. Multiple defects occur as lumps of bulk material randomly fall on the belt, causing the cords in the core to break. With time, the number of defects rises and the rate at which defects occur also increases, since belt covers are subjected to wear and their thickness gradually decreases, making impacts with smaller energy sufficient to cause damage [1, 8, 9]. Damaged rubber structure allows aggressive mine water to penetrate into the core of the belt, leading to accelerated corrosion. This, in turn, is responsible for the increase in the damage area, since corrosion develops along the cords, in locations where water penetrates. Surprisingly, the research identified the damage area to grow laterally to the belt axis. This phenomenon can be explained by the fact that transverse cuts of the rubber propagate due to frequent bending of the belt on idlers and pulleys. With time, water can penetrate also to the cords adjacent to the original area of damage and facilitate the development of corrosion in new locations. The change in the size of the damaged area can be identified and measured using 2D graphs (Figure. 2) to observe the change in the size of blue spots corresponding to the dimensions of the

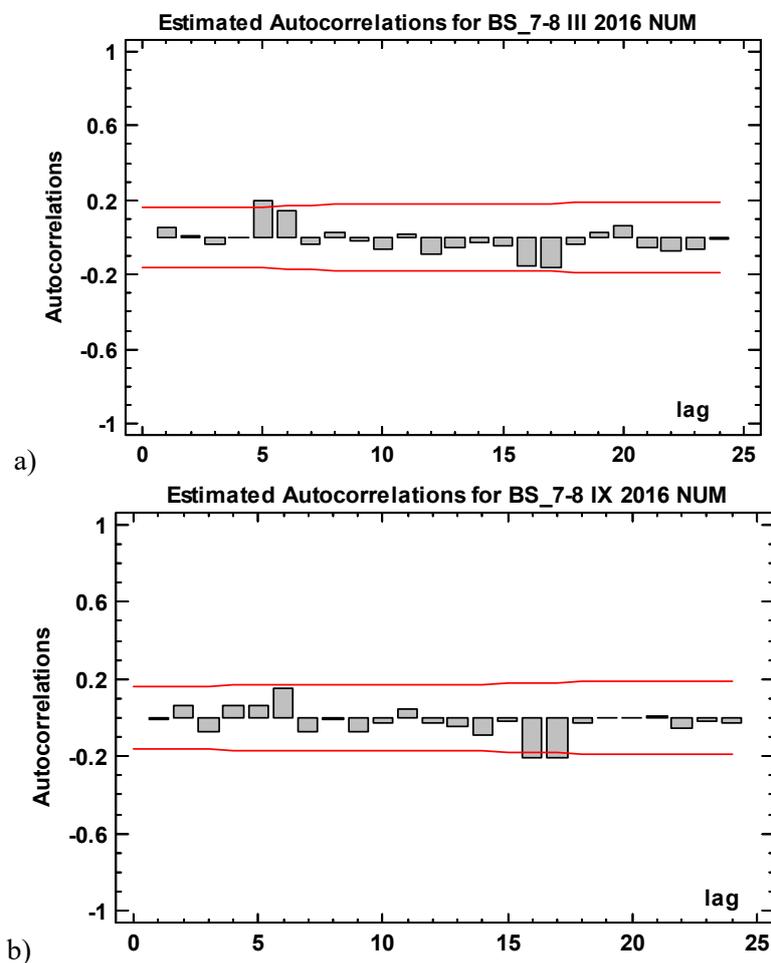
damaged cords in the core. The next issue is whether the increment of damage is uniform for all 1-meter sections and whether time influences the rate of this increment. Increments of mean values are not uniform. The second increment is slightly greater. Until now, not all belt sections were inspected, and therefore the statistical significance of these differences cannot be determined. Apparently, however, the second increment was identified after 50% shorter time (3 months instead of 6 months), which seems to suggest that new defects at a significantly increased rate. In order to confirm this hypothesis, a comparison was made of 141 increments in the number of defects which occurred on the successive 1-meter fragments of the inspected belt section over the time between successive inspections. Summary statistics for the two samples of data are presented in table 1.

