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Sheave axles of mine shaft hoists – difficulties and limitations in assessing their technical condition during in-service tests

The paper discusses the difficulties and limitations in the possibility of assessing the technical condition of sheave axles during in-service tests resulting from the lack of access to many areas of the outer surface of the axle due to built-in bearings and mounted sheaves, as well as from the complex shape of some types of axles. Examples of in-service axle failures are given and the causes are discussed. In addition, information on the legal basis for performing non-destructive testing of sheave axles in service, technical requirements for sheave axles, critical areas found in axles, theoretical basis for ultrasonic testing, and testing techniques including the latest phased array method is presented.

Key words: *ultrasonic testing, UT probe, anomalies, sheave axles, cracks, difficulties and limitations*

1. INTRODUCTION

Periodic testing of sheave axles as an element of the shaft hoist, for which a particularly high degree of safety is required, has been carried out in hard coal mining for more than thirty years.

Non-destructive testing is primarily used to evaluate the technical condition of sheave axles. These tests are conducted using the following methods:
- visual testing (VT),
- ultrasonic testing (UT),
- magnetic particle testing (MT).

The non-destructive character of testing, i.e. not limiting the further usefulness of an element, not causing its damage, is particularly useful for testing sheave axles.

When an axle is in operation, ultrasonic testing is most often used to avoid disassembly for testing. It is a method that in most cases gives a qualitative result, i.e. it allows to obtain information as to the location of the discontinuity, its approximate size, and sometimes even as to its type (service crack, material defect, etc.) [1]. The obtained test results can be the basis for assessing the suitability of axles for continued use in terms of their strength and technological properties. Systematic, periodic inspection makes it possible to detect potential operating defects of an axle at an early stage, to follow their development, i.e. the so-called crack propagation process during operation, thus extending its service life. Detecting in-service cracks at an early stage of formation, monitoring their propagation, also gives the right amount of time to replace the axle.

This paper focuses on the difficulties and limitations in assessing the technical condition of axles during in-service testing, discusses the origins and legal basis for axle testing, presents the current quality requirements for axles, outlines various ultrasonic testing techniques, and describes abnormalities detected in axles during testing.

2. THE GENESIS AND LEGAL BASIS FOR TESTING SHEAVE AXLES

Following the failure consisting in fatigue fracture of the sheave axle of the winding gear installed in the „Jan Henryk" shaft of the Lenin Coal Mine, which took place in 1985, the Coal Mining Department of the Polish Ministry of Economy and Energy, in its letter of 1 April 1985, no. GW4.11/209/85 and Communication no. 4/85 of 14 May 1985, determined the scope of ad hoc preventive measures, including:

- extraordinary ultrasonic testing of sheave axles and assessment of their construction in winding gears in service,
- the obligation of systematic non-destructive testing of sheave axles in periods not exceeding 5 years.

The tests mentioned above were commissioned to Central Research Laboratory of "Ziemowit" Coal Mine, the precursor of the current Research and Supervisory Centre of Underground Mining (CBiDGP).

Currently, the testing of sheave axles in mining plants is governed by sec. 3.12.6.5 of Appendix No. 4 to the Polish Regulation of the Minister of Energy of 23 November 2016, as amended, on detailed requirements for conducting underground mining operations [2].

At CBiDGP – ORiP, as an expert body performing, among others, the 3-year testing of rope sheaves, the issue of axle tests is governed by the relevant test methods and instructions [3, 4].

3. MANDATORY REQUIREMENTS FOR SHEAVE AXLES

The sheave axles for use in mine winding gears are made of steel forgings with multiple steps, supported in two places.

According to the Polish standard PN-G-46203:1996 "Górnicze wyciągi szybowe. Koła linowe kierujące. Wymagania i badania" [Mining shaft hoists. Guide sheaves. Requirements and testing] axles should be manufactured as open-die forgings of type A, category RR, from steel in the normalized state, in the quality class of the forgings no worse than 3 according to BN-86/0601-09 "Stal. Badania nieniszczące wyrobów hutniczych. Badania odkuwek metodą ultradźwiękową" [Steel. Non-destructive testing of metallurgical products. Ultrasonic testing of forgings] [5]. This standard has now been withdrawn and replaced by PN-EN 10228-3:2016-07, which introduces four quality classes for forgings [6]. As a general rule, it should be assumed that the requirements for the quality class of the forging intended for the axle manufacture are to be specified by the design engineer stating which standard the requirements must be met. The forging quality class is determined by ultrasonic testing. Most commonly, forgings of quality class 3 and 4 are used for sheave axles.

