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FAILURE ANALYSIS OF ROTARY SCREW PUMP

ANALIZA HAVARIJE ROTACIONE VIJČANE PUMPE

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- metallography
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- erosion

Ključne reči
- havarija pumpe
- metalografija
- abrazivno habanje
- erozija

Abstract

A case study of damage of a rotary high-pressure three screw oil hydraulic pump for regulator oil in hydroelectric power plant is presented. Results of chemical composition analysis, mechanical properties, impact energy testing and hardness measurement of power and idle rotor materials are presented and discussed. Casing inner surfaces and samples of power and idle rotor materials are examined by metallographic analyses. Obtained results allowed to conclude that life of rotary screw pumps may be extended by regular cleanness inspection of filter and its replacement if necessary, control of rolling bearings condition, oil viscosity and cleanness, and proper operation of valves and automatics.

Izvod

U radu je prikazana analiza oštećenja rotacione vijčane pumpe visokog pritiska za hidraulično ulje u regulatoru u pogonu hidroelektrane. Izloženi su i diskutovani rezultati analize hemijskog sastava, ispitivanja mehaničkih osobina i energije udara i merenja tvrdoće materijala pogonskog i slobodnog vretena. Unutrašnje površine kućišta i uzorci materijala pogonskog i slobodnog vretena su ispitani metalografskom analizom. Na osnovu dobijenih rezultata je zaključeno da vek rotacionih zavojnih pumpi može biti produžen redovnom kontrolom čistoće prečistača i njihovom zamenom kada je to potrebno, kontrolom stanja kotrljajnih ležajeva, viskoznosti i čistoće ulja, i ispravnim radom ventila i automatike.

INTRODUCTION

After 18 years of continuous operation, an accident occurred on the high-pressure regulatory oil rotary pump installed in the hydroelectric power plant. An official record by the plant’s expert team was examined, dimensions of pump elements were measured and damages of the power rotor, idle rotors, and casing recorded.

As stated in the above-specified record, the damage had occurred during the manual pump operation since the pump had not been able to achieve a pressure needed for normal regulation system operation. In addition, the pump continued to operate even after the auxiliary pump was started.

Measurements had found that the length of worn surfaces of the power rotor and idle rotors corresponded to the casing length, Fig. 1. It was also revealed that the oil had changed its colour to black, indicating that the particles, resulting from the wear and tear of the power and idle rotor surfaces had blended with oil and penetrated the regulation system. As a result, oil temperature had increased and the pressure in relief valve had dropped, causing a distributor to open and pass the oil into the relief valve. Later on, the pump continued to operate for 3 hours, during which the oil was heated by a 20–30 kW heat source. Since the system was provided with filters (fine filter in front of converter and a course filter behind it), oil degradation resulted in a mud-like deposit formation, introducing potential danger from device blocking and regulation system clogging.

Technical characteristics of pump are given in Table 1, of pump motor drive in Table 2, and oil properties in Table 3.

Table 1. Characteristics of hydraulic pump for regulatory oil.
Tabela 1. Karakteristike hidraulične pumpe za regulatorsko ulje

Parameter	Unit	Value	Oil temperature
Operating pressure	p_r, bar	57	
Operating temperature	T_r, °C	30	
Flow rate	Q, l/min	753	10°C
		700	45°C
Speed	min^{-1}	1470	
Power	kW	83.4	10°C

Table 2. Characteristics of pump motor drive.
Tabela 2. Karakteristika elektromotora pumpe

Number of motor poles	Unit	4
Power	kW	90
Speed	min^{-1}	1470
AC voltage	V	380
Frequency	Hz	50

