POLITECHNIKA LUBELSKA

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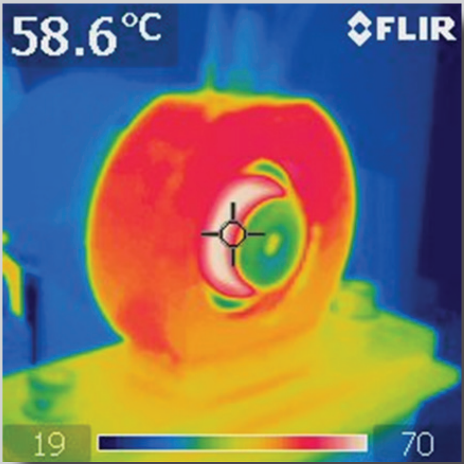
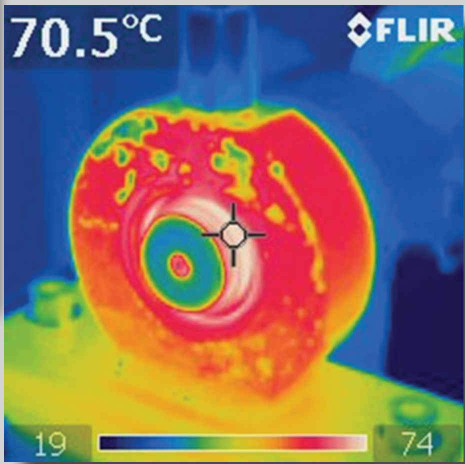
Issues of machine and device operation and maintenance





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1. Process of the machine and device operation and maintenance

1.1. Definition and classification of the machines

Machine [*mechene* (łac.<gr)] – auxiliary measure] is a technical device containing mechanism or an assembly of interconnected mechanisms, used for processing energy or performing specific mechanical work.

Technical object (measure) – general name for any technical object, which may be a machine, apparatus, appliance, structure, building, flat bar, bottle, etc.

Device – there's no precise definition (as in the case of the machine) and in a broader sense it may be any technical object, which allow performing specific process, usually constituting an assembly of interconnected parts, forming a functional whole unit, used for particular purposes and in narrower sense, it means a technical object for processing energy (this definition includes all machines).

Machines may be classified according to various criteria. The most popular ones include classification according to energy criteria and according to intended use.

According to energy criteria, the machines are divided into:

- drive machines (engines, motors) – machines producing mechanical energy at the expense of the different kind of energy; depending on the type of input energy, the motors can be divided into: electric motors, combustion engine, hydraulic motors, etc.,
- working machines – machines collecting mechanical energy to perform a specific job.

According to intended use (function), the machines are divided into:

- technological machines – machines used for the processing of raw materials or semi-finished products (change of shape, volume, physical and chemical properties, etc.) and manufacture in this manner the finished product or semi-finished product; these machines include: machine tools for various types of materials (metal, stone, wood, etc.), spinning and weaving machines, printing machines, processing machines e.g. mining, agricultural, forestry,

- transport machines – machines used for changing position of solids, liquids and gases; these machines include: cars, railway vehicles, ships, aircrafts, conveyors, cranes, fans, blowers and pumps used for transport of fluids,
- power machines – machines that produce other types of energy from the mechanical energy (e.g. electric generators, electrostatic machines, compressors and pumps used for producing fluid pressure energy) or machines that produce mechanical energy from other types of energy i.e. different types of engines.

According to the provided definition, machine is an energy converter that converts other type of energy into the mechanical energy or that is collecting mechanical energy. Characteristic feature of each machine is the motion of its parts due to the activity of forces or moments. Machine operation requires overcoming motion resistances, which are divided into external resistances, deriving from the useful load of the machine and internal resistances, mainly frictions. During the course of operation both types of those resistances occur, however during the idle run only the internal resistances occur.

Working machines may have an external drive – from the engine located outside the machine, or internal drive – from the engine built into the machine hull. Motor and elements transferring energy from the motor to the working machine (shafts, clutches, transmissions) form a drive system.

In terms of structure, the machines are divided into assemblies and elements. An element (part) of the machine is made from one piece or several pieces of material joined in the inseparable manner (screw, bolt, shaft, bearing bush, gear, cover, etc.). An assembly consists of a certain number of elements, combined in order to perform specific task (transmission, clutch, break, etc.).

In the literature, you can stumble upon the attempts to extend the definition of machine to other devices, in particular those, in which energy in the mechanical form does not occur e.g. IT machines, testing and control devices, TV and radio receivers. However, so far no definition has been provided, which would correspond to this extended concept of machine and would not include other technical objects.

1.2. Phases of the machine existence

In the easiest way, time of existence of the most machines can be divided into three stages: pre-utilization period (designing, testing, manufacturing), utilization period (operation, maintenance) and after-utilization period (withdrawal, recycling). In this work, no cases have been analyzed, in which the development or building of the machine wasn't finished or cases when the built machine is not put into operation for some reasons. In specific periods, different activities occur, examples of which are provided in parentheses. Especially during pre-utilization period, we can distinguish specific stages occurring in the chronological order, hence it seems reasonable to additionally divide this stage. Operation and maintenance, although very different in regard to the nature, during utilization period occur alternately.

The life-cycle of a machine, as well as other technical objects, can be divided into five stages (Fig. 1.1):

1) conceptual design,
2) design and development,
3) production and construction,
4) utilization and support,
5) phase-out and disposal.

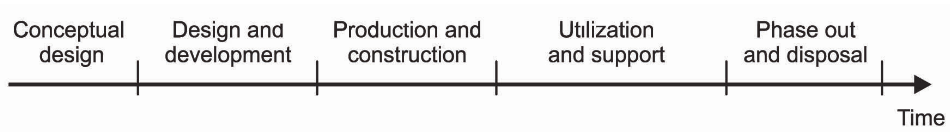


Fig. 1.1. *Existence phases of a technical object*

Conceptual design

Beginning of the machine existence is the moment, in which we find a need that can be fulfilled with new technical object. Motivations for creating new machine may be different: lack of existing machines that can fulfil the given need or their unavailability, conviction that we can create better solution (including less expensive), desire to make a profit from the sale of a new machine. Regardless of the fact, what is the leading motivation, cost calculation should be the basis for decision-making. At this stage, current and projected needs are analysed, including requirements relating to environmental impact, and the possibilities of their implementation are assessed through analysis of the current state of technology and directions of its development. Result of this stage should be the determination of assumptions for the project, among others, defining of: functions that the object has to fulfil and conditions in which it should be operated, functional characteristics (e.g. power, speed, performance, expected durability), guidelines concerning the appearance, planned sized and manufacturing costs.

It must be emphasized that decisions made at this stage of technical object existence have crucial significance for the efficiency of the entire undertaking, and mistakes made in this phase may be very difficult to correct or even impossible to eliminate during later period. For example, if the assumptions regarding the vehicle style (new type of body) or performance of elevators in the building will turn out to be wrong i.e. the car won't be attractive to potential customers, number of people wanting to use elevators will be much higher than assumed, then even the best work done in the designing and manufacturing phase won't make this undertaking successful (low sales and therefore financial loss; non-functional building).

Since the effects of made decisions will appear in the future, the accurate determination of future expectations and requirements is even more important, when the longer are: time since the moment of making decision about creating new machine and its putting into service (length of the design and production phases), planned production period of the given machine and its predicted durability (lifetime).

Design and development

In the designing phase, the best technical solutions are sought, which will allow to fulfil the requirements determined in the previous phase. Usually, at the first stage different variants of technical solution are analyzed (method of operation, drive source, control system, estimated cost of manufacturing, etc.) and while taking into (assumed in the conceptual design phase) importance hierarchy of applying requirements, the most favourable variant is selected – overall design of the machine is developed. For example, in the case of machines and devices for which the aesthetic features (appearance, quality of material) are of vital importance, plastic design of the main body, housing, control unit, bodywork is performed at the first stage and the structures of machine or device are adapted to such design.

Then, the development of detailed structure occurs (dimensions of elements, materials, method and precision of machining, method of assembly, etc.), which results in the design documentation. During these works, it's necessary to take into account technological and economic aspects (possibilities and costs of manufacturing).

In the case of machines, which are to be manufactured in the larger quantities, preliminary structural design is often verified based on the results of tests performed on the built unit (or units) of the complete machine – prototype. Prototype tests allow not only to test the design documentation, but also to determine detailed technical characteristics and operation properties of the designed machine, including its usefulness. Thus, such studies sometimes lead not only to changes in the detailed design of the machine, but may also result in changes in the general project, and even in the assumptions for the project, formulated in the conceptual design phase.