To avoid the notch effect, the joints between axle steps are rounded with relatively large radii. The height of the offsets, for strength reasons, should generally not exceed $h \leq 0.1d$, where d is the axle diameter [7]. Both ends of the axle are free. The sheave axles are mounted in roller or plain bearings.

4. CRITICAL LOCATIONS IN THE AXLES

The axles of the sheaves are mainly subjected to alternating bending loads on both sides. Load distribution in the sheave axles is uneven. This is due to the nature of the load and the shape of the axle being adapted to work with sheaves. Therefore, locations more susceptible to cracking can be identified. These areas are called critical locations (Fig. 1) [7]. Critical locations in axles are as follows:

- in the offset area of the bearing journals (1, 2),
- in the area of the sheave seating edge (3, 4, 5, 6),
- in other offsets determined by the mounting design (7, 8).

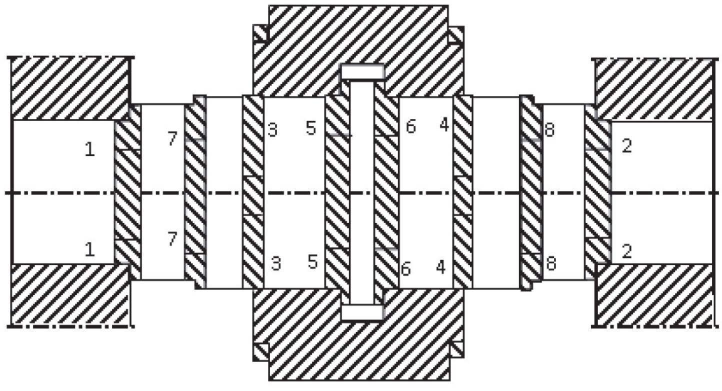

Fig. 1. Layout of critical locations in the sheave axle

The dimensions of critical locations should be determined according to the diameter of the axle in the critical location zone. For cylindrical profile parts, this dimension is 0.25 of the diameter dimension [7].

5. THEORETICAL BASIS OF ULTRASONIC TESTING

Ultrasonic testing involves the use of the interaction between ultrasonic waves and the object being tested. The method enables the detection of discontinuities both inside and on the surface of the test piece.

Many techniques (echo, resonance, transmission, phased array, etc.) are used in ultrasonic testing, but the most popular is the so-called echo technique, which is also used for testing sheave axles.

The principle of the echo method is to transmit ultrasonic waves and receive them after reflection from discontinuities in the material or reflection from boundary surfaces.

Transmission of pulses of ultrasonic waves takes place by means of a probe with a specific transducer frequency and dimensions.

The ultrasonic wave generated by the probe propagates through the tested material and reflects off flaws, discontinuities or boundary surfaces of the tested object. The ultrasound wave, after reflection, returns to the transducer in the probe and stimulates it to vibrate. These vibrations are converted into electric impulses which, after appropriate processing in the electronic system of the flaw detector, give us the image on the screen in the form of a peak (echo) [1].

By measuring the transit time of the ultrasonic wave and knowing the speed of the wave propagation in a given material, it is possible to localize the detected discontinuities.

Single and dual longitudinal wave probes, as well as oblique, angled transverse wave probes, where the ultrasonic wave is introduced into the material at an appropriate angle, are typically used to test sheave axles. Depending on the structure of the tested material (granularity, attenuation), probes with frequencies from 1 MHz to 4 MHz are most commonly used.

A specific variation of the oblique probe is the surface wave probe, in case of which the ultrasound wave is introduced at an angle of 90°. Such probes are particularly useful for testing sheave axles cooperating with sliding bearings, allowing the detection of cracks or tears in the offset zone, which in practice eliminates the need for magnetic particle testing.

6. DIFFICULTIES AND LIMITATIONS IN CONDUCTING THE NONDESTRUCTIVE TESTING OF SHEAVE AXLES

The ultrasonic method is used as the basic method to evaluate the technical condition of sheave axles. Ultrasonic testing of sheave axles during operation can only be performed to a limited extent due to the lack of access to the entire surface of the tested axle, which is largely covered by the sheaves and bearings mounted on the axle, usually impossible to remove under operating conditions.

In addition to the limited access to many parts of the external surface of the axle, additional difficulties in testing are posed by surface irregularities (scratches, corrosion) and internal defects (manufacturing, metallurgical – applies to axles manufactured before the introduction of quality standards)

Ultrasonic testing is always preceded by a preliminary visual inspection of the axle in the condition prepared for testing.

