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Diagnostics and reconstruction of bearing units

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Abstract. This paper presents new research results aimed at ensuring reliability and durability of equipment due to its diagnostics including monitoring and recording parameters changes of bearing units technical conditions determined before the moment of equipment shutdown, dismantling and fault detection of units as well as development of new methods for their restoration. As a method of operability recovery of unique bearing units a progressive approach is offered based on use of composite material 'Multimetal Stahl 1018'. A new field of application of composite material 'Multimetal Stahl 1018' to create temporary bearing sliding support instead of failed unique design construction with rolling bearings is described. Successful operation of majority of industrial equipment units restored using composite materials evidences broad prospects for solving various repair tasks mechanics of repair industries face including protection of foundations from destruction during vibration loads.

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1. Introduction

Reliability and durability of equipment are determining factors for sustainability of any production based on use of continuous production cycles. Ensuring compliance of mechanical equipment with requirements of reliability and durability largely depends on maintaining operating condition of bearing assemblies [1]. Certain system of equipment maintenance has been developed at industrial enterprises that regulates procedure for carrying out work related to operation of bearing assemblies. Part of work is carried out by divisions of enterprises, extraordinary operations are usually carried out by specialized contractors. Diagnostics of mechanical equipment to ensure its trouble-free operation and, in particular, state of its bearing assemblies in combination with modern methods of restoring their performance has become increasingly widespread.

Large number of scientific works devoted to identification of damages of mechanical equipment bearing assemblies has been carried out [1–4]. Types of bearing assemblies damages are usually divided according to location of defects. Following main defects are distinguished: damages of rings, damages of cages, damages of rolling elements, etc. However, the same type of damage localized in different places can be caused by different reasons. Consequently, use of such classification for identifying causes of damage of machine elements, in particular rolling bearings, cannot guarantee acceptable accuracy. It is proposed to identify force effect on detail to determine cause of failure. Nature of wear of equipment detail will depend on type of force and its direction. Appearance of failed detail surface is closely related to nature of its wear arising in damaged unit. It is possible to classify type of force action according to following types: circulating load (shaft imbalance); local load (gravity); axial load (axial forces arising in bevel gearing); load from misalignment of assembly details (misalignment of bearing and shaft) [5–8].

This classification allows localization of damage. Types of damage are proposed to be subdivided into:

1. mechanical ones are fatigue failure, abrasive wear, plastic deformation;
2. molecular mechanical ones are adhesive, selective transfer;
3. corrosion-mechanical ones are, in particular, oxidative wear.

Prevention of these and other types of destruction is the main task of diagnostics. To monitor technical condition of supporting elements of mechanical equipment, in general case, following diagnostic parameters are used [9]:

- visual inspection, including measurement of linear dimensions;
- control of machine noises;
- unit temperature control;
- lubricant analysis;
- analysis of drive current characteristics;
- measurement of vibration parameters.

Visual inspection usually allows identifying already developed damages, e.g. extrusion of end caps arising at the last stage of destruction of bearing assemblies. This method does not represent significant value from point of view of early diagnosis.

Mechanism noise control is based on subjective organoleptic sensations of specialists and allows getting high-quality picture of bearings conditions at 'good-bad' level. Under conditions of working equipment it is impossible to ensure effective listening to noise with help of stethoscope because according to labor protection rules it cannot be, e.g. on moving crane. In addition, experience of operating steel casting cranes has shown that the most likely damage is on internal (relative to the crane beams) bearings which are practically inaccessible for listening. One solution is to use ultrasonic stethoscopes manufactured by SKF.

Controlling temperature of bearing units can be effective if there is insufficient amount or inconsistency of grade of lubricant used at intensive stage of destruction of bearing unit elements during prolonged (more than 1 hour) operation of mechanism. Such solution is possible on practice but it is very difficult to provide:

- placing temperature sensors directly inside bearing assembly and ensuring reliable signal transmission to measuring device in existing production conditions;
- installation of sensors on equipment which has not place for installation of diagnostic devices.

It is preferable to use non-contact temperature measurement methods using pyrometer or thermal imager for temperature control. However, problem of control of hard-to-reach units (e.g. internal (relative to crane beams) bearings of running wheels of casting crane) is also not solved.