At the final stage of this phase, the full technical documentation is prepared and, especially in the case of serial or mass production, a test series is manufactured, which is used for verification of constructional-technological documentation and prepared manufacturing process.

In the case of machines, which lifetime (in particular production and operation) is long, the possibility of machine modernization should be predicted as early as the designing stage.

Design activities shouldn't end with the start of production phase, but should continue throughout the whole period of machine production. Designers should analyze information about the machine obtained during its operation and maintenance and use them to improve the structure of the manufactured machine or gain experience, which can be used in the development of another machine.

Production

In the production or construction phase, the idea – abstract machine written in the form of design documentation, which was prepared in the previous phases, is made into material object. Manufacturing process should ensure the compliance of the product with the documentation developed in the designing phase. Deviations from the design assumption may cause that the machine won't achieve the assumed properties. Hence, the compliance of the process with these assumptions, including reproducibility of manufacturing at its different stages (properties of the used materials, precision of the machining and assembly, etc.) must be controlled. In the case of detecting errors, the process should be appropriately corrected. Method of manufacturing is selected depending on the product type and production size, as well as the environmental requirements, so as to obtain the desired economic results. In case, when the machine is manufactured for a long period of time, manufacturing process should be improved in technical, as well as organizational aspect.

Utilization and support

Machines and devices in overwhelming majority are designed and manufactured for the purpose of their use in this phase. During its utilization, a given machine fulfils the purposes for which it has been created. For the machine to be long and efficiently used, during this phase it must be also maintained i.e. adjusted, lubricated, repaired, etc. In the case of some machines, especially with high durability, they also have to be modified and adapted to the changing requirements. Processes implemented in the utilization and support phase will be discussed in detail in further part of this manual.

During this phase, the verification of the accuracy of adopted assumption, correctness of developed design and quality of manufacturing process, are performed. Errors made in previous phases are manifested by improper adaptation of the machine for use and/or maintenance, insufficient reliability and/or durability, etc. However, even well-designed and manufactured machine must be appropriately operated and maintained to allow for the achievement of the assumed objective, including the economic ones. The reasons for excessive wear, failure occurrence, reduced effectiveness are often the mistakes made by persons operating or maintaining the machine – improper operating or maintaining. At the same time, mistakes made by users or persons handling the machine may also sometimes be a fault of the designers. This happens when the information, recommendations concerning the operation and maintenance and prepared by the designers are improper (operation and maintenance are usually conducted based on appropriate documentation prepared by the manufacturer – operation, maintenance, transporting, assembly and start-up manuals, etc.).

As it was previously mentioned, the effects obtained from the machine operation to a large extent depend on the manner of operation and maintenance. Therefore, the persons responsible for the operation and maintenance must have significant knowledge, in terms of technique (among others: about principle of operation, processes occurring in the machines, including the wear processes), as well as in terms of organization, management and economics. On the other hand, the persons making decisions about the features that machine should be characterized by (concept) and designers must have significant knowledge regarding the operation and maintenance issues, because at this stage, the susceptibility of the machine is decided (adaptation to rational, convenient use and handling, etc.). In the design phase, there are also the greatest possibilities to influence the reliability of the machines. Analysis of the existing machines and devices allows noticing that the designers usually give more attention to the requirements related to machine use, and less attention to the requirements related to machine maintenance and modernization. This hampers the implementation of handling and repair processes, and usually contributes to a decrease in reliability, and this in turn reduces the level of machines availability, increases their maintaining costs and in effect reduces the benefits of their operation.

In conclusions, it must be emphasized that the utilization and support is a particular phase of machines (and other technical objects) existence, because up to this phase the machines are created and in this phase all errors made in the previous phases are manifested, also during this phase the needs of modernization occur and the needs to develop new machines arise.

Phase-out and disposal

Machines, as well as other technical objects, are withdrawn from operation when its users ascertain that their quality does not ensure the required usage effect or that the further use is unprofitable. So, the withdrawal is a result of moral, physical or economic wear of the machine. After withdrawal from service, the last phase of machine existence occurs – phase-out and disposal phase.

Liquidation process should be carried out in such way that will minimize the negative impact of the liquidated machine on the environment. It is achieved through the possibly high recovery of materials, which allows reducing the consumption of raw materials and amount of waste intended for storage, as well as the proper storage of the latter. The activities carried out in the liquidation phase include among others: dismantling, separation of the different materials and their division into the product recycling, material recycling, energy recycling and waste for storage.

Caring for natural resources and environment results in the fact that more and more attention is paid to this phase, and problems of appropriate liquidation, similar to designing, manufacturing and operation, constitute separate and growing field of practical issues. Therefore, the process of liquidation is more and more often implemented by, or with the greater participation of specialized companies.

Effectiveness of the liquidation process, similarly as in the case of operation and maintenance, is highly dependent on the machine design. Therefore, the machine should be adapted to liquidation already at the design stage. In addition, the manufacturer should take part in the liquidation process. With proper adaptation of the machine, such participation may allow not only for a better reuse of materials (product recycling), but can also be a source of additional revenue for the manufacturer. The course and effectiveness of liquidation process, including manufacturer participation, are greatly affected by legal provisions.

1.3. Actions in the phase of machine utilization and support

Operation and maintenance is a set of targeted organizational-technical and economic actions of people with the technical objects and interactions occurring between them from the moment of acquisition of the object for the use as intended, until its withdrawn from service.

In the utilization and support phase, we can distinguish two basic processes: operation and maintenance.

Operation is the use of a technical object according to its purpose and functional properties, in order to fulfil human needs.

Maintenance is the maintaining of a technical object in the state of usefulness and restoring to this objects its required functional properties through inspections, adjustments, lubrications and preventions, repairs and overhauls.

Beside the operation and maintenance, we can distinguish other actions, which may be assigned to one of the above-mentioned basic actions. They are distinguished due to the different nature and easier manner in which they can be discussed. Utilization and support phase includes the following actions (Fig. 1.2):

- preparation, pre-use actions,
- operation,
- maintenance,
- feed,
- management.

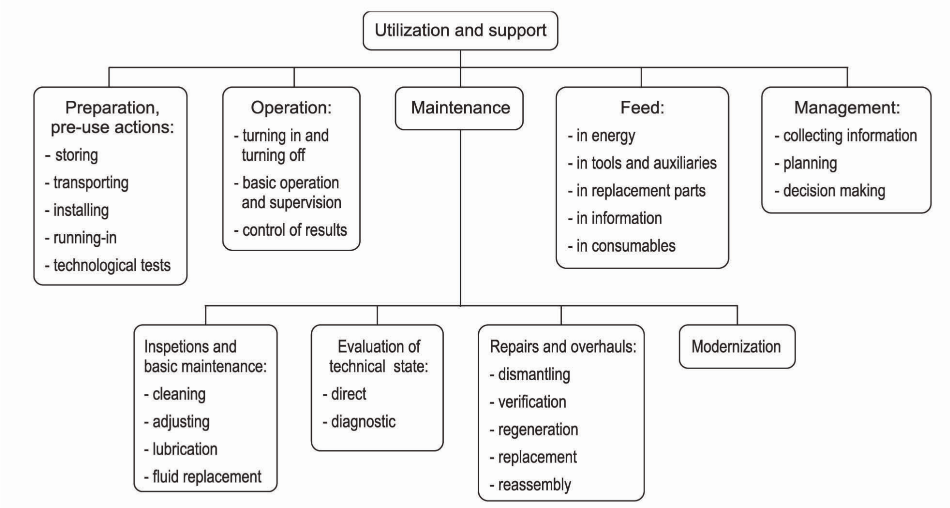


Fig. 1.2. *Actions in the utilization and support phase*

Preparation and pre-use actions

Preparatory actions, including pre-use actions, may include transporting, installing, technological tests, storage, etc. These actions were treated as independent group, because usually they differ from the actions conducted during typical use or maintenance, often they require other qualifications and specialized equipment, and therefore they are carried out by other persons or specialized business entities. Pre-use actions may be performed once, during the putting of new machine into service or repeated during the time of operation. For example, installing and technical acceptance can apply to the new machine, as well as to the machine after general overhaul.

In the case of many machines and devices, their implementation into the use does not require special qualifications, wide range of works and money, and it's carried out by persons who later use them. Sometimes however, especially in the case of large machines, machine installation in the place of use may require a large range of preparatory works. Machines may require: special foundations (including anti-vibration ones), supplying in various media sometimes with very specific parameters (electricity, water, fuel, compressed air, etc.), special working conditions e.g. temperature, humidity, etc. Fulfilling the appropriate conditions may sometimes require the development of adequate infrastructure, including special building or major adaptation of the existing ones.

