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Breakdown of hoisting machine in mining shaft hoist installed in southern section of R-II shaft of KGHM Polska Miedź S.A. O/ZG Rudna

This article applies to a one-of-its-kind case of the cracking of the main shaft of a hoisting machine that occurred in the southern section of the R-II shaft of KGHM Polska Miedź S.A. Oddział ZG "Rudna" in 2011. The mining shaft hoists installed in the R-II shaft are not only the basic extraction equipment in the Rudna mine but also throughout KGHM. The unscheduled standstill cases of these hoists generate huge losses for the mine. These reasons resulted in the necessity for the ad hoc repair of the damaged shaft and operational use of the hoist until a new shaft is completed and delivered.

The article describes the works related to the preparation and execution of the repair of the shaft as well as the tests that were performed. The last stage was the preparation of the operational conditions of the shaft of the machine with the repaired shaft with limited kinematic parameters and under strict supervision until the execution of the new shaft.

Key words: *mining shaft hoist, hoisting machine, main shaft, hoisting machine breakdowns*

1. INTRODUCTION

The mining shaft hoists installed in the R-II shaft are intended for extracting excavated material in skips with a capacity of 33 Mg. After thirty years of intense operational use (since 1974), their comprehensive modernization was ordered. The hoisting machine in the southern section (S) of the R-II shaft was modernized in January of 2004, and the hoisting machine in the northern section (N) of the R-II was modernized in May of 2006. The modernization consisted of replacingthe mechanical part of the machines; that is, the main shaft, hoist drum, bearings, and brake system along with the control elements.

The machine is ready for automatic control and for manual control by the hoisting operator.

The characteristic data of the hoisting machine declared in the documentation is as follows:

– hoist drum diameter	5500 mm,
– nominal diameter of hoist ropes	50–54 mm,
– number of hoist ropes	4,
– maximum static overweight	350 kN,
– maximum static force in the four hoist ropes	1200 kN,
– shearing force of the four hoist ropes	4 · 2130 kN,
– maximum speed of excavated material pulling	20 m/s.

The hoist drum of the hoisting machine is set on the main shaft supported by two rolling bearings on both sides of the hoist drum. The bearings are lubricated with oil (under pressure) in a closed system. On both of the free ends of the shaft, the rotors of the driving motors are set. The driving system of the hoisting machine consists of two separately excited PW-106 direct current motors with 3600 kW of power each and powered from DCA 600 series thyristor converters.

The break consists of four break bands with sixteen pairs of actuators (four in each band), and the control and power supply unit are composed of two hydraulic units (one of which is the reserve). The bearings of the main shaft, break bands, stators of the driving motors, and equipment for machining the rope grooves are set on the steel hoist tower structure.

This machine in the mechanical part consists of a main shaft set on two rolling bearings, a hoist drum ready for cooperation with four load-bearing hoist ropes, a break acting on two brake discs composed of four bands withfour installed pairs of hydraulically restored brake actuators controlled with a double-unit control and power supply set, two driving motors, and equipment for machining the rope grooves.

The pulse transmitters connected to the main shaft are used to supervise and control the operation of the machine; i.e.:

- a pulse generator installed on one side of the shaft,
- a tach generator with a pulse generator are set on the other side of the shaft.

The pulse generator driven from the axle of the shaft rope roller pulleys is used to control the travel of the vessels of the shaft hoist.

Both hydraulic units of the control and power supply unit of the break are located at the level of the hoisting machine. Figure 1 presents the view of the machine in the (S) section after modernization.

Fig. 1. View ofhoisting machine in section (S) of R-II shaft after modernization in 2004 [1]

On April 17, 2011, the operators of the hoist noticed damage in the shaft of the hoisting machine in the southern section in the area of the passage of the shaft in the flange used to connect with the hoist drum on the eastern side.

A crack as well as chips of the material in some places were visible along about half of the circumference of the shaft. The nature of the damage indicated fatigue crack (Figs. 2 and 3).