Lubrication analysis involves performing control operations of lubricant flow into friction zone and determining quality of lubricant. Problem of sampling lubricant from bearing housings during their operation is practically insoluble which makes this method inapplicable in real operation conditions.

Analysis of drive current characteristics on practice of support units diagnostics of equipment has not found wide application because it requires use of systems for recording electrical parameters of drive in production conditions which is difficult to implement on equipment. In addition, it needs involvement of qualified personnel to analyze obtained records in conjunction with technological processes and emerging loads in mechanical system.

Above analysis based on well-known publications showed that the most acceptable data sets in real operating conditions (allowing to assess condition of units with rolling bearings) are vibration parameters taking into account such factor as their negative impact on durability of foundations. Measurement of vibration parameters as effective method for detecting malfunctions of mechanical systems is widely used in practice of operating mechanical equipment [1–4, 6–10]. Well-developed algorithms and diagnostics standards including bearing assemblies are based on measurement of vibration parameters. However, experience of operating mechanical equipment has shown that this method also has limitations in terms of assessing state of bearing assemblies in specific operating conditions of construction industry. There are cases when with favorable vibration parameters bearing units of critical equipment suddenly failed during absence of their obvious overload by external forces which could very likely be a consequence of deformation of foundation supports and, as a result, it resulted in uncontrolled misalignment of mechanism. As a rule such incidents remain in materials of factory investigations of accidents causes of operating equipment and are not subjected to thorough analysis and, accordingly, remain unknown to operational and design personnel involved in ensuring use and design of mechanical equipment. Familiarization with the results of investigations of such accidents will, from point of view of authors of this paper, improve work on ensuring reliable and durable use of mechanical equipment.

As it was mentioned above, condition for ensuring stable operation of construction industry is use of diagnostics of mechanical equipment and state of its bearing assemblies in combination with modern methods of restoring their performance. There is a problem associated with uniqueness and high cost of mechanical equipment bearing assemblies which makes it economically inexpedient to manufacture replaceable set of spare parts in advance or use reserve piece of equipment [1] during restoration of defective surfaces of mechanical equipment bearing assemblies. There is a danger of prolonged downtime of equipment which determines possibility of fulfilling production program of any enterprise in the event of premature or unpredictable failure of such units. This is due to need to wait for unique unit newly manufactured at machine-building enterprise (e.g. pins of support ring of oxygen converter) or with sufficiently long recovery cycle of expensive unit (e.g. custom-made gearbox housing). In the latter case, classical recovery technology is used including dismantling of defective assembly followed by transportation to mechanical workshop to remove defective fragments by machining, restoration of metal surface by cladding, heat treatment and finishing machining to achieve nominal size. At the same time, experience of solving problems of restoring various units using composite materials [1] or using composite elastomers [11, 12] is known. Use of composite materials to restore performance of unique and expensive bearing assemblies of mechanical equipment allows, in some cases, to solve problem arising from sudden failure of unique assembly with long production time and significantly reduce recovery time for single-piece products.

New results obtained during the performance of works to ensure the equipment reliability and durability can be shown. The complex of works comprise stages from diagnostics, that includes monitoring and recording of the parameters changes of bearing assemblies technical conditions, to determination of the equipment shutdown moment, disassembly and detection of assemblies, selection and assignment of a recovery method. Problem of assessing applicability of monitoring vibration parameters for determining performance of bearing assemblies is considered on example of wheel assemblies of steel casting crane. Problem of restoring unique and expensive bearing assemblies of mechanical equipment was solved in two versions, namely, temporary solution to restore operability of bearing support of support ring trunnion of the steelmaking converter and complete restoration of operability of worn surfaces being in contact with bearing of reducer of screw-down mechanism of hot thick strip rolling mill rolling stand. Progressive approach based on use of composite material 'Multimetal Stahl 1018' was used as method of restoring operability of bearing assemblies.