Table 1. Summary Statistics

	Increment 2	Increment 1
Count	141	141
Average	2.39716	2.12057
Standard deviation	7.90016	5.98149
Coeff. of variation	329.563%	282.07%
Minimum	-17.0	-15.0
Maximum	42.0	32.0
Range	59.0	47.0
Std. skewness	8.69314	5.59922
Std. kurtosis	17.8547	13.3423

Mean increments in the second, shorter period between inspections are slightly higher (2.39 vs. 2.12). Standard deviation is also significantly higher (7.90 vs. 5.98), as is the coefficient of variation (329.6% vs. 282.1%). Negative increments suggest that despite the high resolution of the system, the measurement results, although repeatable, are not fully precise. Of particular interest here are the standardized skewness and standardized kurtosis, which can be used to determine whether the samples come from normal distributions. Values of these statistics outside the range of -2 to +2 indicate significant departures from normality, what invalidate the tests which compare the standard deviations. In this case, both samples have standardized skewness and kurtosis values outside the normal range. The suggested distribution is Laplace distribution. Importantly, maximum increments may also reach significant values, which illustrates the fact that over just several months as many defects may develop on 1 running meter of belt as would normally develop over several years on the most worn fragments. This phenomenon is a confirmation that the rate at which new defects occur increases significantly and the measurements started at a time when it accelerates. The user confirms that the belt has been already designated for disassembly. The change of damage should be analyzed not only over time, but also along belt axis. Intuitively, the distribution of defects along belt axis should be uniform, since the stream of bulk material which falls on the belt is random and no important reason seems to exist that would cause the changes of belt condition not to be random. In an underground copper ore mine, however, the loading of bulk material on the conveyor takes a cyclical form and over one shift the grizzly is approached by more than ten or even several tens of haulage vehicles and loaders. It is difficult, however, to correlate the points in time when bulk material is fed on the belt with the movement of the belt under the feeding hopper. The difficulty is caused by the fact that the conveyor does not start to move at the moment when material is fed, but works constantly over the whole loading process. Although some works are currently performed to adjust speed to the conveyor filling degree and thus to save energy, but as a result, the belt will be filled more evenly along its length – diversification will not be increased and hence the belt will not be subjected to increasingly uneven wearing process. Since a conveyor belt remains in operation for several or even more than ten years, the belt passes under the feeding point so many times that local differences in the abrasiveness and in the size of the lumps of bulk material, which may occasionally occur at the feeding point, should be levelled with time. In order to find whether the successive meters in the belt section are subjected to

identical load, autocorrelation of damage density was investigated. On 3 charts (Figure 7.) it was shown the estimated autocorrelations between values of belt failures densities (state in March, September and December 2016) at various lags. The lag k autocorrelation coefficient measures the correlation between values of series of data at time t and time $t-k$. Also shown are 95.0% probability limits around 0. If the probability limits at a particular lag do not contain the estimated coefficient, there is a statistically significant correlation at that lag at the 95.0% confidence level. Only one of the 24 autocorrelation coefficients from March scan is statistically significant at the 95.0% confidence level, implying that the time series may not be completely random (white noise). In September only 2 autocorrelations are significant and in December 2016 only one. This fact proves that it is practically impossible to identify any spatial relationship between the level of damage along the complete length of the inspected section. In the future, when all belt loop sections will be analysed in detail, it will be possible to repeat autocorrelation checks for complete sections in the loop.



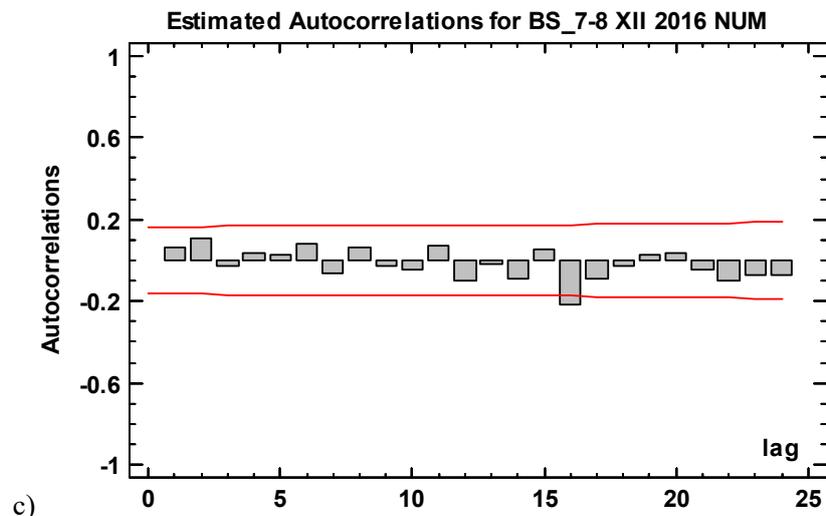


Figure 7. a-c) Relationship between the level of damage along the complete length of the inspected section