After installing, the machine must be prepared for its first start-up. Among others, you need to remove mechanical safeguards and protective layers, clean the machine, lubricate the required places, provide appropriate operation fluids, perform proper adjustments and settings. After checking the correctness of the installation and preparing for launching, the tests aimed at verifying the correctness of machine operation are conducted, and usually the technical acceptance is carried out.

Transport of some machines or equipment may require just like the installation a wide range of preparatory work. These actions are aimed at minimizing the adverse impact of a transport on the technical condition of a machine (this applies to the devices especially sensitive to weather conditions, vibration, etc.) and minimizing the risk of mechanical failure of a machine itself or the objects in its surroundings during transport. For large machines or equipment transport may require disassembly and transferring in batches.

Transport operations include an external transport i.e. transfer of a machine from the production place/storage/ repair to the plant where the machine is to be used, as well as internal transport – inside the plant. External transport involves ships, railway and trucks.

To carry large or heavy equipment it is sometimes necessary to use transport for oversized loads. Internal transport uses gantry cranes, cranes, forklifts, etc. Sometimes the machines are rolled on the special rollers.

Preparation of the machines for transport may include: disassembly of selected parts, securing moving parts against displacement, protecting machine or some of its parts from external factors by choosing appropriate packaging or placing the machine in a container, box, etc. During transport, especially in the case of external transport, the machine must be mounted as to prevent it from falling over or from moving around the vehicle. The machine or a container with the machine should be lifted in a way preventing failure. Elements to which the chains are attached must be of appropriate strength. When using ropes they should be tied in a proper place and in a manner that protects the machine components from failure e.g. by placing wooden blocks or other elements between the rope / belt and the surface of the machine. When lifting, the machine must be secured against uncontrolled fall (overturn).

During transport great caution should be applied and health and safety regulations should be followed since transport operations carry a significant risk of an accident. The transport equipment should have a proper lifting / load capacity and the ropes, slings, hooks, etc. should have a known and proper strength as well as good technical condition.

For some machines and equipment storage may be one of the most important activities during utilization and support stage. This is the case of machines and devices rarely used which for the majority of their life-cycle are stored e.g. rescue and military equipment. Storage is also an important issue for machines used seasonally e.g. some agricultural machines or equipment in which the wear processes are intensively taking place just at a time when they are not in use. Storage and transport are often related with packing and unpacking activities.

All of the above actions i.e. transport, storage, installation, preparation for launch and checking the operation of a machine should be carried out in accordance with the technical documentation enclosed. The manufacturer should therefore prepare a documentation containing relevant requirements and instructions with description of the activities related to the above mentioned operations in order to eliminate possible error.

Operation

The actual use is the essence of the existence of machines and equipment as it is when they satisfy the needs for which they were being manufactured. Machines satisfy different needs and are used in different situations e.g. in the household, in plants as a mean of production, in the service industry etc. For this reason different types of measurement are taken into account in order to assess the degree of satisfaction of these needs and the effects of use. These measurements are often economic effects (profits), but can also derive from satisfaction resulting not from material benefits, but from the fact of performing some work and from sensation of pleasure associated with the operation of a given device. Even in factories oriented on making profit the assessment of a use of a machine is based not only on profit but also on the security issues (of both humans and the environment) and users' experience.

During the operation stage following tasks are carried out: delivering a machine to the work place and its proper setting (it mainly concerns non-stationary or movable machines), preparation for work (connection to the power supply and possibly supplying other resources, mounting tools and appropriate equipment, adjusting appropriate settings), the machine start-up, the direct implementation of the tasks (running machine, change settings, change modes and other tasks specific to the given machine performed by the user at the time of the work), quality control of operations and results of the work, turning off the machine.

The efficiency of the use is influenced not only by the machine itself, but also by the organization of the use process and the direct operation of users as well as the environment, including the economic and social situation etc. The use of a machine is managed by a man. This is done at different levels: from the strategic decisions taken for example by the director of the plant, decision on the current tasks taken for example by department manager up to the decisions on the direct actions executed on the machine taken by the operator at the time of completion of a the task. Sometimes all of these decisions are made by the same person e.g. the owner and at the same time the user of the device. Operation control at a higher level than decisions made by the operator will be discussed in the subsection dealing with management issues.

Machines perform a variety of tasks and work in different ways but usually the analysis and proper organization of jobs for the operators can increase the efficiency of use. Many machines during operation phase work only for a certain period of time, for example, the machine interacts with the raw material and during the remaining time it is idling or is switched off. Period when the machine does not doing any useful work is necessary for its removal (e.g. tool) from the raw material, removal and putting in place of the raw item, change of settings of a machine and change of tools etc. Proper planning of the method and order of these tasks can increase the useful participation of the tool in the working cycle and so to make it more efficient.

For many machines a user (an operator) determines to a significant extent how the task is being executed and therefore affects the instantaneous working conditions of a machine, including the loads of its components, what may in return significantly affect not only the quality and time of the task execution, but also the degradation of the machine. For example, a driver of a vehicle assigned to carry a cargo from A to B is able to use more or less fuel, wear to a greater or lesser degree tires, driving system, braking system, suspension etc.

In addition a user at work evaluates the effects of a machine work as well as its operation and base on that decides whether to continue the work or to stop the machine altogether. Indications of a technical malfunctioning of a machine which a user should consider are:

- excessive number of manufacturing defects (e.g. departure from dimensional tolerances, required shape of the item, excessive surface roughness),
- reduced output (e.g. a small number of products produced per unit of time),
- increased energy or other supplies consumption (e.g. fuel, lubricants),
- failure to obtain operating parameters (e.g. too low temperature, pressure),
- excessive wear of tools,
- indication of abnormal operation (increased noise, clatter, squeal or other unusual sounds, vibration, overheating, sparking, unusual smells etc.),
- malfunctioning of operating and auxiliary mechanisms (jams, poor response to the control signal, presence of palpable backlash etc.).

The right decision of a operator may prevent serious failure of the machine and other consequences associated with it (property damage, the risk of an accident).

In summary, in the sphere of production or services, the effects of the use of a machine are the result of cooperation between a man and a machine. Although the aim is to reduce the impact of human factors on the effects of use of a machine (in terms of replacing human labor with machines as well as reducing the impact of an individual traits of a user on the effects of use) is still a direct user (operator of a machine or device) who decides to a greater or lesser extent on:

- the quality and duration of a task,
- the consumption of energy and other materials needed to complete the task,
- the change in a technical condition of the machine accompanying the completion of the task.

Qualities of an employee that decide on the efficiency and effectiveness of operation:

- qualifications i.e. vocational training, experience, appropriate psycho-physical and mental conditions,
- commitment or willingness to work and temporary physical and mental state (depending on the working conditions, fatigue, motivation, factory atmosphere etc.).

Maintenance

It should be noted that a maintenance has an ancillary role in regard to the operation. If not for the imperfections of machines and equipment i.e. the fact that they are not fully resistant to the environmental influence and are subject to aging processes, maintenance would be unnecessary. The need to support is disadvantageous since it generates losses (direct maintenance costs and losses associated with the exclusion of the machine from use). Therefore the aim is to minimize the frequency, scope and cost of maintenance. Unfortunately the complex technical objects including machines require support. The maintenance quality usually has a big impact on the durability, reliability and the benefits achieved from the use of a machine so the maintenance has an important place in the utilization process.

Operating activities include:

- basic maintenance,
- control of the technical condition,
- repair,
- modernization.

The basic maintenance activities are aimed at maintaining the state of usability of a machine or device. These activities include lubrication, cleaning services, protection against the harmful impact of the environment e.g. protecting the surface from corrosion. The scope of basic maintenance sometimes includes activities related to the regulation and setting of a machine or equipment. The basic maintenance has a major impact on the wear and durability of the parts and mechanisms of the machines and equipment.

Technical condition is evaluated on the basis of an assessment of the machine performance, direct measurements or diagnostic measurements (see Chapter 4). Usually the purpose of these checks is not only to determine the current technical state of a machine, but also to forecast its future condition and a result of this assessment should be to decide on the need to carry out preventive repairs. Sometimes, especially in the case of checks carried out at the request of the user who suspects a machine malfunction, the aim should be to identify the causes of potential failure.

The repair activities are aimed to restore the technical or functional efficiency of a machine. The activities carried out during repairs include: disassembly, cleaning, verification, regeneration or replacement of defective parts or components, assembly, adjustments.

The modernization activities are aimed at: improving the quality of products or services carried out with the use of a machine, increasing efficiency and reducing the cost of manufacturing or services, improvement of working and safety conditions, reducing the negative impact of a machine or device on the environment. Sometimes the goal of modernization is to adopt the machine to carry out a new task for which the machine was not originally intended. The modernization of a machine can have, just like a repair, a various scope: from partial (e.g. frequently the control system of a machine of older generation is replace by a new one) to complex modernizations improving most of the essential features typical for operating characteristics of a machine.