2. Methods

Steel casting crane is moved by four movement mechanisms where two ones are on each side of bridge. Each drive of the travel mechanism consists of an electric motor, a brake and a gearbox connected to driven wheel. The driven wheels of the crane are located in non-driven and driven balancing trolleys to main balancers. The main balancers are pivotally connected to the bridge. Wheels are installed in roll-out axle boxes connected to trolley frames. During operation of the crane there were sudden failures of the running wheel bearings with jamming of the mechanism and violation of technological sequence of steel smelting. During elimination of consequences by shop personnel reasons for sudden failures were not identified and therefore task was set to assess performance of units using vibration diagnostics methods.

To determine vibration parameters in the bearing assemblies of the driven wheels of the movement mechanism of the steel casting crane following instruments were used: 795 M vibration spectrum analyzer, vibrometer 107 B. Sensor is mounted using a magnet. The sensor installation place is on the driven wheel bearing assembly. The sensor orientation is in vertical direction.

Measurements were carried out in several frequency ranges: 2…400 Hz, 2…1000 Hz, 10…1000 Hz, 10…2000 Hz, 10…4000 Hz. Lower limit of ranges was determined being based on basic informative frequencies of bearing 3632 that has following data: rotation frequency (at nominal speed of the crane movement) f_{rot} = 3 Hz; number of rolling bodies z = 15; diameter of rolling elements d = 45 mm; contact angle α = 14^0; diameter of circle passing through centers of rolling elements D = 250 mm. Calculation based on known dependencies [10] showed that frequency associated with damage to:

- outer ring is 18.5 Hz;

– inner ring is 26.4 Hz;
– rolling elements is 16.1 Hz;
– separator is 1.2 Hz.

Repair of bearing assemblies was carried out according to:

– temporary option for destroyed roller spherical double-row bearing on trunnion of support ring of the 300 tons converter from drive side;
– full restoration option of operability for worn surfaces being in contact with bearings of screw-down mechanism reducer of hot thick strip rolling mill rolling stand.

Standard measuring tools such as calipers, micrometers, internal micrometers, locksmith rulers and sets of probes were used to assess size of defects in bearing assemblies as well as dimensions of technological equipment used for repairs and reconditioned surfaces.

3. Results and Discussion

In described case of studying vibration parameters of bearing assemblies of running wheels of steel casting crane choice of control points for measuring vibration was decided unambiguously due to design of bearing assembly. All wheel bearings are installed with transition fit and without bushes. Loading zone of external force and support reaction are located in the upper part of rings. Therefore, sensor for measuring vibration parameters must be located on top, in radial direction, vertically, in the middle of bearing.

Preliminary measurements of vibration parameters were carried out on operating equipment when the crane was moving without load to select frequency range and vibration parameters.

Spectral analysis of vibration parameters data obtained during experiment indicates quasi-polyharmonic composition of vibration signal with broadband components of shock processes. Spectrum contains components with frequencies: 6 Hz, 40 Hz, 50 Hz, 75 Hz, 86 Hz, 97…100 Hz, 120…123 Hz, 177…200 Hz, 256 Hz, 300…315 Hz, 400…444 Hz, 525 Hz, 1395 Hz, 1985 Hz, 2339 Hz, 2870 Hz, 3262 Hz, 4024 Hz. Signal is modulated by frequencies: 5…6 Hz, 24…27 Hz, 82 Hz.

Numerical results of eleven measurements of vibration parameters of the running wheel outer bearing using equipment described above are given in Tab. 1. The Tab. shows frequency ranges of measurements, root mean square values (RMS) of corresponding parameters and peak values of vibration acceleration recorded during the experiment.

Disassembly of failed bearing assembly of the running wheel during repair showed presence of traces of thickening and oxidation of lubricant (so-called 'lubricant coking'). General view of this unit is shown on Fig. 1. Traces of the bearing rotation in its housing were revealed on the outer surface of the outer ring of the bearing.

Below there is example of repairing a bearing assembly that has failed as a result of coking lubricant. As mentioned above, the repair of the bearing assembly according to the temporary option was carried out for surfaces being in contact with destroyed spherical double-row roller bearing on the trunnion (850 mm in diameter) of the bearing ring of the 300 tons converter from the drive side (refer to Fig. 2).

Table 1. Vibration parameters measurement results.

