

Experimental identification of the impact of sectional satellite wheels on the load distribution in the meshing of the planetary gear in mining machines

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INTRODUCTION

Working conditions of machines used in the mining industry are characterised by a high rate of start-ups and load variability both in the start-up phase and regular work. Therefore, in the drive systems of these machines, and especially in the planetary gears, innovative methods of effective protection against additional dynamic loads generated by the gear meshing are required. These gears are classified as so-called multipath gears, characterised by the fact that power is transmitted in at least two ways. The transmitted power is separated at the input and then joined at the output of the gear. The problem related to the construction of more torque transmission paths is their even distribution. Due to manufacturing and assembly defects there are inaccuracies that affect the distribution of the load on the meshing on the respective paths of the power transfer (Bodas and Kahraman, 2004, Lamparski, Placzek, 1988, Schulze et al., 2010, Schulze, 2009).

SECTIONAL SATELLITE WHEELS

The common design solutions minimise the diameters of the satellite wheels, and at the same time, because of the high torque transmission, the wheels must have a large width and are often mounted on the axes of the planetary cage on several (usually two) conventional ball or roller bearings, which often leads to an over-rigid construction.

The large width of the wheels, in particular at the output stage, even with a high accuracy of assembly and manufacture as well as the form of their bearing, become the cause of an uneven load distribution across the width of the wheel with spur teeth. The linear contact of the meshing teeth assumed in the design of the gears, as a result of the occurrence of i.a. construction shortcomings, axle shafts non-parallelism, axis twist, tooth direction errors, tooth deformations or installation errors, differs from the expected and is often quasi-pointwise. This

irregularity of the load transfer along the length of the tooth results in a significant increase of the contact pressure and the stress at the base of the teeth, which can lead to their destruction (Fig. 1) (Börner and Senf, 1995, Chaari et al., 2006, Cheon and Parker, 2004, Vonderschmidt).

In planetary gears, the relative width of the gear wheels, the central (sun) wheel and the satellite wheels is relatively large. The value of the quotient of the wheel's width to its diameter is often close to one. Large wheel widths, in particular at the output stage, even at a high accuracy of assembly and manufacture, result in significantly uneven load distributions in the teeth (Boguski and Kahraman, 2012, Ligata et al., 2008).

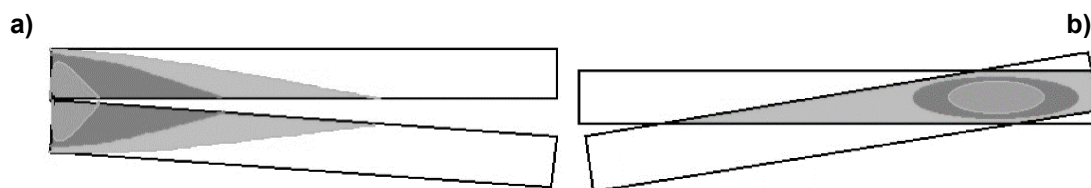


Fig. 1 Simplified image of the inaccuracies in the co-operation of the teeth and the contact pressure, where: a – non-parallelism of wheel axis, b – twist of wheel axis

The reason for the uneven load distribution over the width of the spur wheels is usually faulty mechanical treatment that gives rise to deviations that have a direct effect on the tooth contact, and these deviations include: axis non-parallelism, axis twist, tooth direction error; the teeth do not touch along the entire width of the wheel.

Satellite wheels are most often mounted on axes fastened in a two-plate cage, which often leads to an over-rigid construction. For this reason, any inaccuracies in the manufacturing of the gear wheels, axes and cages have a significant effect on the uneven load distribution in the meshing and uneven load transfer along the length of the mesh (Linke, 1978).

At large widths of gear wheels in parallel gears, a modification of the tooth line is also applied – in such a way that the teeth adhere uniformly across the width of the wheel only after the load and the deformation occur. The basis for designing the modifications of the tooth line in the case of the precise performance of the meshing teeth is the knowledge of the flexural and torsional deformation of the shaft, especially at the location of the pinion (Gurumani et al., 2011).