In the case of axles with roller bearings, these will be the exposed two faces of the axle, and for axles with plain bearings, additionally the exposed sliding surfaces of the bearing journals after removal of the upper covers and half-shells.

Hence, a distinction can be made between the following basic cases for conducting the test:

- from both end faces and partially from the side face in the journal areas – the axles mating with the plain bearings (Fig. 2),
- sheave axles with roller bearings from both end faces with complete inaccessibility of the side faces.

For axles with plain bearings, the basic test is the inspection from the lateral surface with transverse wave probes (T) with angles of refraction of 45°, 60° and surface wave probes of 90°. In addition, a test with longitudinal wave normal probes (L) is performed from both faces (Fig. 2). In the case of echoes on the flaw detector screen suggesting the presence of cracks in the axle, the defective areas are subjected to magnetic particle inspection (provided that the places of possible cracks are visible and not covered by structural elements cooperating with the axle) for final verification of indications.

The testing of axles with rolling bearings is only carried out from both end faces, in several phases, using longitudinal and possibly transverse waves. Initially, high energy normal probes are used to penetrate the full length of the axle material with waves. In the front part of the axle, echoes from cracks appearing mainly in areas of section changes or under the edges of mating parts (bearings, pulley hubs) are looked for. Offset echoes are observed at the rear of the axle, the presence of which is of control significance.

The next phase, if necessary, is a detailed testing using oblique probes. This allows the ultrasonic wave beam to be directed into the corner that the hypothetical crack forms with the lateral surface of the axle (Fig. 2).

In the third stage, explaining tests are conducted to avoid the misinterpretation of the inspection results. Angled probes are used, mainly with an angle of refraction of 45°.

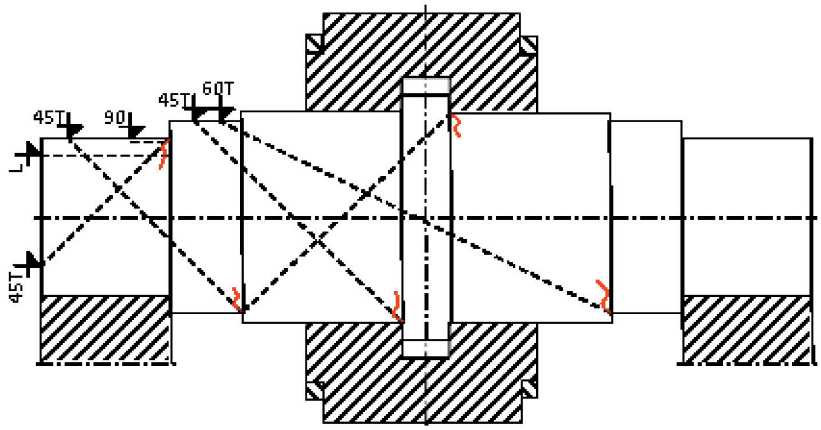

Fig. 2. Ultrasonic testing of sheave axle with plain bearings

One such case is the distinction of ultrasonic wave reflections originating either from the edge of a rolling bearing withdrawal sleeve or from fatigue cracks originating in the axle under that edge. As a result of the good adhesion of the sleeve to the axle and the filling of the gap with grease, the ultrasonic waves penetrate the contact surface between the components and are reflected by the edge of the sleeve. The location of the wave reflection is identified by the position of the probe on the axle face (Fig. 3) [8].

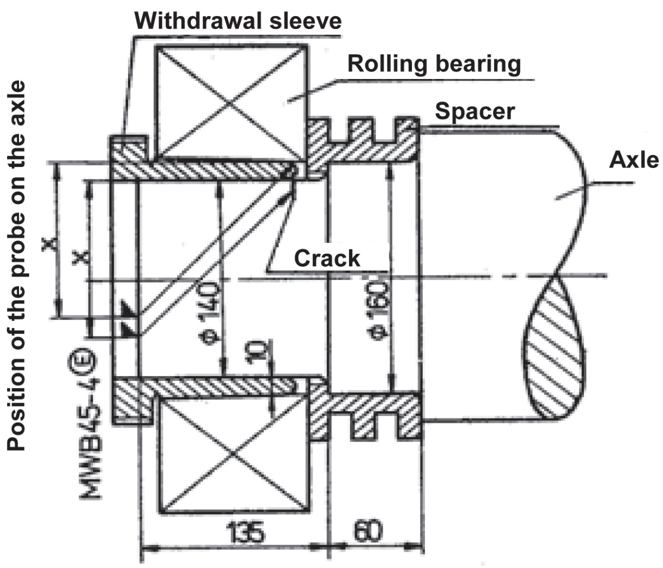

Fig. 3. Distinguishing the edge echo of rolling bearing sleeve from the axle fatigue fracture [8]

A major complication of ultrasonic inspection of sheave axles is the significant variation in their shapes and dimensions (Fig. 4 and 5).