During utilization of a machine and equipment a variety of maintenance activities is carried out. Their frequency, scope and the place of execution depends on the type of a machine, way of use, the strategy of maintenance etc. The following types of maintenance can be listed:

- daily services,
- seasonal services,
- technical inspections,
- running repairs,
- overhauls.

Daily services include: general checks of the machine, in particular those units and systems whose condition has a significant impact on the safety and effectiveness of a carried work (vehicle tires and lights condition, safety elements condition, including mounting enclosures in machine tools), lubrication, regulations and other basic maintenance. Daily maintenance is usually performed by the user at the site of operation.

Seasonal services are carried out in order to adapt a machine to seasonal changing of weather conditions. These activities generally concern the machines working outside and include: replacement of fluids (lubricants, cooling agents and others, e.g. winter windscreen washer fluid), replacement of equipment (change of summer tires for winter tires, heating system installation in the operator's cabin), environmental impact protection (covering certain surfaces with a protective layer, the use of additional covers), regulations (reducing the amount of cooling), and the like. Sometimes seasonal support is executed right before or after the storage.

The technical inspections (services) can be carried out at various frequency and scope. Usually they include a control of the technical condition, basic maintenance activities and often also the repair or replacement of worn out parts and units that do not ensure the correct operation of a machine to the next inspection. Depending on the chosen maintenance strategy the aim of the technical inspection apart from above mentioned basic maintenance and repairs is to specify as well the date of the next inspection. The technical inspections, depending on the type of a machine and the scope of the review, may be performed in the place of use (applies mainly to the heavy and stationary machines), in the assigned areas where the machine is delivered for the time of inspection (applies especially to the machines and movable devices that are easy to transfer, install and uninstall) or in the special service stations (e.g. in the case of vehicles).

Running repairs are intended to remove a failure or faultiness. The scope of running repairs includes activities related to the replacement of damaged components, systems, or even whole units. Defective elements can be renovated. At the end of the repair the proper adjustments and tests are being carried out in order to assess the repair. Running repairs are to be carried out during technical inspections or if needed. Those repairs are carried out in the proper repair shops, service stations or in the area where the failure occurred.

An overhaul is an extensive and simultaneous reparation of many (the so called medium-scale overhaul) or even all the units of a machine (a general overhaul). The aim of the repair is to rebuild the functional potential of a machine. The decisions to carry out an overhaul are taken after a thorough analysis of their validity (mainly economic) and the deadlines are planned in advance (although sometimes an unplanned failure speeds up an overhaul). The overhaul, especially the general ones, are carried out in specialized shops. The scope of work related to the general overhauls includes:

- preparatory work (removal of a machine from the workplace and its transport to a repair shop),
- repair work (removal of parts, components or units, washing and cleaning, assessment of their technical condition and determining of the further works, regeneration or replacement of worn out parts, sub-assemblies or sometimes even entire units, assembly of a machine, lubrication and filling with operating fluids),
- regulations, run-in, proper operation trial,
- preparatory actions for re-use (transport of a machine to the operation area, installation, tests and technical acceptance if is not being done at the repair shop).

Usually when undertaking overhaul, especially a general one, the modernization of a machine is being done.

Maintenance activities including their scope, frequency and quality to a large extent determine the durability of the various components, assemblies and complete machines. Through appropriate support services sudden failures of the components and machine breakdowns can be prevented. The consequences of such failures may damage other components or other nearby objects and may cause an accident or be a threat to life, health or environment. Failure of a machine element that causes more extensive failure increases the cost and duration of a repair. Furthermore, exclusion of a machine from operation for the time of repair generates losses associated with the production process or services in which it participated. Unexpected repairs usually last longer than the planned ones and disrupt to a larger extent business activity. Therefore, the aim is to minimize unplanned stoppages related to technical maintenance. It should be emphasized that unplanned stoppages can be associated with a sudden failure (nonfunctioning machine) but they can also be the result of a conscious decision of a user or a person who assesses the technical condition of a machine and after finding technical failures decides that continuation of use could lead to an accident, serious damage to the machine or losses associated with the production of defective products.

Maintenance should be carried out by people with the right qualifications. In factories, especially in the large ones, the maintenance of the machines in proper working condition i.e. maintenance activities is carried out by maintenance departments (head mechanic division). The activities of maintenance departments usually are aimed at obtaining high durability, high technical availability of machines as well as at minimizing the cost of technical services. The influence of the frequency of inspections (inspection and maintenance activities) at their expenses, the cost of repairs and the sum of these costs is presented in Fig. 1.3. The chart shows that there is an optimal frequency (range) of services where the total operating costs are the lowest.

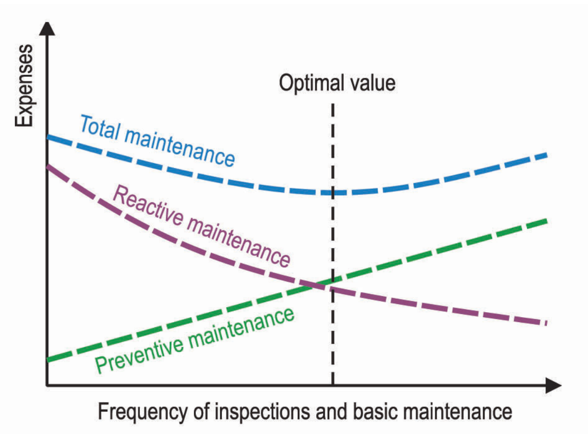


Fig. 1.3. *Influence of the frequency of technical inspections on the overall cost of maintenance*

Methods of organization and approach to the maintenance of the machines and equipment have been changing over the years. We can distinguish several basic strategies of maintenance:

- corrective maintenance,
- scheduled preventive services,
- condition-based maintenance,
- mixed.

Corrective maintenance

In the strategy of using the machine until its failure only basic maintenance are carried out and repairs are done after the failure.

The disadvantages of this strategy are: the need to perform repairs at unexpected times, possible high repair costs compared to the planned repair, incomplete repair at times (removal of visible signs of malfunctioning not causes), unplanned and usually longer exclusion of the machine from operating.

The advantages of this strategy are: low cost of technical inspections and full utilization of the machine or its selected elements.

This strategy cannot be used for machines or to the types of failure that could cause a threat to life or health or a serious threat to the environment. This strategy is not being applied either if the failure results in a large financial loses (significantly increased repair costs, large losses associated with unplanned exclusion of a machine from use). The use of this strategy may arise due to the low technical culture, but it should be stressed that this strategy, although the least advanced, in many cases, may be the most reasonable.

Scheduled preventive maintenance

The strategy of planned preventive maintenance assumes that the maintenance activities, regulations, replacements or repair of components or subassemblies will be carried out before any failure resulting in unplanned downtime of a machine or device is done. These activities are carried out according to a predetermined program; however the frequency of technical services is usually constant. In this strategy the technical services usually have a hierarchical structure i.e. higher order services carried out selectively contain a range of activities from lower order services. The frequency of services is represented through a variety of units, usually characterizing the amount of work done by the machine (working time, number of cycles, number of kilometers or operating hours, calendar time or other). The program i.e. the frequency and the range of the individual technical services are determined on the basis of structure analysis, the assumed conditions for operation as well as years of research and experience with similar machines. Such strategies often include overhauls of the machines which may also have hierarchical structure (medium scale overhauls, general overhauls).

The advantages of this strategy are: easy planning of services, including delivery of supplies and spare parts (i.e. parts replaced periodically), predictable and more evenly distributed in time maintenance costs, lower operating costs achieved by preventing more extensive failure and unplanned downtime.

The disadvantages of this strategy are: carrying out a regular range of services, including repairs, regardless of the state of the machine, relatively high cost, lower certainty of the system in contrast to the condition-based strategy, especially in the case of the machines used in severe conditions (in this strategy variations in regard to the conditions of use are not considered).

Condition-based maintenance

In this strategy, similarly to the planned preventive maintenance strategy it is assumed that the maintenance activities are intended to prevent failure causing unplanned downtime of the machines or equipment. However, according to this strategy, the maintenance activities should be carried out when they are actually needed. So it is assumed that this strategy should eliminate the biggest drawback of scheduled strategies i.e. carrying out services, including repair, regardless of the actual technical condition of the object. In order to implement this strategy, it is necessary to monitor the state of a machine. Technical condition can be monitored continuously or periodically, with the use of diagnostic methods. In this system there are no fixed time of the maintenance or repairs, but the decisions about performing them are taken in relation to the current technical condition and the predicted changes of this condition in the time of the realization of the planned tasks. Therefore, it is vital in this strategy to build the reliable system of the assessing the technical condition, including predicting its changes, but it is also usually the biggest challenge in introducing this strategy into practice.

