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Application of Ferrography in Condition Based Maintenance

Ivan PLAŠČAK, Tomislav JURIĆ* and *Rudolf EMERT

Poljoprivredni fakultet u Osijeku
(Agricultural Faculty from Osijek),
Trg Sv. Trojstva 3, HR - 31000 Osijek
Republic of Croatia

iplascak@pfos.hr

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The model of maintenance is an algorithm of activities which aims at achieving the condition of a technical system that can ensure fulfilling the goals as well as predicting possible equipment breakdowns. Researches point out that corrective maintenance is associated with high cost and considerable time consumption. On the other side there are method of predictive maintenance, which presents a possibility to detect and predict a technical system failure and method of preventive maintenance, which performs the set tasks on technically correct systems in order to avoid failures. The paper accentuates and reviews the position and significance of the technology used for an early prediction of machinery wear by means of one out of a series of analyses of lubricant oils known as ferrography.

Ferografija u službi održavanja po stanju

Pregledni članak

Model održavanja jest algoritam aktivnosti koji ima za cilj dovođenje tehničkih sustava u stanje koje će omogućiti postizanje ciljeva, istovremeno predviđajući i mogućnost zastoja u proizvodnji. Istraživanja su dokazala kako korektivno održavanje ima za posljedicu visoke troškove i produženo vrijeme zastoja. Nasuprot ovim metodama postoji i prediktivno održavanje koje predstavlja mogućnost otkrivanja i predviđanja kvara tehničkog sustava te preventivno održavanje koje provodi zadane zadatke na tehnički ispravnim sustavima nužne za izbjegavanje kvara tehničkog sustava. U radu se izdvaja i daje pregled stanja i važnosti tehnologije koja služi za vrlo rano predviđanje stanja procesa trošenja tehničkog sustava i to uz pomoć jedne od niza analiza ulja za podmazivanje nazvane ferografija.

1. Introduction

The maintenance strategy used for addressing complex machinery has been improved by the development of technical systems, automation and complex elements. Equipment maintenance is an interdisciplinary activity which involves experts from different fields of mechanical engineering, electrotechnics, electronics and other scientific branches in order to ensure the most favourable maintenance as well as to improve, modernize develop, and reconstruct the existing equipment. [1]. Maintenance involves all technical and other procedures performed in order to maintain a satisfactory working condition of a part or a whole complex. Maintenance also means restoring the working condition so that the set tasks can be performed in the scheduled time and under set conditions [2].

Maintenance method is an algorithm of procedures which aim at producing the conditions which will enable technical systems to reach certain goals. It is also expected to be able to predict production downtimes [3].

Maintenance is often considered a separate and independent activity, sometimes even a minor one compared to other production subsystems [1].

Maintenance of technical systems is a factor which influences their reliability. It increases their productivity and decreases the occurrence of failures, which means that it increases the system efficiency. This further implies lower production costs. Oil properties are under the influence of many factors. During the regular lubricating procedures metal particles can appear due to the regular wear of machinery parts. In case of a sudden increase of the particle concentration you can conclude that a part of the machinery system is wearing out significantly, which is a sign of a possible failure. A major failure can be prevented in case when you first determine the failure possibility and then fix it timely. For more than two decades The Canadian Pacific Railway has used this way of failure prediction for diesel engines of their locomotives. This way has proved to be very efficient and low-cost. It is based on the analysis of the kind of metal particles and their concentration in motor oil. The oil sample is examined by spectrophotometer controlled by a computer. Based on the input data, the computer produces a written report stating which elements should be serviced and preventively maintained, and which are likely to fail and when the failure could occur. The precision of the procedure is extremely accurate (98 %), because the human agency factor is decreased to the minimum level. If out of control, the problem of oil contamination can cause a loss of $8 million. The maintenance expenses are lower than one tenth of the expenses which could result from negligence. The US Air Force report shows that oil analysis on fighter aircrafts F-16 saved them as much as $15 million [5].

Tribotechnical diagnostics solves two significant problems. Firstly it is the determination of composition, extending the lifetime and the prediction of oil degradation. Secondly, it is scheduling the way, place, and frequency of maintenance [6].

2. Wear and failure occurrence

Every man-made system is bound to fail. As a result of technology development we have very complex technical systems, which more often fail due to their complexity. The result can be a very serious damage of the system. A great number of major failures occur as a result of wear, corrosion, and fatigue of the material which the system is made of. Great effort has been made to reduce the failure occurrence and to determine the procedures which can take control of wear, corrosion and similar. A failure of an assembly is inevitable, but the causes can be quite diverse.