This article attempts to solve the presented problem by using an innovative design concept based on the increased plasticity of one of the cooperating wheels. In case of a planetary gear it is a division of the satellite wheel, perpendicular to the main axis, into at least two parts – in other words, replacing the single satellite wheel with at least two satellite wheels placed on a common axis the total width of which corresponds to the structurally defined width of a single wheel (Fig. 2) (Kowal, 2003, Kowal, 1999).

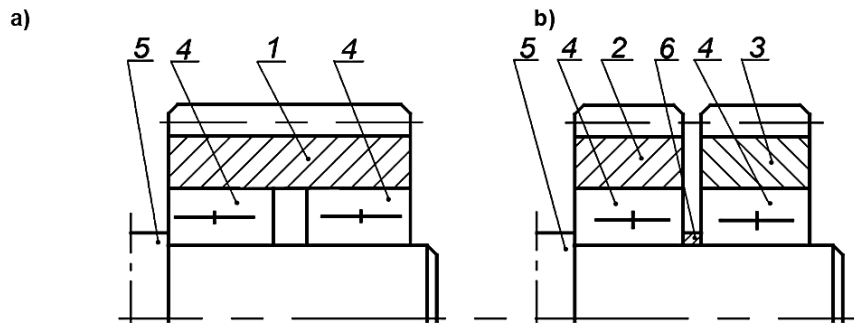


Fig. 2 Example of the solution of the bearing of satellite wheels, where:
 a – typical wheel with a large width, b – an innovative bearing of a sectional satellite wheel,
 where: 1 – single satellite wheel, 2, 3 – sectional satellite wheels,
 4 – bearings, 5 – planetary gear axis

The independent bearing lock of each narrow wheel on one bearing allows for the adequate fit of the position of the narrow wheels relative to the cooperating ring gear (solar wheel) and internal gear.

Figure 3a and 3b exhibit sample distributions of q unit loads on the satellite wheel tooth, resulting from the F_o circumferential force, wherein the $q_{\max b}$ unit load refers to a b full-width planet wheel, while $q_{\max b/2}$ refers to the two wheels characterised by a $b/2$ width.

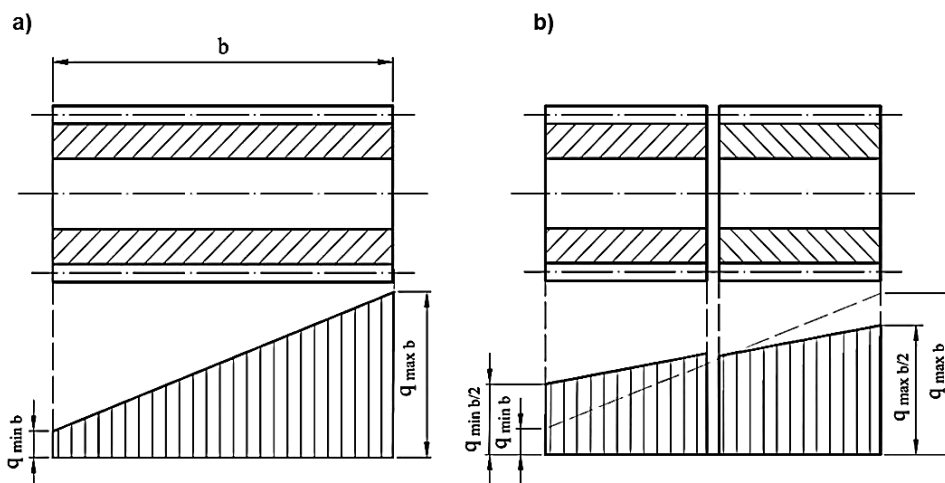


Fig. 3 Example of the expected load distribution in a satellite wheel, where:
 a – a single wheel, b – two planetary wheels

The identification of the impact of satellite wheel division and their width on the gear teeth load has been a key reason for developing a research methodology and building a test stand to investigate the processes within the planetary gears. Achieving this goal requires an in-depth analysis, preceded by experimental studies on a specially built stand.