This results in a number of apparent indications on the flaw detector screen. These are the echoes:

- associated with the flaw detector-probe system,
- arising from the transformation of ultrasonic waves at offsets, keys, etc.

Therefore, an accurate interpretation of the indications is only possible with detailed drawings of the axles and the extensive experience of the staff carrying out the inspection.

The phased array ultrasonic method offers great potential for early detection of sheave axle cracks. In this technique, phase-controlled multi-transducer (mosaic) probes cooperating with multi-channel flaw detectors are used. If during the tests performed with a standard flaw detector the occurrence of in-service fatigue cracks is suspected, the results obtained can be verified by means of the phased array technique.

The advantage of this technique over the conventional method is that having only one probe, it is possible to shape the ultrasound beam by stimulating the transducers at the right time (change the beam introduction angles and focus the beam). This allows for the selection of optimal beam insertion angles relative to the detected discontinuity (e.g., 18°). When testing with a standard flaw detector, several probes and many angle pads with different, unusual angle values would be needed.

Application of phased array technology for axle and shaft testing:
- increases the effectiveness of the test – allows for detection of in-service fatigue cracks in the initial stage of their formation (scanning in the full range of useful angles, and not only a few as in the case of ordinary ultrasound testing),
- allows to shorten the test time – lesser number of probes used (flaw detector settings),
- facilitates the interpretation of the results (easy change of beam introduction angles – it is possible to determine at what angle the signal from a possible crack is the strongest, presentation of the indication e.g. on S-scan) (Fig. 6).