The input value of every maintenance or monitoring programme understands the wear model of an assembly and how it causes a failure. Every failure model has a certain start point and a certain speed from the very beginning till the downtime or complete failure point [7] and [8]. Failure occurrence and its frequency depend on the construction of the assembly (tolerance, etc.), the lubrication procedure, and lubrication working temperature, exposure to contaminants, workload and speed rates as well as the way the equipment is used and maintained [9].

The main characteristic of condition monitoring is that every form (model) of failure will show a measurable value which can be used as an indicator of its presence and degradation. Failure models, which show the wear of certain assembly parts and the fluid, are regularly followed by an unusually high level of metal particles, as well as contamination, vibration, etc. Sometimes failures may occur due to faults of the material the basic component is made of. This kind of failures is solved by non-destructive testing (NDT). Most failure models tend to receive further damages with correspondently measurable symptoms. The symptoms of further failures should not be used for the indication of the primary failure model. A wrong conclusion would cause higher costs for failure fixing.

3. Mathematical reliability model

A function represents a mathematical research model between a mathematical function which can completely or precisely enough follow the course of empirical results and empirical distribution, which is a result the inspection of failure occurrence or their monitoring when they occur in certain parts, equipment or working assemblies. The function of failure intensity has a characteristic time-dependent form, which is based on empirical results (Figure 1).

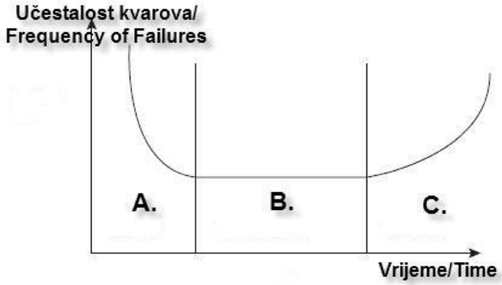

Figure 1. Curve showing the probability of failure occurrence

Slika 1. Krivulja vjerojatnosti pojave kvara

Failures happen during the design lifetime of a machine. It is necessary to know why they happen. Failure rate is shown by the so called "bathtub curve" (Figure 1). It is obvious that the function of failure rate has three characteristic areas, i.e. three periods of failure distribution:

- 1st period (A.) – early failures
- 2nd period (B.) – useful lifetime
- 3rd period (C) – wear-out of machinery parts or whole assemblies

In the early life, the failure rate is high and intense, but this tends to decrease. This period can be omitted by using a test device and by close inspection and constant survey. Every fault pertaining to design, production and installation should be removed. During the useful lifetime some random failures can occur. The failure rate during the third period is rapid due to age and wear. This means that machinery is old and should be replaced

4. Maintenance – task and aim

The aim of maintenance is achieving the maximum availability of machinery and as low maintenance costs as possible. Other aims are failure prevention, removal of weak spots, maintenance innovation, longer machinery lifetime, less time spent on maintenance, decreasing the cost of material, space, workers, tools, equipment, and spare parts [10].