The advantages of this strategy are: minimalizing the amount and the cost of the maintenance activities and repairs and the loss related to the equipment's downtime, increased reliability of the machines operations.

The disadvantages of this system are: high cost of introduction it into practice, complicating the technical system (expanding the machine or device with the elements of systems that are monitoring, sending, gathering and processing diagnostic data, which also have to be maintained), the need for highly qualified staff supervising the diagnostic system, and thus possible high costs, difficulties with planning the conservation and fixing costs.

Mixed maintenance

In practice there is never only one strategy used at a time in the complex machines and devices, even more so in the whole systems of, for example, production lines. Usually the basic strategies or some of their modified forms are used to service individual elements or units of the machines or devices.

Currently the most common mixed strategy of servicing any given machine or system is based on scheduled preventive maintenance. In this strategy the basic maintenance and preventive activities are performed on these elements whose technical condition significantly influences the usability of the machine and whose life is definitely lower than the durability of the given machine. In relation to the elements and the subassemblies the failure of which is not significantly influencing the machine's operations, usually the strategy of using until failure is implemented. For some chosen, important subassemblies condition-based maintenance might be used. Sometimes the time between the individual planned maintenance procedures is shortened or lengthened based on the results of the technical condition control and taking into account the working conditions of the machine.

Mixed strategies, based on the condition-based maintenance strategy, in spite of the obvious advantages, are not widely used, especially in the cheap machines, because of the high costs of implementation. In these strategies the diagnostic methods are used for many significant machine subassemblies, whereas the strategy of scheduled maintenance is used for these important units, for which the reliable assessment of the technical condition is difficult or using the diagnostic methods is uneconomical (e.g. the elements important for safety, but cheap and easily replaced). The maintenance systems based on the condition-based maintenance are used in the machines and devices that must to be highly reliable because of the human or environment safety or because of the high risks caused by the machines breaks. Thanks to the decreasing cost of the diagnostic systems and the advantages of the condition-based maintenance, such strategies are increasingly common. What's more, systems like that are becoming more automatic, that means that the machine informs the user about the need for maintenance procedure.

Feed

Machines and appliances if are to be used, must be supplied with various materials and media: energy required to perform work (electric energy, fuel, steam, compressed air etc.), fluids and other materials used during the machine operation, maintenance and other activities (lubricants, coolants, preserving and washing means), tools used in the machines work and required for maintenance procedures and other operations, instruments and other equipment, spare parts, information (in case of the machines controlled numerically), etc. In big production factories there are special departments dealing with shopping or supplying, taking care of these procedures. These departments should closely collaborate with production departments and maintenance departments for keeping the machines in constant motion, for the purpose of ensuring the continuity of supplies. The lack of proper supplying for the materials or media mentioned above causes the stops in the labour or lengthens the machine downtime, which has the same result. To prevent such events from occurring, the supply provision should be appropriately organized and suitable amount of spares should be ensured. Moreover, the amount of the spares should be as low as possible, to decrease the cost of the storage.

Management

Managing the machine utilization involves such actions that are directed towards utilizing the possessed supplies to achieve a desired goal. The goals of the utilization systems of machines and appliances might be following:

- rational use of the machines in agreement with their purpose, allowing for maximal economic effects while simultaneously meeting other requirements, including those regarding safety,
- maintaining the machines in the condition of ability, ensuring that they are able to perform their tasks, with present supplies, limits and disturbances in given conditions in given time,
- limiting the negative effects of the technical objects on the human or environmental safety.

In the case of majority of the enterprises, the main goal of utilization is the maximization of the economic effects, which is the first of the aims mentioned above. The second goal might be the main goal in case of emergency services, army, etc. The third – in case of managing objects whose breakdown comes with a threat of ecologic disaster.

Management includes such activities like: gathering information and analysis, planning and organizing, deciding and directing, controlling and supervising.

Management includes managing the entire machine utilization, as well as the managing the individual kinds of activities (operation, maintenance, etc.). In the process of managing, beside decision-makers on various levels, also support services take part: analysis departments, finance and economic departments, etc.

To reach the established goal the specific procedures are assumed, so called utilization and support strategies. It is worth remembering that the realization of any given strategy usually involves all the machinery or chosen production line, but it does not mean it includes each individual machine. For example, fulfilling a task in any given time might require overworking the machine or omitting a valid maintenance procedure. The decision-maker must decide if the realisation of the task can happen at the expense of increased machine's deterioration or not. The decision should be supported by appropriate economic analysis.

The case described above is the example of so called utilization conflict. It is the conflict between the users (production department) and the people responsible for maintenance (maintenance department). The conflict is the result of the opposing interests and the fact that usually the maintenance procedures require the machine being taken out of use and vice versa, maintenance activities cannot be performed on an operating machine. The conflict should be controlled by the appropriate management. From the level of the supervisor of the sides of the conflict, this issue becomes an internal conflict of the superior (the owners of the machines sometimes find themselves in similar situations). In such situation usually helpful are cost analyses. The range and frequency of maintenance procedures should be established in such a way that the sum of the costs of the maintenance activities and the cost of loss in production caused by the machine downtime when it is serviced was as low as possible (Fig. 1.4).

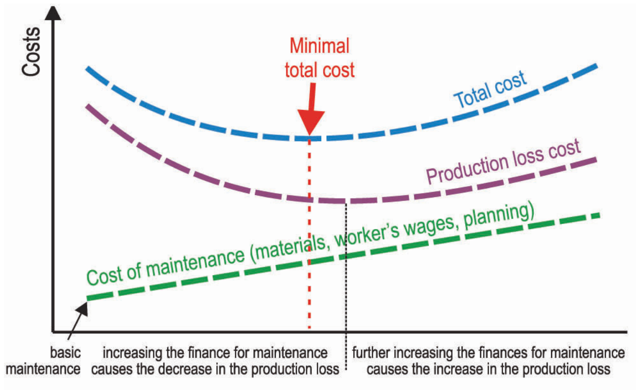


Fig. 1.4. *The relation between the costs of the maintenance, financial loss in production and total cost*

While managing the utilization, the maintenance and other actions should be organized in such a way as to decrease the cost of maintaining the machines to as low as possible. But the analysis cannot be limited to the cost of the worker's wages, material and the services maintaining the machine. It should also include – as costs – the losses related to the inappropriate organization of the maintenance and use of the machine (Fig. 1.5).

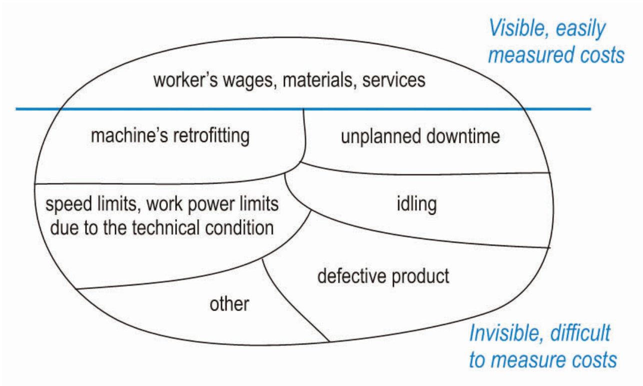


Fig. 1.5. *The costs of utilization presented as an iceberg*

The evidence above is taken into consideration in the modern strategies of technical object utilization directed towards the technical safety and minimizing the costs of the maintenance (RCM, RBI, RBM, TPM). Total Productive Maintenance (TMP) is the local system of machine and appliance maintenance that is aiming for the maximization of the efficiency. The aim is reached by following means:

- minimizing the defects of the machines,
- minimizing the production of defective products,
- minimizing the accidents in work.

Measures of the efficiency of the machine maintenance system

In the management of machine and device utilization it is very helpful to use the numeric measures or coefficients characterizing the achieved or predicted results. There are many measures of this kind, regarding the following aspects: economical, technical and organizational. Moreover, these parameters might be assigned for different organizational levels, which means that they might describe the whole enterprise, individual production line or individual machine.

Some of the measures of the machine efficiency:

Use efficiency ratio:

$$K_w = \frac{T_u}{T_u + T_n + T_o}$$

where: T_u – use time, T_o – time spent in maintenance, T_n – the length of time during which a machine is not productive because of organizational reasons (technically is available).

The value of the use efficiency ratio depends on the technical features of the machine and on the functioning of the maintenance system and use organization.

Technical availability coefficient:

$$K_g = \frac{T_{up}}{T_{up} + T_{down}} = \frac{T_u + T_n}{T_u + T_n + T_o}$$

where: T_{up} – the time spent in condition of ability, T_{down} – the time spent in a condition of inability.