The scientific purpose of the designed research is conducting a comparative identification of the impact of sectional satellite wheels and their width on the course of the load on the meshing of a planetary gear.

The innovative and original design solution proposal, based on the division of the planet wheels may allow for the creation of innovative planetary gears characterized by an increased durability and reliability.

EXPERIMENTAL TEST STAND AND RESEARCH METHODOLOGY

Due to the innovative nature of the design and the fact that the use of sectional satellite wheels entails a considerable complexity of the strength analysis, the most appropriate way to determine the characteristics of these wheels are experimental tests. The research will be conducted on a prototype stand which has been developed at the Department of Mining Mechanisation and Robotization of the Silesian University of Technology in Gliwice. This stand is based on the design of the planetary gear of an ECO-C-7 mine windlass. The construction of the stand is shown in Fig. 4.

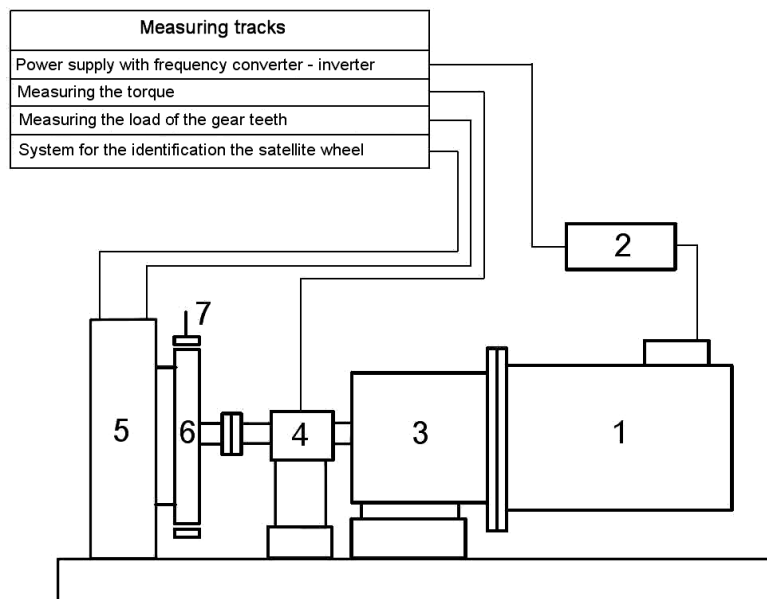


Fig. 4 Diagram of test stand, where: 1 – electric motor, 2 – inverter, 3 – input planetary gearbox, 4 – the measuring gauge, 5 – tested planetary gearbox, 6 – band brake, 7 – brake control system

The stand has been equipped with three specialised measuring tracks:

- the load at the base of the teeth of the internal wheel gear (intertooth force) of the gear unit using strain gauges (6 channels),
- the torque with the conditioning systems, which is loading the tested planetary gear,
- the identification of the satellite wheel which is loading the measuring tooth during the rotation of the planetary cage at a given moment.

As it has been already mentioned, all the measuring signals obtained from the sensors of the test stand are sent to a specialised measuring and recording apparatus, using modern modular A/D cards and measuring signal conditioning cards.

The developed concept of the test stand and of the experimental research methodology uses elements of a 2K-H (AA/AI) type planetary gear of an EKO-C-7 mine windlass. A typical satellite wheel of the output planetary gear of a mine windlass has been used in the research. The tothing of the satellite wheels of the gear is straight.

The internal wheel of the 2K-H (AA/AI) type planetary gear is stationary. The gear input shaft is connected to a torque meter. On the input shaft, the sun wheel

of the planetary gear is mounted. The output shaft is connected to the rotating planet cage.

The research program assumes taking the measurements for:

- two types (forms) of satellite wheels – single wheel and sectional wheels (Fig. 2a, 2b),
- different values of the torque loading the tested planetary gearbox, changed in a discrete manner with adequately adapted jump from a minimum to the maximum value (resulting from the limiting parameters of the test stand).