#	Frequency range, Hz	Vibration displacement, RMS, μm	Vibration speed, RMS, mm/s	Vibration acceleration, RMS, m/s^2	Vibration acceleration, peak, m/s^2
1	2…400	5.7	0.10	0.004	–
2	2…400	5.7	0.10	0.004	–
3	2…400	78.0	1.30	0.070	0.3
4	2…1000	263.0	43.40	0.800	–
5	2…1000	477.0	75.70	1.200	–
6	10…1000	603.0	44.70	1.800	2.1
7	10…1000	12.0	0.90	0.100	–
8	10…2000	14.0	1.30	0.200	–
9	10…4000	6.0	0.46	0.390	4.1
10	10…4000	10.0	1.00	0.400	–
11	10…4000	35.0	2.40	0.300	–

Figure 1. Coking traces of lubricant on the running wheel bearing details.

Figure 2. Surface of the trunnion of the converter support ring after the destruction of the bearing.

The unit is slow-moving (about 1 rpm) so its failure was not diagnosed in a timely manner. Due to it degree of damage done to the trunnion seating surface was very high. As it is seen on Fig. 2, the trunnion surface after contact with destroyed bearing elements and rollers is covered with dents and has noticeable wear of outer diameter surface. Such damage done to the bearing seat on the trunnion makes it impossible to further use the trunnion without dismantling and subsequent laborious restoration.

Considering that the trunnion is made as one piece with the converter support ring solution seems to be obvious. It is to order a new ring and a new bearing keeping in mind its unique characteristics both in size and design. But this rather long way did not exclude necessity of putting the converter into operation with some kind of temporary technical solution until moment of overhaul with installation of a new support ring and bearing.

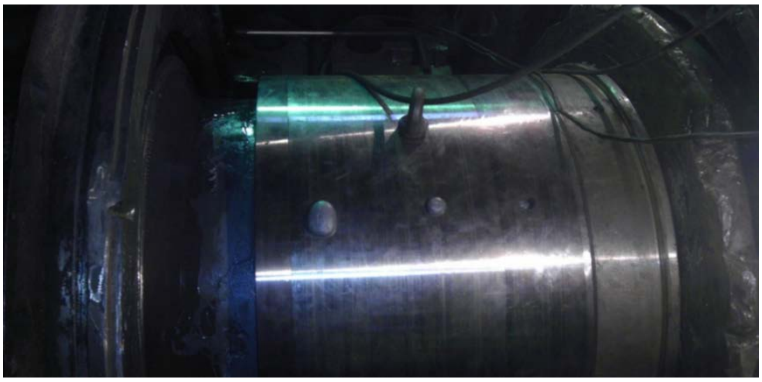
It was decided on this support to switch temporarily to a sleeve bearing. To implement this idea it was necessary to restore the trunnion surface and install assembled cage on it which would subsequently be used as trunnion surface being in contact with inserts of sliding bearing. It was proposed using composite material 'Multimetal Stahl 1018' produced by company 'Diamant Metallplastic GmbH'. Technical characteristics of 'Multimetal Stahl 1018' are given in Tab. 2 [13, 14].

Table 2. Technical characteristics of 'Multimetal Stahl 1018'.

Compressive strength	N/mm^2	max 160
Tensile strength	N/mm^2	76
Shear strength	N/mm^2	89
Bending strength	N/mm^2	22
Elastic modulus	N/mm^2	14.000
Linear elongation ratio		32 × 10^{-6} °K
Long-term temperature resistance	°C	– 40 / + 90
Resistant to aging and weathering		very good
Processing time at +20°C	min	~ 45
Hardening at +5°C	hour	~ 72
Hardening at +20°C	hour	~ 24
Specific weight	gram/cm^3	2.4

However, doubts arose whether the material could withstand part of weight of the converter with steel acting on the support. Theoretical calculations have confirmed possibility of using the composite when temperature of contact details does not exceed 80 °C. Preliminary temperature measurements showed that its values within area of the trunnion do not exceed 60 °C, hence restoration of the bearing surface of the trunnion was performed using the composite. Technology of using the composite and restoring the trunnion is illustrated on Fig. 3. The stages of this work included: degreasing the trunnion surface, preliminary installation of two parts of assembled cage 50 mm thick on base screws and centering it along axle of the trunnion, then dismantling the cage, applying the composite material (refer to Fig. 3a) and subsequent installation of the cage on the base screws with further connection of both parts with screws installed in recesses relative to their working surface. Excess of the composite is visible, squeezed out through control holes which confirms complete filling with the composite of cavity between the old trunnion and inner surface of the cage (refer to Fig. 3b).