The technical availability coefficient describes the probability that in the moment *t* the machine is or is not in the condition of ability. The value of this coefficient depends on the technical features of the machine and on the functionality of the maintenance system. Figure 1.6 presents the changes of the technical availability coefficient in time during the utilization of the two groups of machines of the same kind, used in similar conditions but with different strategies of technical maintenance.

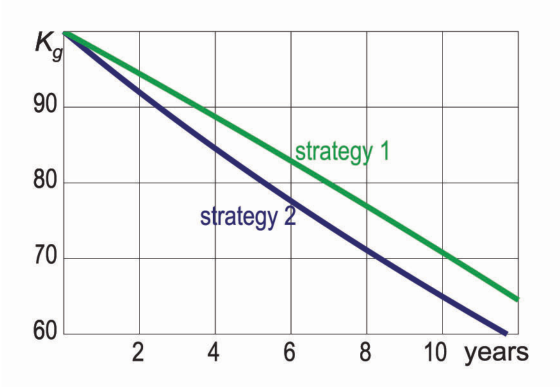


Fig. 1.6. *Time and maintenance strategy influence on K_g*

Relative coefficient of the passive stops in the maintenance:

$$k_{o1} = \frac{T_{o1}}{T_o}$$

where: T_{o1} – time of the passive stops in the maintenance.

This coefficient depends on the functioning of the maintenance system.

The composite measure used in the modern methods of the efficiency management (e.g. in the TPM) is Overall Equipment Efficiency (OEE):

$$OEE = K_w \text{ x } K_e \text{ x } K_j$$

K_w – availability index, the time of machine in uptime compared to the unit of time (the length of time the factory is working, the time of shift),

K_e – performance and productivity index, the efficiency of a machine in the given unit of time compared to the ideal efficiency,

K_j – quality index, the number of the products meeting the requirements compared to the overall number of the produced objects.

The OEE describes the gap between the actual and ideal conditions, where the appliances work through the 100% of the estimated labour time with 100% efficiency and with the end product being 100% consistent with the requirements. This measure presents the potential possibility for improving the process of operation and maintaining the machines and devices.

While assessing the calculated measures, especially while comparing them to those obtained by other enterprises, it should be stressed that the actual results depend on many factors:

- external (e.g. localization, social culture, law regulations, labour costs, sector/branch, market situation),

- internal (e.g. organizational culture, production requirements, diversity of the production, the size of the enterprise, equipment use, the age of the equipment).

Risk analyses are often conducted in managing the utilization. The risk in utilization is defined as an quotient of the probability or frequency of the event occurrence and of the consequences or the significance of this event (e.g. the financial losses related to the event). In practice the evidence shows that usually less than 20% of the forms of failures is responsible for more than 80% of the losses related to all of the failures (Fig. 1.7). This means that in managing the maintenance system it is important to pay special attention to those failures that generate the greatest loss, and at the same time – resign from preventing that failure that generates low loss, because the cost of this prevention will surely exceed the gain.

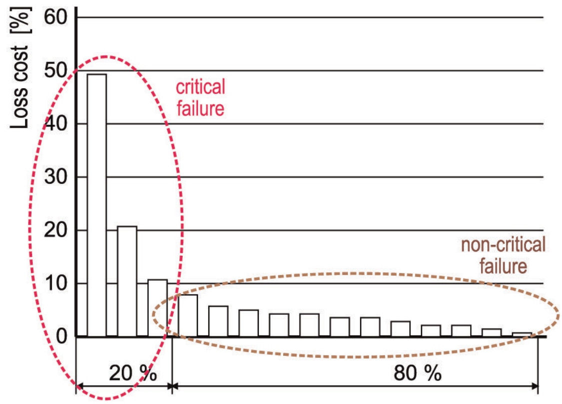


Fig. 1.7. *The loss cost related to various machine failures*

1.4. Operational requirements that apply to the machines

Evaluating the machines, e.g. before making a purchase, there are things to be considered:

- usefulness or functionality, that is the degree to which the machine is adapted to perform given tasks; the requirements that the purchased machine must meet are following:
  - performing the demanded task,
  - appropriate range of regulation,
  - sufficient power and efficiency,
  - providing suitable safety for the operator and the environment;
- utility, that is the features responsible for the quality of the fulfilled requirements; these features allowing to choose the machine from the group of machines meeting the usefulness requirements are following:

  - reliability and durability (endurance, inflexibility, resistance to wear, starting-up ability, resistance to vibrations and various conditions, prevention from the overworking),
  - usability and maintainability,
  - ecology, low noise labour,
  - size and mass as low as possible;
- economy:
  - the cost of purchase,
  - the cost of operation and maintenance (material use and their quality, energy efficiency, the amount of work and funds required for maintenance).

Usability and maintainability mean the quality of a machine (created in the process of design and development) responsible for the possible easy and rational use and maintenance of the machine. The adaptation of the machine to various activities in utilization phase might vary, thus we can define the following -abilities: usability, maintainability, reparability, transportability, ability for modernization, diagnostic, etc.

Usability is the adaptation of the machine to use, depends on, among other:

- the requirements of the machine regarding the installation and the range of preparation work necessary for the task to be carried out,
- materials and equipment necessary for proper operation,
- the requirements regarding the qualifications and individual traits of the operator,
- ergonomics.

Maintainability depends, among others, on:

- easy accessibility to the elements requiring frequent regulation or changing as well as periodic lubrication and other basic maintenance,
- the simplicity of the repair and servicing,
- the frequency and the labour intensity of the service and reparation,
- unification of the machine parts,
- universality of the tools, devices and instruments necessary for the reparation and service.

Diagnostic ability depends on:

- the possibility to carry out diagnostic measurements,
- the reliability of the information and the possibility of using this information in assessing the current and future technical condition of the machine (taking into consideration the influence of the surroundings and the operator).

2. Changes in technical condition of machines

2.1. Machine failure

In the phase of utilization and support the machine is exposed to the following impact factors:

- operation factors – the impact factors influencing the machine in the process of work done by the machine – caused by the machine operation (mechanic load, temperature, vibrations and tremors, chemical factors etc.),
- external factors – the impact factors describing the influence of the surroundings on the machine – they are not conditioned by the machine operation (weather conditions, the environmental influence, human influence).

As a result of the factors mentioned above the machine is undergoing the process of physical aging, that means natural changes causing the changes in the functional features of the machine. Physical aging of the elements and the units leads to their failure, that is the loss of the ability to carry out their tasks. These failures are called gradual or wear. Besides the gradual failure, which is expected after a given amount of time and which can be prevented by the preventive repair (e.g. replacing the element), there are also sudden, emergency failures (Fig. 2.1). There are also temporary failures, that are such failures which subside spontaneously after some time (e.g. the first try to start up fails, but the second one is successful) or failures which are easily repaired (fixing the jam, simple regulation).

It should be emphasised that the failure in some cases is easy to notice (e.g. damaged bulb, busted bolt), but in other cases the failure might be called conventional (e.g. such damage to the elements surface which creates clearance between the cooperating elements, which in turn makes it impossible to achieve the desired accuracy and recurrence of the process).

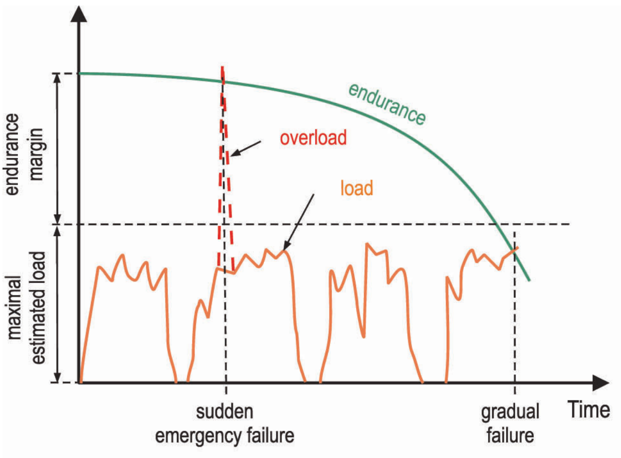


Fig. 2.1. *The process of the occurrence of the failure – gradual and sudden*

The causes for the sudden or premature wear failures are:

- construction errors (erroneous conception, too low endurance etc.),
- production errors (errors in technology during the production of elements or during montage, material defects),
- maintenance errors, that is inappropriate use (e.g. overload), incorrect maintenance (e.g. lubrication, regulation, repair), incorrect transport, storage, etc.,
- the natural occurrences in the nature or other random events that the machine is not prepared for, which has been deemed improbable during the design of the machine (e.g. excessive mechanical load caused by the hit, or thermal – caused by the fire).