All the results obtained from the experimental measurements allowed to identify the impact of the sectional satellite wheels on the tooth load in the planetary gear.

DETERMINING EXPERIMENTAL RESEARCH

The achievement of the basic objective of the experimental tests, i.e. the measurement of the load of the wheel teeth of the planetary gear required the development of a special measurement concept. This concept was based on the measurements of the load (deformation) of the teeth of the internal gear wheel at its base. For the measurement of the load on the tooth, strain gauge bridges were used (1/2 type), affixed at the base of three teeth of the internal gear wheel on either side (i.e. on both sides of the tested tooth). In total, six sensors were made: strain gauge bridges 1A - 1B, 2A - 2B, 3A - 3B. These bridges were placed about each 120° . A diagram of their arrangement is shown in Fig. 5a.

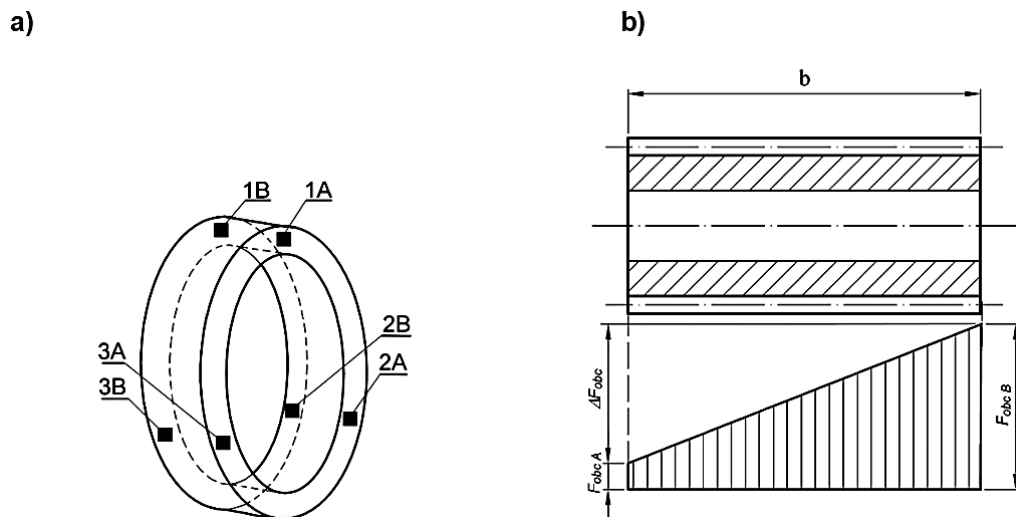


Fig. 5 A graphic of the concept of measuring the load on the measuring teeth, where: a – scheme of the distribution of tensometric bridges, b – the principle of measuring and reading F_{obc} forces loading an internally meshed tooth on both its sides

This concept allowed for a direct reading of the value of the F_{obc} loading force on a given tooth on both its sides, working in the normal direction to the tooth's working surface. In the adopted research methodology, the purpose of which was the comparison of the load distribution along the length of the tooth for two constructional forms of satellite wheels, the measure of the load on the

measuring tooth of the internal gear were the measured values of the F_{obc} forces loading the tooth on both its sides (side A and B) (Fig. 5b).

Based on this assumption it can be indicated that the measure of the degree of non-uniformity of the mesh load on the tooth length can be the difference between the values of the F_{obc} forces loading the tooth, measured on both its sides, i.e. on the A side (F_{obcA}) and B side (F_{obcB}), expressed with the ΔF_{obc} indicator (Fig. 5b). Therefore, this indicator can be used to compare and assess the impact of innovative constructional solutions of satellite wheels, i.e. sectional and standard satellite wheels, on the distribution of load along the length of the tooth.

In order to graphically display the measured values of the F_{obc} forces loading the measuring teeth both on the A and B side of the tooth, for the two constructional forms of planetary wheels, i.e. standard and sectional wheels, an example of the obtained results in the form of diagrams has been shown in Fig. 6.