Due to the possibility of accessing the place of the damage only from the side of the shaft bearing (eastern), an accurate assessment of the damage was possible only after dismantling the hoist drum and completing specialized inspections with visual and magnetic particle methods. These inspections were done on April 17, 2011, by an expert from Autorytet Spółka z o.o. [2]

Fig. 2. Cracks in circumference with crushing [1]

Fig. 3. Cracks oncircumference andradial cracks [1]

On the basis of the inspections, Figure 4 was drawn up with the discovered damages marked.

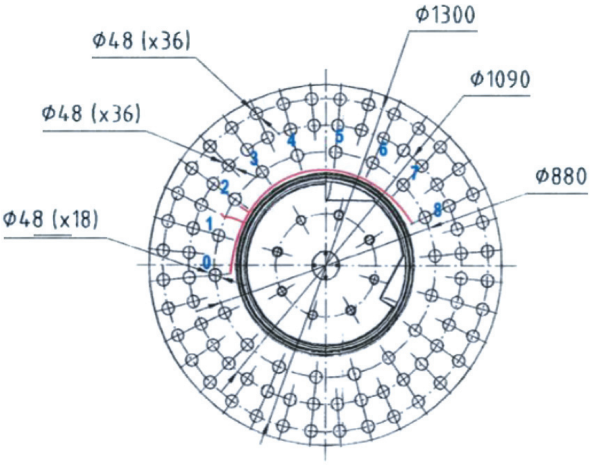

Fig. 4. Side disc of hoist drum of hoisting machine in southern section (eastern side) with cracks marked (red) [2]

The inspection resulted in the following conclusions:

- a crack on the circumference ~ 1000 mm long in the axial direction (in parallel to the axle of the shaft) through the material,
- a crack with some crushing of the material ~ 460 mm long in the axial direction through the material,
- two radial cracks (perpendicular to the axle of the shaft) from the circumference ~ 100 mm long and ~ 60 mm between the Bolts 1 and 2.

The found damages did not allow for the further operational use of the hoisting machine. The consequence of the above inspections was the decision of the Director of the Mining Office to the Power and Mechanical Equipment Test Inspections to stop the operation of the mining plant in the part related to the mining shaft hoist installed in the southern section of the R-II shaft O/ZG Rudna [3].

2. CONCEPT OF REPAIR OF SHAFT

The decision was made to repair the cracked shaft by welding in accordance with the technology developed by the Institute of Welding in Gliwice and agreed with by ZG Rudna [4]. Due to the vast loss of the material of the flange, the preparation of a weld groove was necessary; that is, the execution of the appropriate undercuts (geometry) of the connected elements (Fig. 5). After the appropriate preparation of the edges of the weld groove, penetration tests were conducted (to detect any cracks).

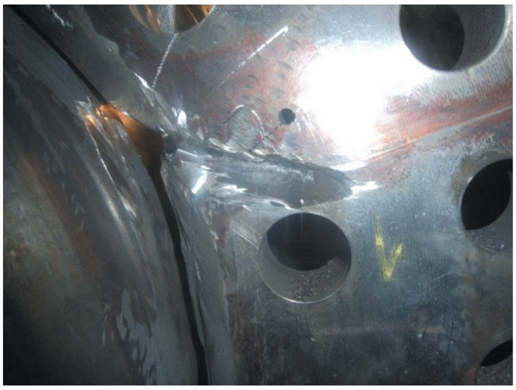

Fig. 5. The repair. Preparation of weld groove with view on depth of flange and size of crack [1]

The area around the site of the repair was isolated and then heated up to a temperature of ca. 100°C with an electric heating unit and heating mats ata rate of about 25°C/h. After stabilizing the temperature on the shaft and the flange, the welding work was started while at the same time continuously recording the temperature of the elements neighboring the site of the welding (Fig. 6). Special attention was paid to maintaining the difference of the temperatures of the elements of the bearing supporting the shaft within the proper range [5–7].