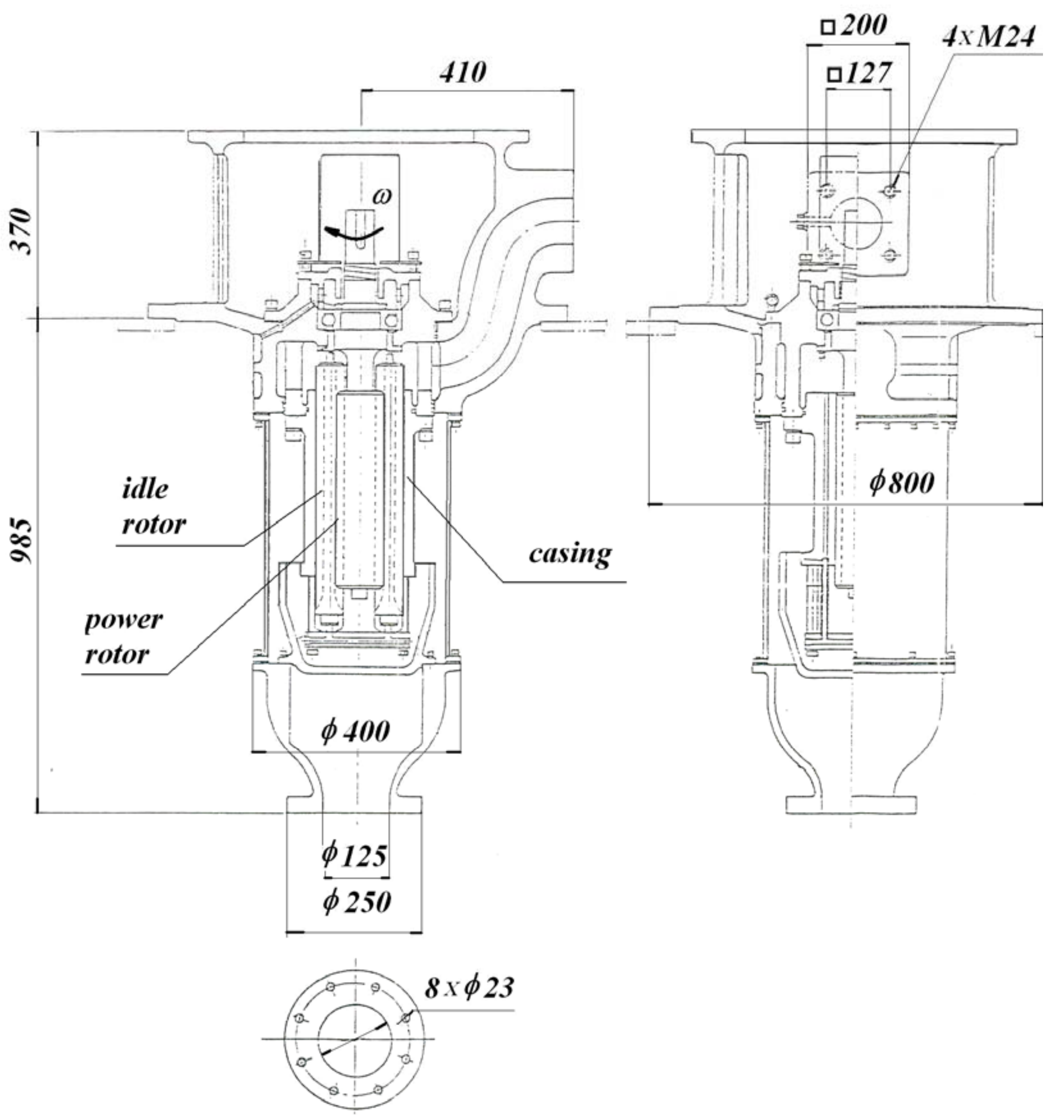


Figure 1. Assembly drawing of rotary screw high-pressure pump for regulatory oil.
Slika 1. Sklopni crtež rotacione zavojne pumpe visokog pritiska za regulatorsko ulje

Table 3. Fluid properties.
Tabela 3. Karakteristike fluida

Type of fluid	oil	
Viscosity grade	TURBO VL (INA) VG-32 (ISO)	
Density	g/ml	0.872
Viscosity	mm^2/s	3 at 50°C
		3.1 at 40°C
		5.25 at 100°C
Viscosity Index	100	
Flash point	°C	220
Pour point	°C	–10
Temperature range	°C	10–45

At the moment of accident, maximum pump pressure was 18 bar and temperature on pump release side was 85°C.