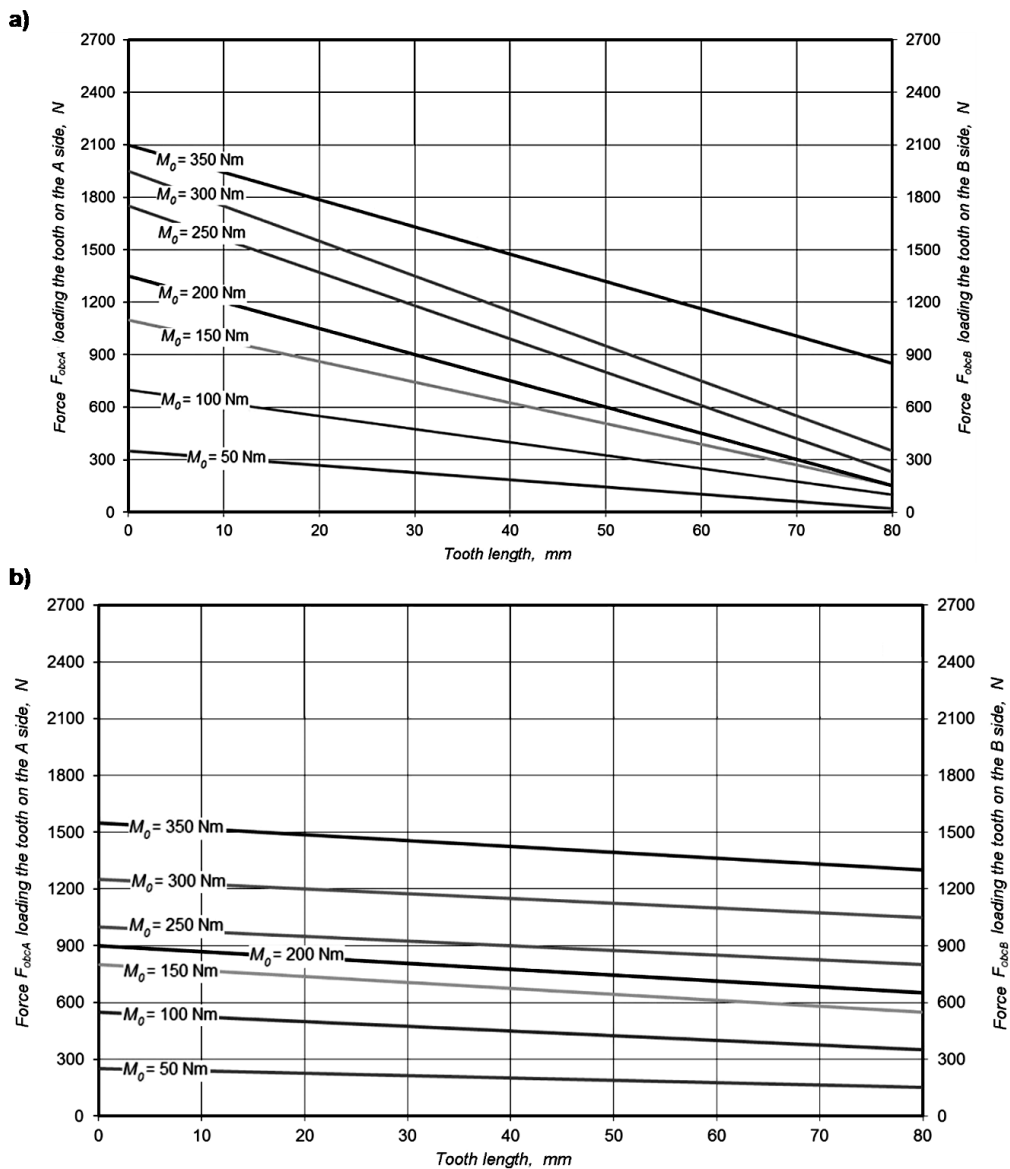


Fig. 6 An example of the illustration of the value of the F_{obc} force loading the measuring tooth on both its sides (A and B) in cooperation with the planetary wheel depending on the set M_o torque, for the case of: a) standard wheels, b) sectional wheels