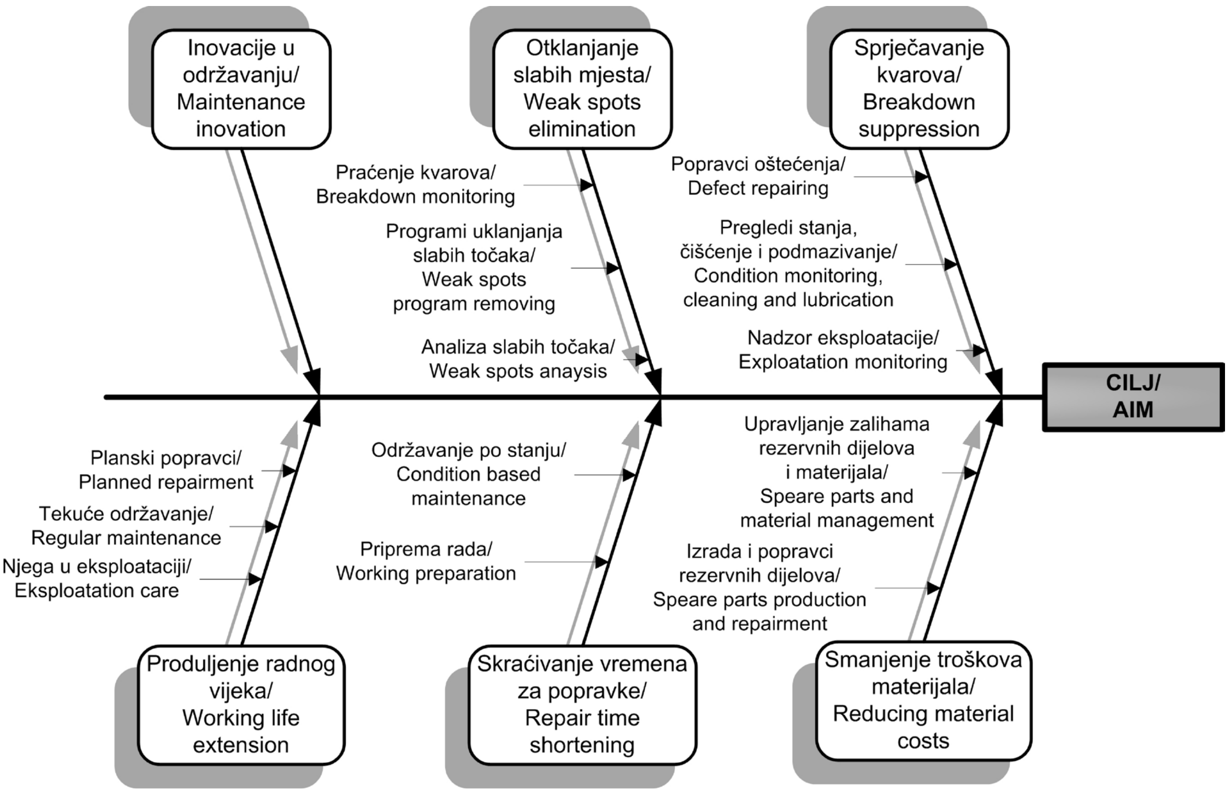

Figure 2. Maintenance aim [10]
Slika 2. Cilj održavanja [10]

When buying machinery you want to get the most reliable equipment, the most favourable price, working cost, and maintenance expenses. Even highly reliable machinery will be deteriorating and maintenance will be needed to re-establish the reliability. The maintenance costs are considered unfavourable, but they are necessary during machinery lifetime. The primary maintenance tasks are as follows:

- deterioration causes should be predicted,
- a strategy should be made to control deterioration and to avoid faults,
- solve the problems accurately as they occur,
- detect and solve the key causes where possible,
- perform the above mentioned in an economical way.

5. Maintenance concept

The maintenance should be scheduled, managed, and observed because both of increasing cost and complexity. From the theoretical point of view, all the latest maintenance programmes contain one or more than one basic concept (model) such as:

- corrective maintenance,
- preventive maintenance,
- condition based maintenance and
- reliability based maintenance.

5.1. Corrective maintenance working on the principle “use it until it fails”

The steps taken by corrective maintenance have not changed a lot during history. Corrective maintenance means fixing when machinery fails. This method involves maintenance personnel to address the machinery when it fails and to detect and fix the failure. This means that they should find and confirm the failure, detect the cause, fix it, note it down, and produce a report on the activities taken.

5.2. Preventive maintenance

Machinery need to be reliable and efficient, because it is complex and produces high cost of work. This situation started with steam engines and later with internal combustion engines. In order to meet the demands and to affect the process of work to the least possible degree, different methods have been made to schedule and programme maintenance procedures at the most favourable points. Machine operators are in charge of monitoring and evaluating the best mean time intervals between failures of parts as well as scheduling the maintenance programmes adjusted to certain operations performed by machinery, i.e. between two working operations or out-of season operations. Shortly, this method is based on the assumption that the highest reliability can be achieved by continuous and proper maintenance and failure mending at scheduled intervals. The basic tasks of preventive maintenance are:

- to determine the activities which are economically favourable and can be done at certain intervals,
- activity planning – each activity should be planned as well as the accompanying tools and instructions,
- activity scheduling – activity schedule should be made, which will enable an efficient maintenance and it will not cause any production disturbance,
- activity performing – trained staff should be assigned tasks to and
- Monitoring and analysis – monitoring and machinery data evaluating. The data are collected during the machinery working operations. Analyses are the key to constant improvements when applying this kind of maintenance.