PROGRAMME OF TESTING

Causes of failure were investigated at the Faculty of Technology and Metallurgy, University of Belgrade. The programme for damage investigation included the following testing and analysis of power and idle rotor materials:

– chemical composition;
– tensile properties (3 + 3 specimens);
– materials impact energy tests (3 + 3 specimens);
– material hardness measurements;
– metallographic analysis (3 + 3 specimens);
– and metallographic analysis of two replicas taken on the casing internal surface.

RESULTS

Chemical composition

The chemical composition of materials is given in Table 4.

Table 4. Chemical composition of power and idle rotors materials.
Tabela 4. Hemijski sastav materijala pogonskog i slobodnog vretena

Component	Material	C	Si	Mn	P
Power rotor	S55C	0.55	0.28	0.81	0.01
Idle rotor	FC25	3.3	1.33	0.42	0.012

Based on tested chemical composition, it is confirmed that the power rotor is produced of S55C steel, and the idle rotor of FC25 gray cast iron, as specified.

Tensile properties

Tensile properties (JUS EN 10 002-1) are determined by testing 3 specimens ∅6 mm of S55C steel (Table 5) and gray cast iron FC25 (Table 6).

Table 5. Tensile properties of S55C steel (average).
Tabela 5. Zatezne osobine čelika S55C (prosek)

	Yield stress	Tensile strength	Elongation
Material	$R_{p0.2}$ (MPa)	R_m (MPa)	A_t (%)
S55C steel	395.3	816.1	21.37

Table 6. Tensile properties of cast gray iron FC25 (average).
Tabela 6. Zatezne osobine sivog livenog gvožđa FC25 (prosek)

	Yield stress	Tensile strength	Elongation
Material	$R_{p0.2}$ (MPa)	R_m (MPa)	A_t (%)
FC25	–	220.5	1.38

Steel S55C corresponds to quenched and tempered steels Č1630 or Č1631 (JUS C.B9.021), and gray cast iron FC25 to SL250 (JUS C.J2.020).

Measured values of material tensile properties have shown that no decrease in ultimate tensile strength values occurred during the operation, indicating there was no exceeding of transformation temperatures A_{C1} and A_{C3}. In addition, the measured values of mechanical properties of power rotor material corresponded both to normalized and quenched and tempered delivery state. Exact delivery state of given steel is determined by metallographic tests.

Impact toughness tests

Impact energy was tested on instrumented pendulum according to JUS EN 10 045-1 and ASTM E23, using 3 specimens of each S55C steel and of gray cast iron FC25.

Impact energies for S55C are 8.8 J in average (individual values 8.4 J, 7.8 J, and 10.2 J), and for FC25 3 J in average (individual values 2.9 J and 3.1 J).

Both materials exhibited extremely low impact energies making them sensitive to defects such as cracks. Built-in materials had no remaining plasticity because the total impact energy had been used for crack initiation. Moreover, these materials are sensitive to abrasive wear because they have no hardened surface.

Hardness test

Hardness of both investigated materials was measured by Vickers HV30 method according to JUS C.A4.033. Obtained values are HV30 for S55C steel and 162 HV30 for gray cast iron FC25. Obtained values indicated that these materials are sensitive to wear.

METALLOGRAPHIC EXAMINATION

Testing of casing inner surface by replicas

Replicas for metallographic analysis on casing inner surfaces were taken at locations R1 of power rotor rest and R2 of idle rotor rest, as presented in Fig. 2, /1/.

Material surface on replica locations was machined and grinded with SiC paper of six granulations and polished with three granulations of diamond paste. Sample R1 is chemically etched in nital (3% solution of HNO_3 in ethyl-alcohol) at room temperature during 45 s, and sample R2 is only washed in ethyl-alcohol, but not etched.