Because of the huge amount of technical solutions and the materials applied, the form of the failure might be vastly different and dependent on the complexity of the damaged object (element, subassembly, the whole machine). In case of the element it might be: losing the internal integrity (ripping, busting, breaking, burning), the change of the shape or the size (bending or other deformation, surface wear, melting), changing the characteristic features (change of the: flexibility, hardness, viscosity). For the mechanisms and units, these might be: lack of action or improper action, jamming, losing or blocking the electric current, short circuiting, too much or no enough space or movement resistance, leakage, too intense vibrations, etc.

Various failures of different elements influences the utility features of the machines and their surroundings in many ways. Therefore, it is possible to classify failures according to the results, taking into account:

- the possibility of carrying the task by the machine, classifying the failures as: preventing the completion of the task, limiting the completion of the task, indifferent to the completion of the task,
- the safety of the people and the machine and its surroundings; the failures can be classified as: posing a great risk to the life or health, posing little risk to the life of health, not threatening to life or health, causing a devastation or severe damage of the machine or surrounding devices or the environment, causing a slight damage of the machine or surrounding devices or the environment, not causing the damage of the machine or surrounding devices or the environment,
- economy; classifying failures as such that generate or not the following: increase in the cost and the time of the repair, increase in the losses related to the process in which the machine was involved, general social or environmental costs.

The failure might be primary, that is such which is not caused – directly or indirectly – by the failure of other elements of the machine or the cooperating devices; or secondary, caused by the failure of the other elements of the machine or other devices.

Elimination of the failure (repair of the machine) might include regulation, part replacement or regeneration of the element or the whole subassembly, and in some cases might require the repair of the whole machine. Sometimes the repair of the damaged machine might be ungrounded speaking in economic terms or technically impossible, e.g. the devices after the serious fire, cars after serious road accident.

2.2. Technical state

As the result of the influence the operation and external factors the technical condition of the machine in the phase of utilizing and support is undergoing constant changes. It means that the number of the temporary technical states can be boundless. However, usually while assessing the technical condition, the machine is described by one of the condition from the limited chosen number of technical state.

In the classic theory of reliability it is assumed that the technical object might be in one of the two technical state:

- state of ability – the condition in which the object is able to complete the tasks according to the given requirements (e.g. described in the technical documentation),
- state of inability – the condition in which the object is unable to complete the task according to the given requirements.

According to the two-state model of reliability, the technical object in the state of ability, in case of failure – that is an event causing the loss of ability to complete the task – the object moves to the condition of inability. If the object is renewable, as a result of repair, that is the operation restoring the ability to completing the task according to the given requirements, the object moves to the condition of ability.

In case of the complex technical object or the elements undergoing the gradual wear it is reasonable to introduce additional, intermediate technical states. In maintenance practice the three-state models are generally sufficient. There are different names given to the individual states in three-state models:

- state of ability (good condition, condition of technical and functional ability),
- state of the limited ability (passable condition, condition of technical inability and functional ability),
- state of inability (unfit condition, condition of technical and functional inability).

The three-state models are especially reasonable in the relation to the machines and the units able to be repaired, and when their technical condition is assessed by diagnostic methods.

While assessing the technical state the values of the parameters characterizing the technical condition of the machine are assessed. In the two-state model the boundary values (limit values) are assumed. In the three-state models there are passable value and boundary value of the parameter. Exceeding the passable value means moving from the first to the second state (from the state of ability to the state of limited ability, or from the good condition to the passable condition), and reaching the boundary value is equalled with the failure and means passing to the state of inability (Fig. 2.2).

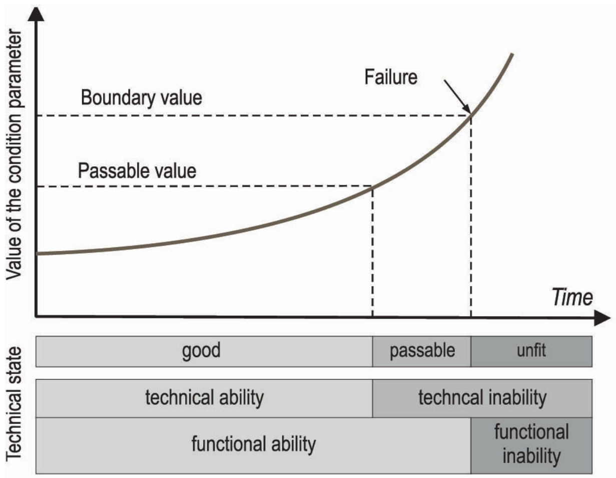


Fig. 2.2. *The changes of the technical condition according to a three-state model*

Taking these information into account it can be assumed that in the machine maintenance the failure occurs when at least one of the assumed measurable or immeasurable features characterizing the object's condition is not meeting the requirements necessary for proper functioning (it reaches the boundary value), or that the object is physically unable to function.

To assess the technical condition of the machine these features are chosen from all of the measurable and immeasurable features characterizing the machine, which are the most important from the utilization point of view. These are generally features describing the functionality and the safety.

The features characterizing the machine from functional and safety point of view might be divided into:

- critical features – surpassing the established boundaries causes the serious decrease in the efficiency of the machine's functioning and might cause its destruction and also poses a risk to the people and the surroundings of the machine;
- important features – surpassing the established boundaries causes the decrease in the efficiency of the machines functioning and poses the risk of serious failure to the machine,
- less important features – surpassing the established boundaries causes the passable decrease in the machine's efficiency,
- negligible features – insignificantly decreasing the functionality and insignificant from the point of view of safety.

In case of the machines capable of carrying out many tasks, it is not necessary for all the features to meet the stablished criteria to fulfil a given task (for each task the individual criteria might be established). In case of the machines designed for various tasks, we distinguish:

- functional ability (full) – when the machine is capable of completing all possible tasks,
- task ability (limited) – when the machine is capable of completing only selected tasks from the collection of the all tasks the machine is designed to carry out.

Preventing the physical aging is endeavoured in the phase of utilization and support via practices directed at minimizing the impact factors (proper working condition, lack of overload, influence of the aggressive surroundings, etc.) and to increase the elements' resistance to those factors (lubrication, protection, preventing from overload, etc.).

Apart from the physical aging, the machines are prone to so called moral aging. Moral aging is connected to the technological advancement (the appearance of more modern devices, with greater energetic efficiency, productivity, universality, etc.) and to the changes of social needs (lack of demand for some products or service). The process of moral aging might be prevented by modernizing the machine (it makes sense only if it is economic).

With regard to the information above, there are other criteria that might be taken into account in the process of assuming the boundary values, apart from the technical criteria (functionality, safety): economic (the profit, costs of the renewal, of using), maintenance (technical availability, operation availability), legal (norms and regulations), sociologic (trends, aesthetics), ergonomic.

2.3. Wear processes

Wear is a process of unfavourable changes of the surface of the machine components occurring during their existence. The changes include the mass loss, permanent deformations of the surface and the changes in the chemical composition and other alternations in the structure and physical properties of the surface.

The mechanisms of surface wear are different and usually complex. There can be distinguished several basic mechanisms, which in practice occur simultaneously or consecutively:

- abrasive wear,
- adhesive wear,
- surface fatigue,
- corrosive wear.

With regard to the cause, the processes of the surface wear might be divided into:

- tribological,
- non-tribological.

Tribological wear processes

The tribological wear is related to the friction between the interacting surfaces and has mechanical, physical and chemical aspects. Tribological wear includes abrasive wear, adhesive wear, surface fatigue and tribo-chemical wear (oxidation wear, fretting).