a)



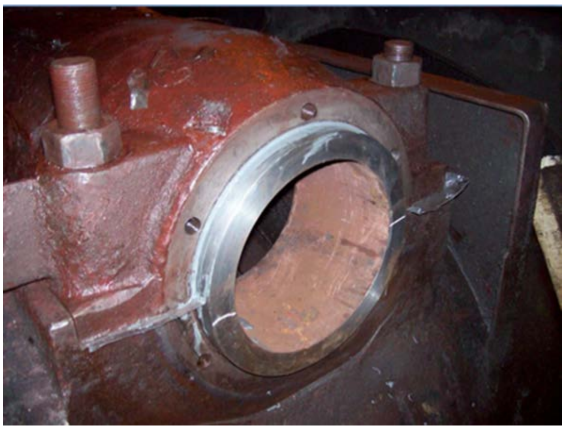
b)

Figure 3. Stages of the trunnion restoration: a) the composite application; b) installation of the assembled cage.

Rebuilt according to this temporary scheme unit worked from March to June and was dismantled due to failure of the composite material because temperature in zone where the composite was located increased (when outside temperature increased) and during its destruction it was around 140 °C.

Complete restoration of operability of housings worn surfaces being in contact with rolling bearings is described using example of restoration of the screw-down mechanism reducer housings of the hot thick strip rolling mill rolling stand. The housings worn surfaces of the screw-down mechanism reducer are shown on Fig. 4. Standard technology for restoring those surfaces requires dismantling worm gear and transporting the reducer housings to machine shop for restoration. In this case, use of the composite material 'Multimetal Stahl 1018' made it possible to abandon operations performed in the mechanical shop. For this specially made polished template with diameter equal to diameter of outer ring of bearing was processed with special separator and after applying the composite to machined groove the template was installed on unworn surfaces being in contact with rolling bearing on both of the housings (refer to Fig. 4b).


a)



b)

Figure 4. Restoration of housings worn surfaces being in contact with rolling bearing of the screw-down mechanism reducer housings of the hot thick strip rolling mill rolling stand: a) worn surfaces of the housings; b) formation of support surfaces using the specially made polished template.

After 16 hours of complete polymerization of the composite the template was removed, excess of extruded and hardened composite was also removed. Restored housings worn surfaces are shown on Fig. 5. Restored unit was returned for another restoration after 3 years of operation.

a)

b)

Fig. 5. Restored housings worn surfaces being in contact with rolling bearing: a) bottom housing; b) top housing.

From data given in Table 1 it is clear that overall level of vibration parameters (except cases 4-6 in terms of vibration speed and vibration displacement) is low. Thus, RMS of vibration speed in most observations remain within limits corresponding to good technical condition of casting cranes that is less than 2.8 mm/s [9]. Cases 4-6 (where range of values is over 18 mm/s) correspond to unsatisfactory technical condition [9] and they can be apparently associated with insufficiently reliable fastening of the vibration sensor (using a magnet) which leads to jumps in readings when the casting crane passing joints of its rails.

In low-frequency region of spectrum which includes informative frequencies of bearings used in running wheel assemblies all recorded parameters have significant scatter of values, i.e. ratio of the highest value of RMS parameters to the lowest is around ten or more times. At the same time, in measurement range from 10 to 4000 Hz RMS vibration accelerations are quite stable, i.e. ratio of the highest RMS value to the smallest is approximately 1.3 with peak value exceeding RMS by about 10–13 times. For the first stage of further research it is advisable to use specified measurement range (from 10 to 4000 Hz) with vibration acceleration control as a parameter giving relatively stable readings. To assess effectiveness of proposed measures to improve monitoring system of technical condition of running wheels bearings it is necessary to carry them out for at least 6-12 months with statistical analysis of obtained results and subsequent refinement of monitoring method and frequency range of controlled parameters.