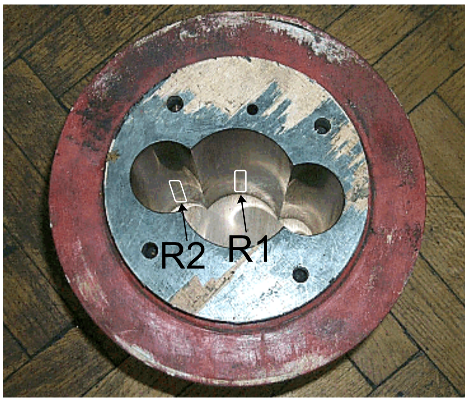
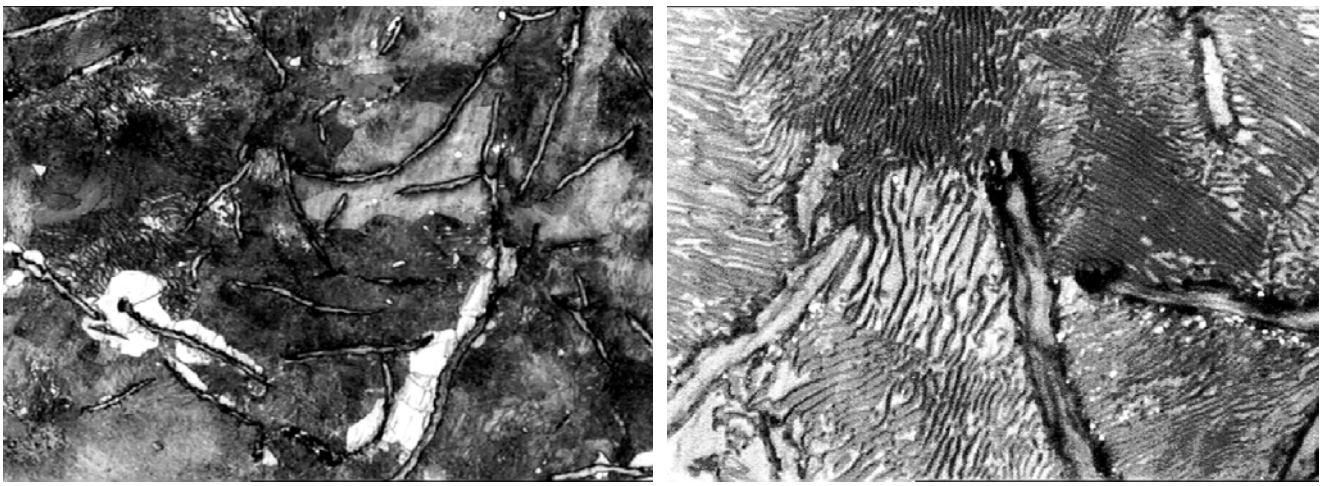


Figure 2. Positions of replication on casing inner surface.
Slika 2. Mesta uzimanja replika na unutrašnjoj površini kućišta

Metallographic analysis of R1 replica revealed a ferrite-pearlite structure of gray cast iron with lamellar pearlitic matrix in which graphite lamellae are segregated with a small amount of ferrite, Fig. 3.



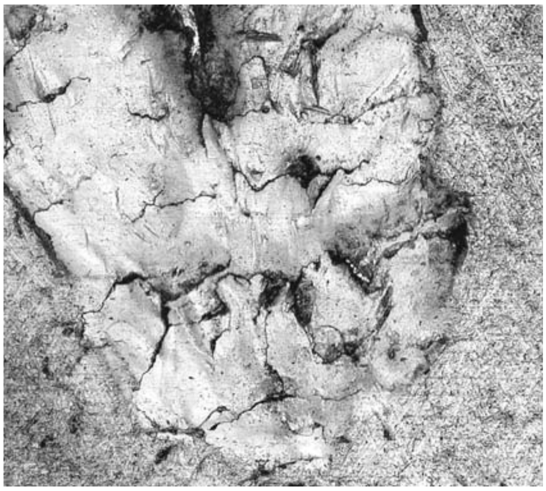
R1 magnification × 200 R1 magnification × 1000

Figure 3. Microstructure of casing material, replica location R1.
Slika 3. Mikrostruktura materijala kućišta, replika na mestu R1

The examination of replica R2, taken in position of detected damage, revealed local deterioration as craters on very fine prepared surface, Figs. 4 and 5. The material is partially torn, i.e. small particles and pieces of casing material fell out. Weak bonds on metallic grain boundaries are most likely the cause, and may be the consequence of some alloying elements segregating or accumulation of impurities in manufacture, or continuous use of the casing. On the other hand, the weakening of bonds may be provoked by diffusion of detrimental chemical elements from the environment, like hydrogen, oxygen or nitrogen.