Fig. 7 presents a graphical example of the conducted analysis of the obtained measurement results, which illustrates the degree of unevenness of the distribution and the comparison of the load along the length of the tooth, the measure of which is the calculated difference of the ΔF_{obc} forces loading the tooth on both its sides, i.e. on the A side and B side, for the tested construction forms of satellite wheels, i.e. sectional (narrow) and standard (wide) wheels.

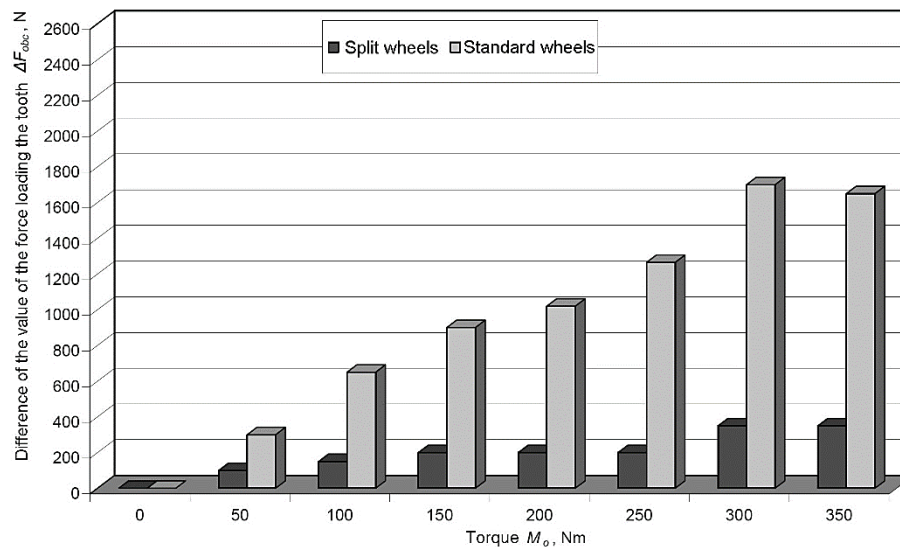


Fig. 7 An example of a graphical illustration of the degree of unevenness of the load distribution along the length of the tooth, expressed by the difference of the ΔF_{obc} force loading the tooth on its both sides, for sectional and standard satellite wheels

As it can be noticed, the difference (absolute value) of the ΔF_{obc} forces loading the measuring teeth, which is the measure of the unevenness of the load distribution along the tooth line, is much greater when using standard, wide planetary wheels as compared to the structural solution proposed in the paper in the form of sectional, narrow planetary gears.

For the analysed measurement conditions, an improvement in load uniformity for sectional satellite wheels is visible.

Due to the complexity of the issues related to the determination of load status, the next step of the conducted experimental investigations of the described constructional solutions of satellite wheels in the aspect of the distribution of load along the length of the tooth was to perform analyses and numerical calculations using the finite element method (FEM) (Gurumani, R., & Shanmugam, S., 2011; Linke, H. 1978).

After the preparation of geometrical models, a computer simulation of the tooth load of individual gear wheels was performed. This allowed for both the visualization of the load distribution and the determination of stress values along the length of the tooth.

Fig. 8a presents the stress distribution for the internal gear wheel in cooperation with a standard, wide satellite wheel. In this case, there is considerable stress at the base of the tooth on its squeezed side. Figure 8b exhibits the stress distribution in an internal gear wheel in cooperation with sectional satellite wheels. In this case, the maximum stress value does not exceed 160 MPa and

is lower by about 20% than in the case of cooperation with a standard wheel. Moreover, the stress distribution along the length of the tooth is more even, which confirms the validity of the proposed structural solution.