Fig. 6. Area around place of welding was isolated and then heated up with electric heating unit and heating mats. Heating speed was about 25°C/h [1]

To protect the rolling bearing against possible damage as a result of thermal expansion, the bearing case was heated up so that the temperature difference between the internal and external races would not exceed 15°C.

Due to the fact that the material of the shaft is made of steel with highly difficult weldability (as well as considering the scope of the damage), the welding process was done in two stages. First, the buffer layer was done on the side of the shaft and of the flange. Then, the surface of the buffer layer was properly smoothened by grinding, and the weld groove was started in accordance with the prepared instruction (Fig. 7). Figure 8 presents a view of the part of the shaft in the area of the crack after applying the buffer layer.

The next stage was connecting the flange to the shaft (closing the weld). An ENiCrFe-3 wire was used as a binder according to AWS A 5.11. After connecting the flange with the shaft, the whole weld groove was filled in along with the machining allowance (Fig. 9).

In each stage of the welding work, penetration tests were executed. If cracks were detected, the material was ground to remove them, with the welding work being continued only afterwards. The additional materials used for the welding were selected so as to enable the execution of the weld of the difficult-for-welding shaft material and obtain the properties of the weld deposit as close to the properties of the native material of the shaft as possible. The welding work related to the repair of the shaft was executed uninterruptedly (day and night) for about a week.

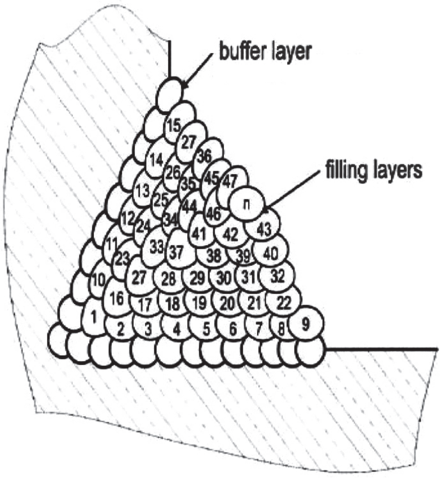

Fig. 7. Order of execution of welding work: buffer layer and filler layer [4]

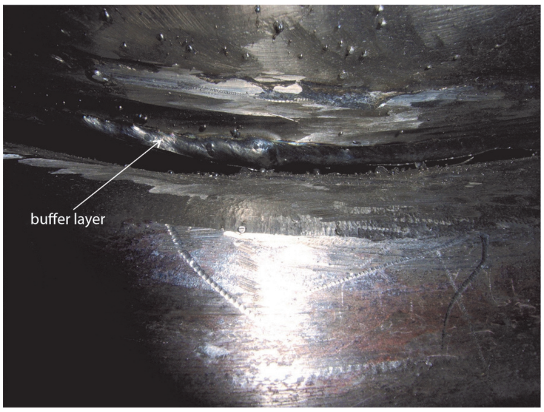

Fig. 8. View of shaft after applying buffer layer [1]

Fig. 9. Machining of shaft after welding to render proper curvature radius for part of shaft [1]

3. INSPECTION OF MACHINE SHAFT AFTER REPAIR

After the repair, an inspection of the machine shaft was conducted in order to confirm the readiness of the repaired shaft for further operational use. The inspection was executed by experts from Autorytet Spółka z o.o. [8, 9] (a non-destructive inspection of the shaft) and by employees of the Rope Transport Department (Katedra Transportu Linowego) of AGH University of Science and Technology in Krakow (the stress tests), among others. The extensometric tests of the stresses executed by KTL-AGH University of Science and Technology in the cylindrical part of the shaft and in the flange connecting it to the hoist drum as well as the thermovision tests of the repaired part of the shaft were to confirm the lack of stress accumulation in the part of the shaft where the repair was done.