R2 magnification × 150

Figure 4. Microstructure of casing material, replica location R2.
Slika 4. Mikrostruktura materijala kućišta, replika na mestu R2



R2 magnification × 150

Figure 5. Microstructure of casing material, replica location R2.
Slika 5. Mikrostruktura materijala kućišta, replika na mestu R2

Metallographic analysis of power and idle rotors

Three samples (Fig. 6) were taken from idle rotor – S1 at rotor end, S2 thread crown, and S3 at thread bottom. Same samples (Fig. 7) were taken from power rotor, S4 (not visible in Fig. 7), S5 and S6, respectively. Micrographs S2 and S3 of idle rotor material are shown in Fig. 8, and S5 and S6 of power rotor material in Fig. 9.

Figure 8 shows typical gray iron structure with presence of graphite eutectic containing silicon on specimens S2 and S3. The eutectic grows as cellular with fine graphite eutectic indicating higher cooling rate of casts. No differences in microstructure that can show eventual overheating of the material caused by friction and abrasion during the accident were noticed among tested positions of idle rotor.

Figure 9 shows a ferrite-pearlite microstructure of power rotor material on both specimens S5 and S6. The matrix is predominant pearlite and the structure is lamellar pearlite. Having in mind that cementite lamellas inside the pearlite matrix are not broken, it is possible to conclude with enough certainty that during operating lifetime, the power rotor did not reach temperatures at which cementite breaks or coagulation occurs. The minimum temperature of soft annealing or cementite lamella breakup and coagulation for steel S55C is 650°C. In spite that power rotor material S55C belongs to quenched and tempered group, a normalized microstructure of steels was found.

DISCUSSION

Most probable causes of pump failure are discussed, based on results of performed tests and detailed literature consultation, /2-16/.

Revealed surface damages of the tearing type at typical locations of casing inner surface indicate that some deviation from normal operating regime of pump rotary parts occurred. Torn material particles had entered the oil stream flow and produced wear on all three gapping surfaces (between casing and rotors, at the bottom and on flank surfaces between power and idle rotors), thus producing a pressure decrease on the pump outlet.

Clearances

Clearance regions of rotary pumps are the most susceptible to damage and abrasion from solids, contaminants, and foreign material. Running clearances are those spaces between stationary and rotating parts and between adjacent rotating pump components, Fig. 10; in a pump they can range from less than 0.025 mm to about 0.254 mm depending on pump size and pressure rating. Internal slip flow (volumetric inefficiency) carries the liquid born debris towards pump running clearances. This debris can cause jams or pits on pumping elements, scoring of clearance surfaces and abrasive erosion of clearance components. Jamming or breakage is catastrophic in nature and can cause immediate system shutdown with its attendant outage costs, as well as extensive repair time and cost. Scoring and abrasion of clearance surfaces will usually reduce the pump output flow by allowing increased slip through increased clearances. This is usually detected as a loss in system discharge pressure, due to the loss of pump flow rate.

Filtration

Filtration refers to the deliberate addition of components to the liquid system to remove undesirable solids. The term “filter” is more frequently applied to a component in the discharge side of the pump system and intended to protect downstream equipment.

At least one installation of a 91 m^3/h high speed rotary lube oil pump was inspected after 60 000 hours operation and required only new gaskets, shaft seal, and ball bearing during reassembly. This provides evidence that systems that stay clean can provide extraordinarily long pump life. On the inlet side of the pump, filtration devices are usually called "strainers". The name implies a coarser degree of contaminant removal, far poorer than a system filter. It is this inlet or suction strainer that provides the most immediate short term protection for the pump.