Three tests have been run to determine whether or not BS_7-8 XII 2016 NUM is a random sequence of numbers. A time series of random numbers is often called white noise, since it contains equal contributions at many frequencies. The first test (*Runs above and below median*) counts the number of times the sequence was above or below the median. The number of such runs equals 69, as compared to an expected value of 71.0 if the sequence were random. Since the P-value (0.799) for this test is greater than or equal to 0.05, we cannot reject the hypothesis that the series is random at the 95.0% or higher confidence level. The second test (*Runs up and down*) counts the number of times the sequence rose or fell. The number of such runs equals 86, as compared to an expected value of 93.6667 if the sequence were random. Since the P-value (0.1497) for this test is greater than or equal to 0.05, we cannot reject the hypothesis that the series is random at the 95.0% or higher confidence level. The third test (*Box-Pierce Test*) is based on the sum of squares of the first 24 autocorrelation coefficients. Since the P-value for this test is greater than or equal to 0.05, we cannot reject the hypothesis that the series is random at the 95.0% or higher confidence level. For earlier data (failure densities for 141 parts of the 7 - 8 belt section from March and September) only *Box and Pierce test* gave P-Values above 0.05. Since the three tests are sensitive to different types of departures from random behaviour, failure to pass any test suggests that the time series may not be completely random. Therefore, only for data from the last measurement in December 2016 we cannot reject the hypothesis that the series is random at the 95.0% confidence level and previous data show departures from random behaviour, however not seen in autocorrelations (Figure 7).

4. Conclusions

The change in the method of belt damage visualization from a single dimensional signal into a 2D signal (Figure. 1.) allows users to quickly interpret data and evaluate the condition of the belt. Concentrations of defects which threaten the continuous operation of the belt loop on the conveyor may be identified with a single glance. Users can estimate the number, the scale and the location of defects on their own. The analysis of traditional single dimensional signals (Figure. 1) from multiple measuring circuits requires a trained specialist and detailed interpretation is time-consuming. Quantifying the size of a single defect and observing its change over time is very difficult or practically impossible.

A digital record (-1, 0, +1) of the changes in the magnetic field which correspond to defects enables the compression of the resultant description of belt condition (by removing the meaningless zeros from the record) and the storage of data from subsequent scans of the same belt loop for individual conveyors. By recording these changes on various levels of sensitivity, it is possible to evaluate not

only the location and size of damage, but also its intensiveness and then to visualize it in 2.5D and 3D graphs (Figure. 1).

Records in digital form allow uncomplicated quantification of belt condition by introducing such measures as damage density per 1 running meter and further statistical analysis of the acquired data related to the belt's condition.

The analysis of the aggregated changes in the level of damage in the belt section inspected at three points in time showed that the number of defects increases with time. The rate of damage increment increased – it is an observation confirmed by the fact that in the first period, the monthly increment was at an average of 0.35 defect per 1 running meter of belt, and in the second period the monthly increment was at an average of 0.8. As can be seen, the increment was twice greater.

Mean increments and mean damage density seem insignificant (at an average of 11.3 defect per 1 running meter in the last inspection). Unfortunately, the distribution of those defects along the belt's axis varies significantly. After 5 years of operating the belt in difficult conditions in the mine, many belt fragments still do not show any significant core damage. Some locations, however, show high damage concentration (up to 70 defects per 1 running meter of the belt), which threaten the continuous operation of the conveyor. Therefore, using aggregated measures for complete sections may be confusing, and hence it should only serve the initial evaluation of belt condition with reference to other sections in the loop. It is necessary to identify the concentration of defects for smaller belt fragments (e.g. sections 1 meter in length), since the range of changes in this case is very wide (between 0 and 68 defects per running meter) and the coefficient of variation reaches up to 160% (330% for increments). Significantly, the changes may be rapid: over the period of 3 months the maximum increment was 42 defects per 1 running meter.

Therefore, it seems valid to limit the belt monitoring periods as the belt becomes worn, and towards the end of belt life a period of 3 months does not seem too long. As the belt approaches the end of its life, the measurement may even be performed continuously.

The investigation into the autocorrelation of damage density along belt axis did not show any significant spatial relations (especially visible in autocorrelations). Uniform distribution seems to provide an adequate description of damage density distribution along belt axis. Importantly, however, the variation is very high, and the coefficient of variation increases with belt operating time.

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