5.3. Condition based maintenance or predictive maintenance

Condition based maintenance implies that optimum time should be determined when to perform maintenance activities. This point of time is determined by monitoring of the usefulness and the condition of certain components of an assembly [11]. According to this, it can be considered a “dynamic” way of maintenance considering the fact that maintenance is or is not performed, which is based on structure measurements, use, and condition of the machinery. Condition based maintenance is important for the dynamic change of earlier set intervals of preventive maintenance in the sense of predictive ness. A correctly set model of this kind is both proactive and reactive. It is considered proactive when the usual technical data are used to postpone the scheduled maintenance of machinery and fluid, which is due to the fact that they function properly, however they are due to be replaced according to the preventive maintenance schedule. It is considered reactive when technical data point out the problem which should to be additionally maintained. Properly organized condition based maintenance is flexible and allows tolerance when scheduling points of preventive maintenance. It uses early warnings which are the results of condition monitoring and the way in which technical assemblies are used. This method is dynamic and adaptable to the time intervals of machinery use.

Figure 3 shows the real costs of model maintenance, which increase from the minimum amount (poorly organized corrective maintenance) to the maximum amount (poorly organized preventive maintenance). On the opposite side of the real costs, there are operational costs, which are max in case of poorly organized corrective maintenance, and minimum in case of poorly organized preventive maintenance. If you consider the real costs and the operational costs as a whole, the condition based programme is significantly more reasonable from the point of view of expenses. This model reduces both the real and the operational costs; it ensures a high level of usefulness owing to systematic application of data considering the use and condition of an assembly, which are achieved by equipment monitoring [12].

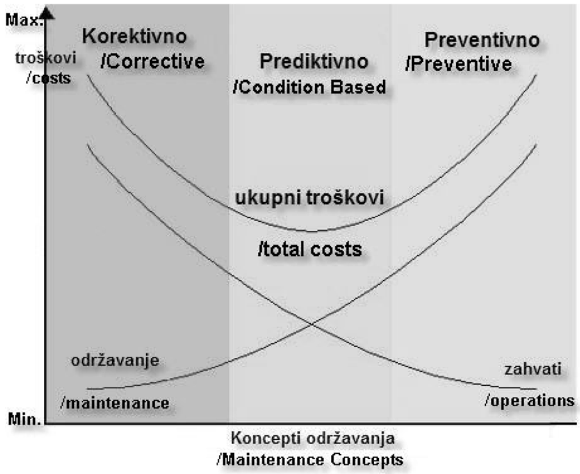

Figure 3. Curves showing costs of various maintenance concepts

Slika 3. Krivulje troškova različitih koncepata održavanja

Advantages of condition based maintenance are as follows: improved usefulness, extended intervals of preventive maintenance, reduced possibility to replace a wrong machine part, reduced number of working hours needed to perform maintenance, reduced time length of maintenance, and a decreased demand for spare parts. Condition based maintenance (predictive maintenance) is the most applicable in cases when the equipment is of key importance in the working operations and when there is an appropriate monitoring system, which should be reliable and economical. It is also applicable in the cases of large fleet systems, but only if they are economical enough to allow for a reasonable monitoring system.

For example, a routine oil check is one of the best ways to monitor assembly condition and it is also very economical, easily applied, and it can serve large fleets from one place. It addresses technical assemblies equipped with a central lubricating system with a constant flow, a common (shared) collecting space or a tank. This kind of sophisticated monitoring has its flaws because it imposes further costs, which belong to maintenance costs. Although they are generally justified, we could emphasize that there are different equipment monitoring methods and that they are not always necessary, economical, and applicable.

5.4. Reliability based maintenance

This maintenance method assumes that there is an optimum combination of the up to now mentioned maintenance methods: corrective, preventive and predictive. It is considered to be the governing part of each well organized method of preventive and predictive maintenance. So, we could say that this kind of maintenance is more a management theory than a standard maintenance method. It is a process of analysis and planning aiming at issuing continuous efficiency assessments pertaining to the assembly and the maintenance quality. It is also a source of suggestions how to improve maintenance [13].