Figure 6. Sample positions on idle rotor.
Slika 6. Uzorci sa slobodnog vretena

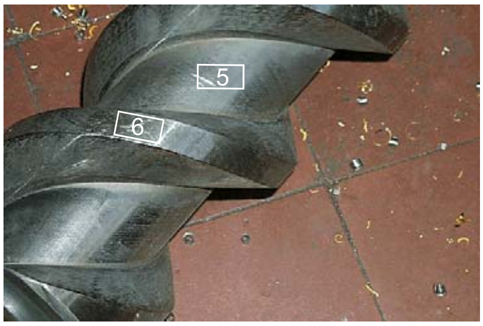
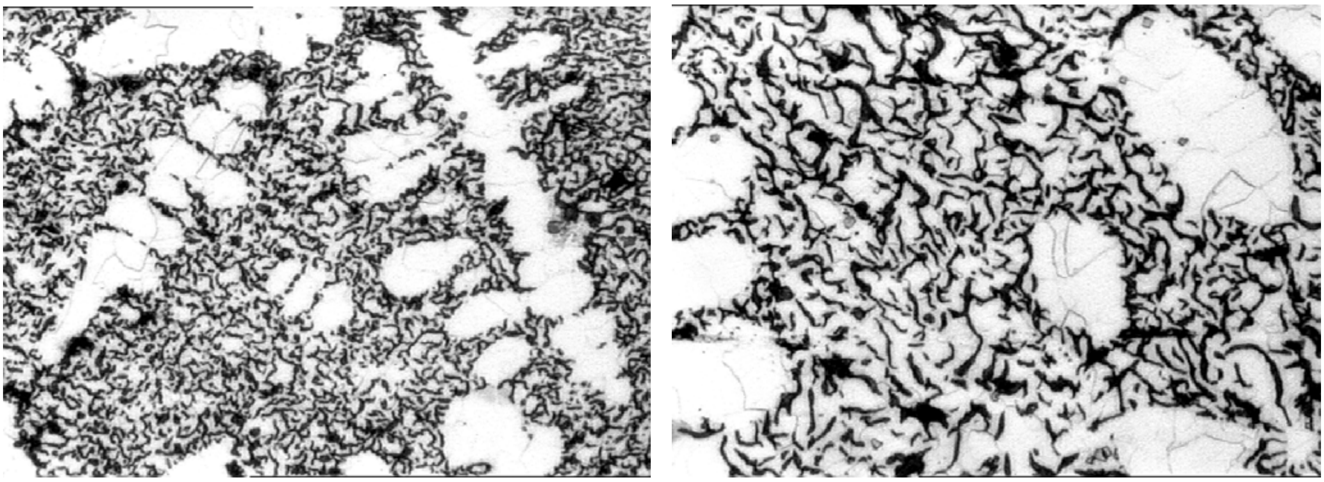
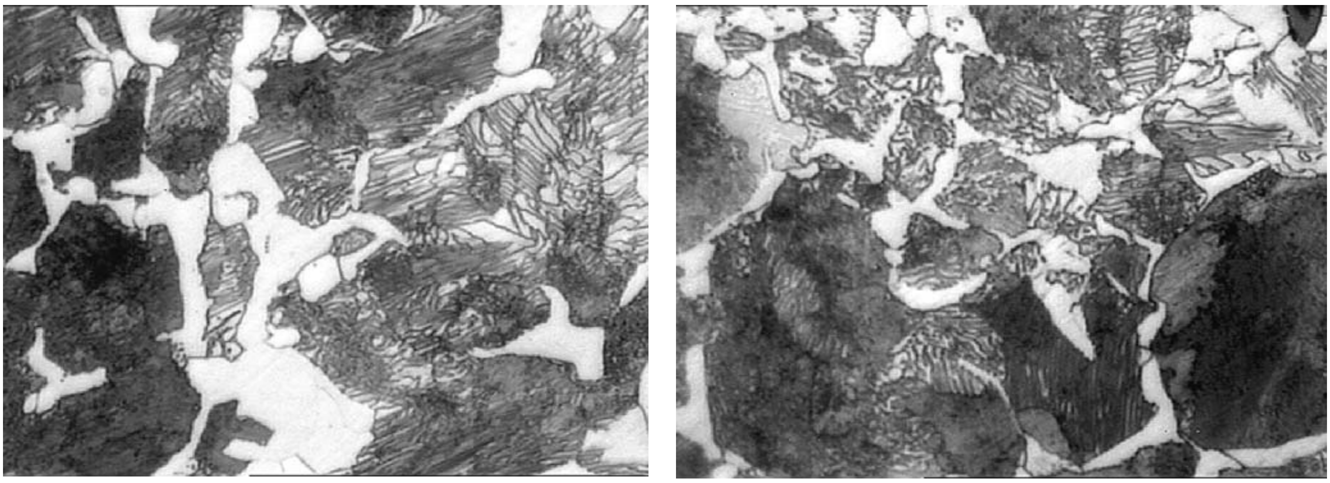