The purpose of the performed measurements of temperature distribution in the machine shaft in the area of the passage to the flange used to connect the shaft to the hoist drum [10] was to determine any changes in the temperature in this spot. An FLIR P660 thermovision camera with a tripod was used for the inspection. The recorded results of the inspection were compared with the results recorded for the same machine on October 23, 2010; that is, before the breakdown [11]. Figure 10 shows the sample thermogram of the part of the drive shaft and of the disk of the drive wheel.

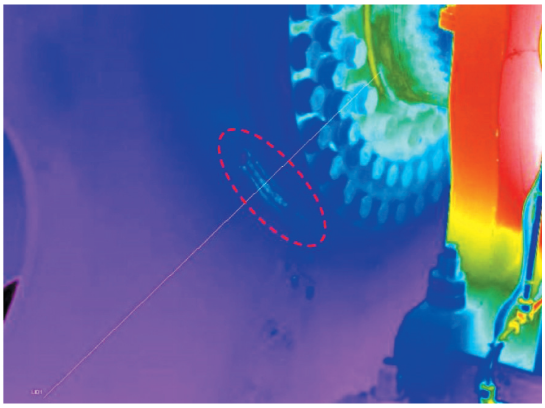

Fig. 10. Thermogram of part of drive shaft and of disk of drive wheel from southeastern side ("rain" pallet) [10]

The thermovision measurements showed a lack of significant temperature differences of the analyzed driving structure (the shaft – the hoist drum). No major differences were recorded against the measurements before the breakdown. The average temperatures of the shaft in both measurements differed due to the differences in the ambient temperature during the measurements. For this reason, the differences in the temperatures were more important at the passage from the cylinder part of the shaft to the flange to the connection with the hoist drum. The temperature difference was about 5.3°C. One should remember that the measurements could be burdened with measurement uncertainty resulting from the different emissivity factors for the different examined structures, flow of warm and cold masses of air forced by the fans of the motors, vibrations of the tower that may have negatively affected the thermovision camera, effect of the reflection of radiation from other sources of heat, etc.

Both extensometric and thermovision inspections showed the lack of a clear increase in the concentration of local stresses (the notch effect) in the examined area of the shaft after its repair.

4. PARAMETERS OF OPERATION OF MACHINE WITH REPAIRED SHAFT

After finding that the shaft after the repair did not show clear defects, documentation of the parameters of operation of the machine with the repaired shaft was started until the time of execution of the new shaft.

The shaft was made of E335 steel with the following values of strength properties:

- yield point $R_{el} = 280$ N/mm^2,
- temporary tensile strength $R_m = 590$ N/mm^2,
- limit substitute allowed stress taking into consideration permanent fatigue strength $R_{limit} = 50$ N/mm^2.

The damage of the cross section was found in the place of the base of the eastern flange of the shaft, with the two halves of the side disk of the hoist drum fixed with three rows of bolts. In the strength calculations of the shaft [12], it is the cross section with the diameter of $\phi 685$ mm with the following coefficients: bending strength $W_g = 31{,}555{,}249$ mm^3; torsion strength $W_s = 63{,}110{,}498$ mm^3. The maximum calculated accident stresses for the given case of load are as follows (respectively):

- normal load $\sigma_e = 30.87$ /mm^2,
- exceptional load $\sigma_e = 179.96$ /mm^2.

It was assumed, however, that the completed repair of the damaged cross section of the shaft cancause a decrease in the general load capacity of the shaft of an estimated value of ca. 30%. Therefore, the reduction of the technical parameters of the operation of the hoisting machine after the repair was proposed up to the following values:

- actual usable mass 25,000 kg,
- extraction speed 12 m/s,
- travel acceleration and delay 0.5 m/s^2.