5.5. Learning about assembly conditions based on oil analysis

Condition based method is of relatively new origin, and it appeared in the 1970-es. It was observed that the signs showing a possible failure appear much earlier than the failure itself. The conclusion was that an assembly should be under scheduled control and analysis of the controlled values, which enables a proactive approach pertaining to the current machinery condition. Lubricant oil analysis is one of the most important ways of machinery monitoring. [14] and [15]. According to different lifetime periods, you can divide oil analysis into the following groups: 1. Unused oil analysis – qualification oil analysis; quality analysis; acceptability analysis; and 2. used oil analysis – performance analysis; condition analysis; wear particle analysis.

In order to gain an efficient monitoring programme based on oil condition monitoring it is necessary to measure and evaluate the wear particle rate in an efficient way [16]. According to [13] the methods which inspect the characteristics of particles and fragments in the oil are as follows:

Wear particle analysis:

- wear particle analyzer,
- particle counter,
- ferrograph with direct readings,
- analytic ferrography and
- SEM.

Electronic particle counting:

- method of obscured light beam,
- method of flow dissipation and
- method of following nets.

Continuous particle monitoring:

- ferromagnetic sensors and
- sensors for all kinds of particles.

5.6. Ferrography assisting the condition based maintenance

Ferrography is one among numerous analysis methods that assists in extracting wear particles out of oil (particles larger than 10 μm). The particles are sorted according to their size in order to be examined by an optical or scanning microscope [17]. The method, the way of sampling, and ferrograph adjustment were first described after the development of a ferrographic analyzer. Since then it has been acknowledged and known as a method for the extraction and inspection of the particles which have worn off different parts of a tribosystem as a result of wear. Ferrography reveals four main particle characteristics: concentration, size, shape, and composition [18]. The method relies on magnetic particle removal out of the medium, which is usually used lubricant oil, but also diesel engine exhaust fumes, jet engine gases, cooling fluid, etc. [19]. Ferrography has proven to be a method for condition monitoring in closed systems, which are inaccessible for a direct inspection of working areas [20-23]. Ferrography uses two basic systems: direct readings and analytic ferrography.

5.7. Direct read ferrography

An oil sample containing metal wear flows directly through a precipitation tube of a reading ferrograph under which there is a strong permanent magnet, which affects metal particles so that it deposits them close to it. Larger particles are removed more quickly compared to the smaller ones, because the force exerted upon a particle within the magnetic field is proportional to its volume, whereas the movement resistance through a medium is in proportion to the cross-section area in the diagonal way to the movement direction [24-25]. After all the particles have been deposited, the light intensity is registered and the percentage of the areas covered by both large and small particles is determined. The researches [22] show that the ratio of large and small particles remains constant up to the point when higher rates of wear occur. The data can be shown in different ways in order to detect abnormal wear rates in a simple way [26]:

- an index of wear intensity – if the readings of large particles or the sum of readings pertaining to both large and small particles are considered to be an indicator or particle size distribution then their product is considered to be the index of wear intensity. If you present in drawing the index of wear intensity as a function of the operation length, you will more easily grasp its changeable characteristic and

- wear particle concentration and the percentage of large particles: this method is appropriate to show the existing wear by on-line ferrographs, although it can also be appropriate to be used by direct read ferrographs. You can compute the concentration of wear particles by adding large and small particles, whereas you can compute the percentage of large particles as a ratio between the difference and the addition of large and small wear particles. In case when both parameters are increased i.e. when both the particle concentration as well as the percentage of large particles increases, it points to a model of an increased wear of machine parts.

5.8. Analytic ferrography

A direct read ferograph is used for a routine wear analysis. When it indicates the presence of undesirable changes, further information is gathered through analytic ferrography, which is based on ferrogram analysis. It is done in the way that a used oil sample is dripped onto a glass slide under which there is a strong magnet.

The particles then deposit on the glass slide selectively, according to their size and in the same way as in the case of a direct read ferrograph. The more magnetic the material is, the stronger the effect of selective extraction. Even large, but least magnetic particles will be extracted along the whole length of the ferrogram, which is due to gravity. After the particles have been extracted, the rest is washed out by a solvent, and then the remaining particles get attached to the glass slide. The sample made in this way is known as a ferrogram. The basic instrument used in ferrogram analysis is a bichromatic microscope or a ferroscope. You can also perform the same analysis by the means of SEM, a scanning electronic microscope.

[27] say that the form and colour of particles, the letter being either induced or existent, can account for the two basic information. The first is what mechanism caused them and the second which part of the tribosystem they originate from.