Figure 7. Sample positions on main screw (sample 4 is on rotor end).
Slika 7. Uzorci sa pogonskog vretena (uzorak 4 je na kraju vretena)



S2 magnification × 500 S3 magnification × 500

Figure 8. Micrographs taken from thread crown S2 and thread bottom S3 of idle rotor material.
Slika 8. Mikrografi uzeti sa spoljnje površine S2 i boka S3 zavojnice materijala slobodnog vretena



S5 magnification × 1000 S6 magnification × 1000

Figure 9. Micrographs taken from thread bottom S5 and thread crown S6 of power rotor material.
Slika 9. Mikrografi uzeti sa boka S5 i sa spoljnje površine S6 zavojnice materijala pogonskog vretena

Contaminant

System contamination has many forms, comes in many sizes and can range from catastrophic to negligible in its impact, Figs. 11 and 12. Fabrication debris is frequently the most serious source of contamination in new systems. Weld bead, slag and spatter, pipe scale, rust, machining chips, all provides opportunities for pump failures or rapid wearouts. Other debris left from inattentive workmanship can be a danger to pumps as well such as extra flange fasteners (nuts, bolts, washers), weld rod stubs, unremoved port dust guards, lacing wire, rags, tools, lunch pails and a nearly endless list of things that would never be expected in a pumping system.

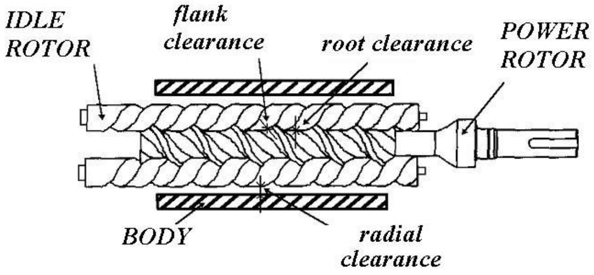


Figure 10. Running clearances of rotary pump elements, /1/.
Slika 10. Radni zazori elemenata rotacione pumpe, /1/

CONCLUSION

During pump operation, there was no heating of rotating parts of pump and casing over 650°C, so there were no changes of mechanical characteristics or modifications of material microstructure.

Surface damage of tearing type, observed in some places of the casing inner surface, suggested that there had been some impairment of normal mode of rotating parts of pump. Spalled material that entered the stream caused the wear on all three clearance surfaces (between casing and idle rotors, at the thread bottom and flank surfaces between power and idle rotors), what led to drop of outlet pressure.

In case of automatics defect, it is possible, in time shorter than 1 hour, for the pump oil volume to be warmed up to the temperature sufficient to annul the running clearances. Idle rotor penetrates the casing surface, tears the parts off, carrying them with stream along the screw thread surfaces that become intensively worn and torn, with erosive damage. On the contact, now worn surfaces, running clearances begin to increase and, in the final phase, when the increase of clearance exceeds the permissible range (0.025 mm to 0.254 mm in relation to pump size and working pressure), sudden loss of pressure occurs at the pump outlet. At the same time, ripped off, ground gray cast elements (3.3% C) are mixed with oil and applied on the filter reassembling the layer of graphite grease. Such filter blocking causes more intensive pump operation in by-pass mode, what subsequently leads to further rise of temperature and more severe abrasion.

Rotary pump service life can be significantly increased if the operation with such clogged filter is prevented. This can be achieved by regular inspection of filter cleanness and, if necessary, by its replacement, controlling the state of roller bearings, controlling viscosity and oil purity, monitoring the functionality of valves and automatics. If installed system components are replaced it is obligatory to install cone strainers that should stop coarse impurities, induced during manufacture of a new part placed into the system.

Based on performed tests and analysis of cited references, it is concluded that the oil filter became excessively dirty with particle paste, mixed with oil, that had been extracted from the material and crushed. Such a compact paste produced irregular pump operation in the by-pass regime and wear of elements on contact surfaces.

Recommendations suggested may significantly contribute to safe pump operation and extend its operating life.

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