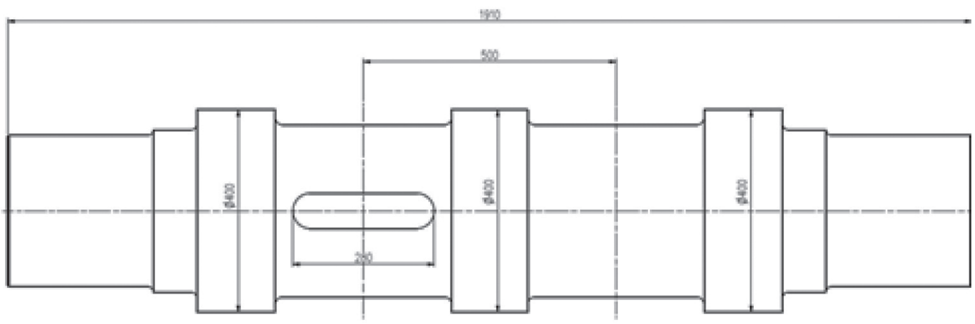

Fig. 4. Example of double-groove sheave axle

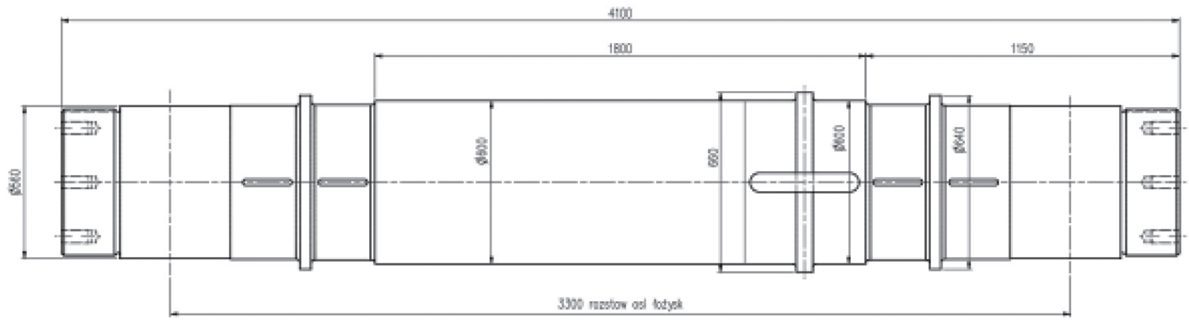

Fig. 5. Example of four-groove sheave axle

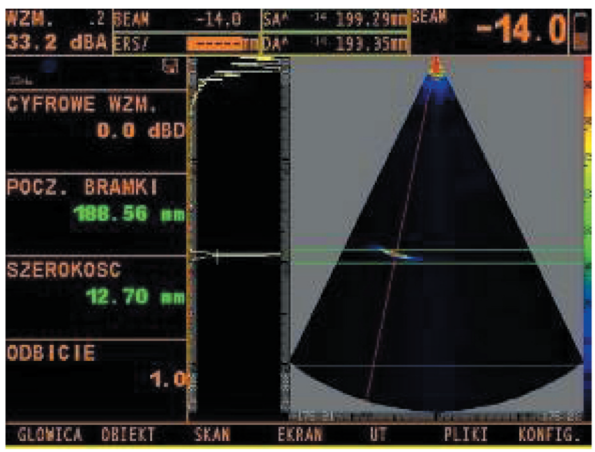

Fig. 6. Phased array imaging of a fatigue crack in the single-groove sheave axle (B2SPA16 16-element 2 MHz probe, ±30° maximum crack indication was obtained for beam insertion angle of 14°)

7. DETECTED IRREGULARITIES IN THE SHEAVE AXLES

During tests of sheave axles, many irregularities are found in the technical condition of the axles themselves, bearing nodes and sheave hub and axle connections, which reduce the service life of the axles or even preclude their operation.

Ultrasonic detected flaws:

- Fatigue cracks. Usually caused by incorrectly manufactured axles, i.e., too small transition radii between successive offsets, resulting in a notch effect in critical areas of the axles, or too large diameter steps causing excessive stress accumulation in these areas. This is mainly the case for axles in double groove designs (Fig. 6 and 7). Sometimes fatigue cracks are initiated by corrosion pitting, often occurring at the axle-sheave hub contact surface.
- Excessive internal defectivity (i.e., excessive size and severity of defects of metallurgical origin) in critical locations. This mainly concerns the axles of old shaft hoists. These defects do not pose a direct threat to the safe operation of the axles, but under certain circumstances (stress concentration in these areas due to overloading or failure of the hoisting plant) they can cause cracks to appear.

Irregularities found during visual inspection of axles with roller bearings: the irregularities concern rather the bearings themselves and the axle to sheave hub connection.

Irregularities of axles with plain bearings:

- sharp, deep (up to about 2 mm) circumferential indentation caused by excessive wear of the bottom shell, which results in axle settling and rubbing against the bearing housing (Fig. 8),
- circumferential cracks on the sliding surface of the journals caused by contaminants getting into the oil (Fig. 8),
- corrosion spots and scuffs on the sliding surface of the journals caused by improper lubrication,
- mild, shallow, circumferential abrasion caused by the felt seal on the bearing housings,
- loose grease rings.

Axles with fatigue cracks should be replaced with new axles as soon as technically feasible, and until their replacement, crack propagation should be monitored by ultrasonic testing over a sufficiently short period of time. Remaining anomalies require immediate remediation of their causes, and axle damage should be controlled during subsequent non-destructive periodic inspections.

Fig. 7. Fatigue cracks detected during ultrasonic testing of single groove sheave axle (at second offset) – imaging using the magnetic particle testing (MT) method

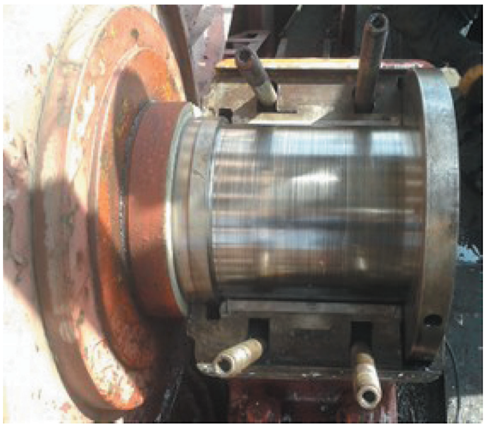

Fig. 8. Circumferential scratches on the axle journal surface

8. SUMMARY

Despite the difficulties and limitations in testing sheave axles, having appropriate testing equipment and certified personnel with many years of experience in ultrasonic testing, it is possible to correctly assess the technical condition of axles during operation.

Early detection of in-service fatigue cracks gives the user adequate time to prepare for axle replacement while ensuring safe operation.

Periodic non-destructive testing of sheave axles prevents the occurrence of emergency conditions while also contributing to the extension of the period of the safe operation of sheaves in mine shaft hoists.

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