For example, occurrence of spherical particles on the ferrogram can be used in an early detection of a propagating fatigue crack, even before larger particles fall off, i.e. before the occurrence of pitting [19]. Fig. 4 shows some wear particles of different tribosystems recorded by a bichromatic microscope.

6. Conclusion

Many different methods for condition monitoring of machinery are used. They are based on analysis of more output parameters. The methods lack anticipation and thus have not proved reliable enough. The method of scheduled maintenance has been developed in order to compensate for the lack of a reliable method which could anticipate the future machinery condition. This method is based on the maintenance of a series of steps regulated in advance by the producer. The steps should be performed on technically correct systems, and should rely on the experience of the maintenance personnel [7].

The biggest disadvantage is the cost due to unplanned standstills. Further disadvantages are the impossibility for scheduling a favourable time interval for machinery maintenance or a machine part maintenance (taking into account the complex nature of machinery), then the fact that their lifetime is of different length, as well as different characteristics of machinery.

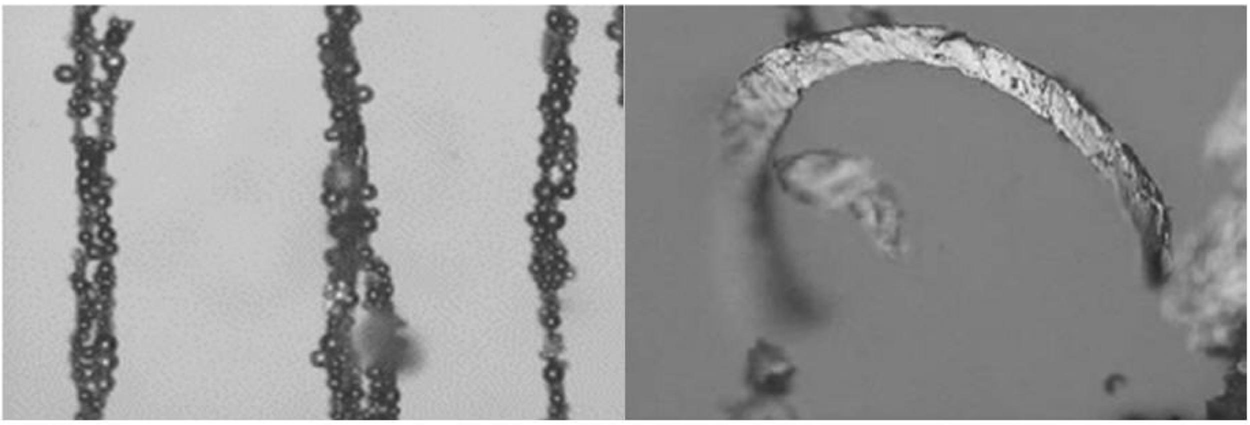

Figure 4. Wear particles originating from different tribosystems as recorded by a bichromatic microscope

Slika 4. Čestice trošenja različitih tribosustava snimljene bikromatskim mikroskopom

A significantly shorter time interval is adopted for maintenance procedures, due to the fact that we do not know the mutual relations of probability pertaining to failure occurrence of certain parts or the whole system. There are more problems, such as that you cannot use the machinery while being unnecessarily maintained. Furthermore, there is increasing probability of making a mistake as a result of repeating the phases the system has already gone through as well as an occurrence of decrease in machine lifetime due to objective and subjective factors during the installation procedure.

The advantages of condition maintenance are that problems are detected as they occur so that you can prevent expensive failures which would occur in the future production. This has recently been acknowledged owing to condition monitoring, which uses oil analysis and ferrography. Ferrography as a method of oil analysis is highly acceptable when monitoring the wear of closed tribosystems. It is one of the ways to monitor technical systems and it is indispensable in well organized predictive maintenance, which aims at optimizing the intervals of scheduled preventive maintenance, the reduction of standstills, and finally the reduction of total maintenance costs to the minimum level. In case of condition monitoring of machine parts by the means of ferrography in the form of constant monitoring of the index of wear intensity, the wear particle concentration, and the percentage of large wear particles you can timely detect the possibility of failure occurrence and react either proactively or reactively.

The situation in Croatia is unfortunately either a combination of the first two maintenance approaches or just one approach is used, either corrective or preventive scheduled maintenance. We think that Croatia should follow if not the best world's practises, then certainly the best European practice, which is the condition maintenance concept and application of at least one method for constant machine condition and operation monitoring.

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