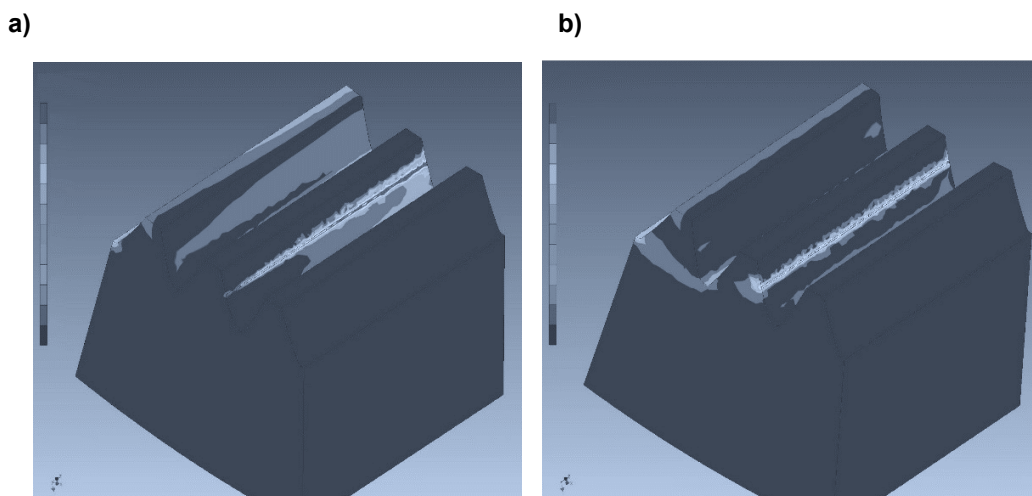


Fig. 8 Image of stress analysis of the internal gear wheel, in cooperation, a – with the standard, wide satellite wheel, b – with the sectional, narrow satellite wheel

CONCLUSION

As a result of the conducted research works, it should be stated that the results obtained from the measurements are qualitatively and quantitatively consistent with the theoretical assumptions which were the basis for the construction of the research stand and for the development of the methodology and the entire research program.

Based on the recorded waveforms representing individual teeth loads, clear differences in the tooth load of the internal gear wheel in cooperation with standard, wide satellite wheels and sectional, narrow satellite wheels can be noticed.

With the use of standard, wide satellite wheels, there is a visible and significant unevenness of the load on the measuring tooth along its length. For the examined constructional forms of wheels, it can be stated that the maximum values of the F_{obc} loading force on one side of the measuring tooth occur precisely when using standard satellite wheels, and their values are several times greater than the values on the other side of the measuring tooth.

The conducted computer simulations (using FEM) allowed for illustrating the stress distribution on the loaded tooth at an uneven load along its length, and a comparative analysis of the obtained images of stresses reduced for both solutions also allows for the conclusion that the use of sectional satellite wheels has a positive effect on the distribution of load along the tooth length.

It should be emphasized here that both the results of experimental research (Figs. 6 and 7) and the conducted analysis of the simulation study (Fig. 8) clearly indicate that the idea of using sectional, narrower satellite wheels in the planetary gearing clearly improves the distribution of the load carried along the length of the teeth.

The obtained research results may find practical application as guidelines directed to planetary gear manufacturers – as a structural solution that can become a structure with improved durability features and increased reliability, which will make them more attractive and competitive on the consumer market.

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Abstract.

This article attempts to solve the problem of load compensation in mesh planetary gearing, with the innovative design idea, resulting from the increased plasticity of the planet wheels (satellite). The cognitive main objective of the experimental work was carried out to identify the comparative effect of the split narrow planet gears, on the load distribution on the length of the teeth of the planet gears of the central wheel of the planetary gear. Achieving this aim, in addition to in-depth analysis, requires experimental research on a specially-built test stand and simulation tests on a solid model of the transmission using the finite element method (FEA). This article presents the concept of a novel test stand, design methodology and research on the influence of the sectional satellite wheels on the load mesh of planetary gears in mining machines.

Keywords: drive system, planetary gear, load condition, design methodology