For such assumed parameters, the strength calculations of the shaft were done, achieving the following maximum calculated accident stresses for normal load $\sigma_e = 21.20$ N/mm^2. Exceptional load causes stress of an unchanged value against the condition before the repair. The reduction of the values of the operational parameters of the machine will cause the reduction of stress in the repaired cross section by 9.67 N/mm^2; i.e., by 31.32%. The limitations of the travel parameters of the hoisting machine (in particular, acceleration and delay to a value of 0.5 m/s^2) will cause a major limitation in the value of the dynamic moment, which is decisive for the fatigue process of the structural elements of the machine.

The strength analysis of the shaft submitted by the producer of the shaft, drafted up with the finite element method (FEM) with the assumed operational parameters of the hoisting machine after the repair of the shaft also showed the acceptable level of stresses, confirming the results of the traditional strength calculations. The reduced values of the proposed operational parameters after the repair of the shaft resulted in ca. 40% reduction in the maximum value of the moment from the overweight in the condition of acceleration of the travel of the machine; i.e., from 1766 kNm to 1046 kNm. It was the significant reduction of the load with the moment of the flange of the shaft in the situation when the load-bearing cross section of the base of the flange of the shaft was damaged. The consequence of the reduction of the operational parameters of the hoisting machine also came in the form of an increase in the strength excess of the connection of the flange of the shaft with the side disk of the hoist drum from a value of 5.62 to 9.49.

It was found that the repair had not caused the material notch that may develop in the case of a significant difference in the hardness in a small area of the element. It is another premise proving that, after the repair and limitation of the load, the further operational use of the shaft is possible.

Considering:

- the assessment of correctness of the technology and execution of the repair of the shaft;
- the estimated assessment of load-bearing capacity of the executed connection;
- the results of the classic strength calculations of the shaft;
- the strength analysis of the shaft provided with the FEM method.

In reference to the above considerations, the decision was made on allowing for the time-limited (up to six months after the time of repair) operational use of the hoisting machine with limited travel parameters until the execution of the new shaft. The internal cross section of the base of the flange of the shaft (where the crack probably started) was invisible from the inside of the hoist drum, as it was covered by the (eastern) side disc of the hoist drum. For this reason, after arrangement with the designer of the shaft, for the inspection of this cross section, three openings were executed in each half of the side disk of the hoist drum to enable a visual or technical inspection of this cross section. The visual inspection of the cross section of the base of the flange of the shaft from the eastern bearing side was fully possible all the time. Due to the accessibility, this cross section could be inspected with the available technical methods.

Control arrangements:

- continuous visual inspection of a properly prepared employee of the area of the shaft of the hoisting machine between the case of the eastern bearing and the flange of the shaft was recommended; this inspection was important due to the fact that the operators do not have visual contact with the machines in the tower of the R-II shaft;
- after each shift, visual inspection of the repaired cross section should be done by entering the interior of the hoist drum through the openings and providing good lighting; the inspection should also cover the western flange of the shaft;
- in the first three weeks of the operation of the machine after the repair, inspections should be done as often as possible, minimum after each shift, as well as during the technological stopping of the hoisting machine;
- after three weeks of operation of the machine, the inspections of the repaired cross section should be conducted once per shift;
- the revisions of the area of the repaired shaft should be conducted following the effective regulations of safety of work.

5. SUMMARY AND CONCLUSIONS

As a result of the breakdown, the R-II mining shaft hoist in the southern section was out of operation for 27 days (April 17, 2011, through May 13, 2011). The hoisting machine was operated during the next 118 days (until September 8, 2011) with limited travel parameters (ca. 54% of the nominal capacity). From September 8, 2011, until September 16, 2011, the shaft was replaced with a new one with a different design.

The breakdown related to the crack of the flange of the shaft caused the total losses in the extraction of copper ore estimated (according to the ZG Rudna data) at 43, 240 skips (1,362,060 Mg). Additionally, due to the emergency stopping of the R-II S mining shaft hoist, changes were necessary in the logistics of deliveries of ore to O/ZWR Rejon Polkowice i Rudna. One should remember that the losses would be significantly higher had the repair of the shaft of the hoisting machine in the southern section of the R-II shaft not been successfully provided.

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