Failure of running wheel bearings at moderate vibration rates of the unit may be due to phenomenon of thickening and oxidation of lubricant ('lubricant coking') revealed during disassembly of defective unit shown on Fig. 1. On the investigated crane this phenomenon was noted: in bearings located on side of heat effect acting from moving ladle with hot steel leading to elevated temperature of the bearing assembly details and in irrational lubricant supply device designed during development of the crane. Coking of the lubricant leads to increase of torque of resistance between rolling elements of bearing and their rolling path; the torque of resistance becomes greater than torque fixing fit of the bearing outer ring in the bearing housing which ultimately leads to wear of the bearing seat and appearance of additional shock loads due to appearance of gaps. Temporarily rebuilt converter trunnion assembly of the converter support ring worked, as indicated above, from March to June and it was dismantled due to destruction of the composite material. Temperature in zone where the composite was located was around 140 °C (before repair measurements on operating converter showed temperature of about 60 °C in this zone at permissible operating temperature of the applied composite material of 80 °C). Thus, it can be stated that the composite material can withstand significant loads in compliance with temperature limits that in this case made it possible to solve problem of starting the converter and using it in time interval necessary to prepare for replacement of the support ring and bearing.

The gearbox housing of the screw-down mechanism of the hot thick strip rolling mill rolling stand with full restoration of performance of worn surfaces being in contact with rolling bearings using the composite material has been successfully operated for three years that exceeds service life of such units restored using known technology including dismantling, moving to specialized section of mechanical workshop, machining in order to remove defective layer, followed by cladding and precise machining.

The restoration technology with formation of worn surfaces of the housings by the composite material using the polished template showed greater load-bearing capacity of restored assembly in comparison with traditional restoration method. This feature can be explained by fact that polished outer ring of bearing contacts restored by the composite material surface and formed, as shown above, using the polished template. At traditional technology of restoring support surface after its machining with milling cutter makes bearing outer ring to be sat on tops of microroughness of milled surface. Even with slight dynamic loads these tops of microroughness can be pressed down which is reason for subsequent wear of bearing seat [15–25].

Another factor providing increase of loading capacity is ability of the composite enclosed in a closed volume, according to developed technical proposals of the restored unit design, to partially damp shock and vibration loads without destruction which contributes to increase of service life of supporting surface of both mechanism itself and metal structures or foundations on which it is installed.

4. Conclusion

The authors analyzed known methods for diagnostics of running wheels bearing assemblies on example of a casting crane in steelmaking shop. Analysis showed that vibration parameters give the most acceptable data in real operating conditions to evaluate technical state of rolling bearings. However, this method is not universal because its application must be combined with thorough analysis of design and loading of diagnosed bearing unit. For the considered crane, there were cases of failure of running wheel bearings with moderate vibration of the unit associated with lubricant coking under influence of elevated temperatures because of peculiarities of technological process structural elements were heated from the ladle with hot liquid steel and influence of irrational device for supplying lubricant material to bearing assembly.

At present, composite material 'Multimetal Stahl 1018' can have a new application of creating temporary sliding bearing support instead of failed unique design with rolling bearings. Usage of such support instead of spherical double-row ball bearing (diameter of trunnion is 850 mm) of damaged roller for support ring of the 300 tons converter allowed the converter to work for three months. This helped to reduce economic losses associated with long production and installation time of new trunnion unit and corresponding downtime of the converter. Longer service life of the temporary support can be provided by combining this method of bearing assembly temporary restoration with additional cooling system.

Restoration of machines housings with worn surfaces under outer rings of bearings using conventional technology requires significant time and money expenses for dismantling and cladding of worn surfaces and subsequent machining.

Usage of composite material 'Multimetal Stahl 1018' to restore support surfaces of bearing units of screw-down mechanism reducer of hot thick strip rolling mill rolling stand allowed to refuse operations carried out in machine shop and meeting deadline for current repair of equipment.

Successful operation of majority of industrial equipment assemblies restored with help of composite materials testifies to broad prospects for solving various repair problems facing mechanics of repair industries.

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