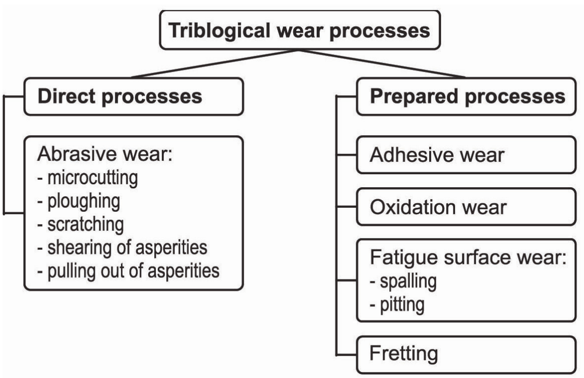


Fig. 2.3. *Tribological wear processes of the machine components*

Abrasive wear is the process of mechanical damaging of the boundary-layers of the interacting elements. It is caused by interactions between the asperities or hard grits as well as the wear debris that are placed between the two surfaces. The abrasive wear is caused by several basic processes:

- micro-cutting, that is cutting of the softer surface by the sharp asperities of the interacting surface or the particles of other foreign material (Fig. 2.4a); the micro-cutting is enhanced by the material's significant hardness, higher than the hardness of the cut element, by sharp edges on the surface, big chip flow α angle;
- ploughing, that is displacing the material on the surface to the sides by the blunt asperities of the interacting surface or particles of other material (Fig. 2.4b); this phenomenon does not cause the direct loss of the material, however, the repetitive deformation of the material results in its fatigue and the separation of the worn particles; ploughing is enhanced by the huge flexibility of the material and the big chip flow α angle;
- micro-cracking, that is the occurrence of the micro crack as the result of the deformations which are caused by the interacting rough surfaces or the particles of other material (Fig. 2.4c); micro-cracking is enhanced by the fragility of the surface, micro-cracks weaken the resistance of the surface, and the wear particles might emerge as a result of the joined micro-cracks;
- shearing off asperities (Fig. 2.4d), it depends on the geometrical features of the asperities, the height of the catch and the mechanical features of the materials, it is especially intensive in the first phase of the work of the interacting surfaces, in the so called 'run-in' period;
- plastic deformation of asperities (Fig. 2.4e); similarly to ploughing does not cause loss of material; it depends on the geometrical features of the asperities and mechanical properties of the materials pf mating surfaces, the phenomenon is intense during run-in period;
- breaking off asperities (Fig. 2.4f) or pulling out the material particles (Fig. 2.4g), the pulling out occurs mainly in the fragile materials with relatively weak ties between grains (e.g. ceramics), while the breaking off is enhanced by the specific geometric features of the uneven surface, the fragility of the material and the micro-cracks decreasing the material's resistance to the breaking off;
- scratching, an intermediate phenomenon between the microcutting and ploughing.

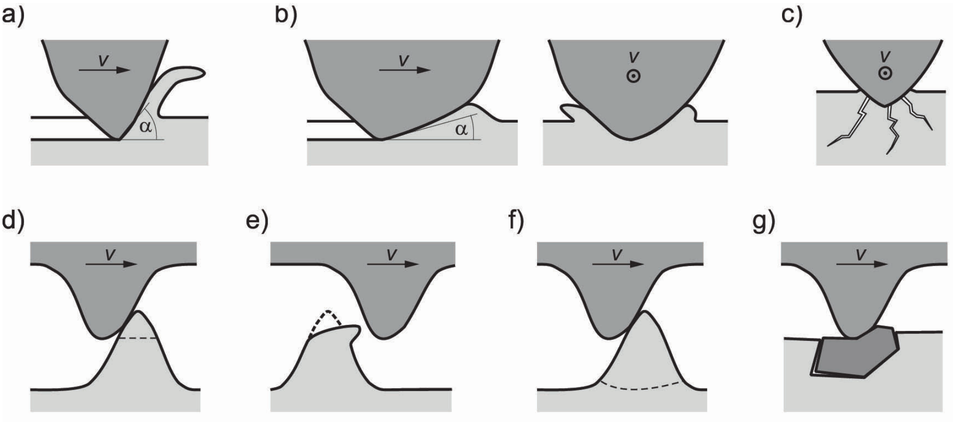


Fig. 2.4. *Mechanisms of abrasive wear: a) micro-cutting, b) ploughing, c) micro-cracking, d) shearing of asperities, e) plastic deformation of asperities, f) breaking off asperities, g) grain pull-out*

During the abrasive wear the phenomena mentioned above are more or less simultaneous, causing the separation of the particles of the material from the interacting surfaces and the permanent deformations of the surface, as well as the changes of its physical properties.

Abrasive wear occurs mostly in places without lubrication in friction knot (dry friction) or when the lubrication is inadequate (mixed friction). Abrasive wear occurs also where the loose abradant moves in relation to the surface of solid object, e.g. working elements of the construction, road, mining, agricultural or transporting machines (e.g. ramps, chutes).

In practice, the abrasive wear is mainly a mechanical or chemical-mechanical process. We talk about chemical-mechanical process when the surface of the element undergoes first corrosive and next the corrosion products are removed from the surface by the friction. This process might involve only removing the corroded layer, but it also might include basic abrasive wear processes, if the roughness of the interacting surface or the loose abradant reaches deeper. In both instances the cooperation of these mechanical and chemical processes intensifies the process of wear: mechanical wear intensifies the process of chemical wear (the non-corroded layer is exposed and might be susceptible to further corrosion corroded) or the oxidation intensifies the process of mechanical wear (e.g. the micro-layer of the oxidized iron arises very quickly, especially on the steel of the normal quality and in wet conditions, and the oxides are less resistant to corrosion).

The factor influencing the intensity of the abrasive wear:

- physical properties, especially the hardness of the material (increasing resistance to wear with increase of the hardness),

- lubricant (the presence of the lubricant and anti-wear supplements in the lubricant lead to decrease in the intensity of the wear),
- surroundings (pollution, especially with hard particles, and the humidity and the presence of the substances accelerating the corrosive processes intensify the wear),
- stress (increasing contact pressure increases the wear),
- the temperature of the elements (increasing the temperature leads to the increase in wear).

The abrasive wear is prevented in following ways:

- constructing the elements from the materials resistant to wear and with suitable hardness and – if it is possible – avoiding the movement knots with dry friction,
- applying lubricants with good anti-wear properties,
- applying air and lubricant filters and also protecting the friction knots in order to limit the influx of the abrasive particles between the interacting surfaces,
- avoiding overload and not allowing the temperature to increase in the friction knots.

Adhesive wear is the process damaging the surface involving creating the friction welds in the microareas of direct contact points and destroying them because of the relative motion of the interacting surfaces. Friction welds are created as a result of a tear in the layer of lubricant and the corrosive layer in turn caused by the too high pressure and/or insufficient or lack of lubrication.

We distinguish:

- cold adhesive wear, sometimes called cold welding,
- hot adhesive wear, sometimes called hot welding.

Cold welding usually occurs in conditions of high pressure and low relative speed, and therefore – not to high temperatures of the rubbing elements. The intensity of the wear depends on the endurance of the created adhesive welds. If their endurance is not sufficiently high, the cut happens along of the primary plane of the division and there is no loss of material, but it results in weakening of the surface. Otherwise, if the endurance is high, the particles of one of the surfaces are cut or pulled out. In this case, the pulled out and welded particles (sometimes there are even so called friction accretions) accelerates the destruction of the surface and the intensity of the wear might be quite high.

Hot welding occurs when the friction speed is high and the pressure that causes the emission of lots of heat is also high, which lead to the increased plasticity or even melting of the metal in contact points. It results in the deformations of the surface, exposing the bare metal layers, creating welds and damaging the surface because of the pulling out the particles and smearing them on the opposite surface. As a result the process quickly escalates – the initiation of this process usually leads to the seizing, that is the failure to the friction knot.

The adhesive wear might occur in:

- plain bearings, and the cold welding might happen especially in the slow speed bearings, also in pendulum bearings (joints),
- sliding units in the machines (the piston-rings-cylinder, the elements of cam systems),
- worm drives and gears.

The adhesive wear must be prevented, because it usually leads to emergency destruction of the machine's elements. The prevention methods:

- selecting the interacting materials of low inclination towards adhesive welds (unipolar and relative materials are more inclined to weld),
- shaping the mechanical and physical-chemical properties of the surface through the mechanical, chemical or thermal processing (e.g. increasing the hardness by pressure or hardening, creating solid surface through chemical processing, oxygen or carbon saturation, etc.),
- providing suitable method of lubricating, including the selection of the proper lubricant able to create the tear-resistant border layers (with good anti-wear and anti-seizing qualities),
- using construction solutions with relatively low surface pressure, also preventing the local accumulation of the pressure with higher loads (e.g. edge pressure in the stiff plain bearings),
- providing such solutions where the elements work in relatively low temperatures (suitable cooling, minimizing the friction, using the material conducting heat and resistant to high temperatures).

Oxidation wear is the process in which the surface of the metal machine elements is damaged due to the loss of surface material caused by the creation of the oxides and their removal in the process of friction. The oxidation wear is typical of the interaction between the metals and their alloys (which have different chemical and mechanical properties) in the conditions of profuse lubrication. For the process to proceed stable, the speed of oxides production cannot be lower than the speed of their destruction. If the produced corrosive layer limits the subsequent corrosion and is at the same time sufficiently solid, then the intensity of the wear is low. This is the most desirable type of wear.

Wear through oxidation occurs both with the slide and rolling friction. It can happen in: plain and roller bearings, piston-rings-cylinder units, the elements of engine valvetrain.

The wear thorough oxidation is not usually prevented, but it is manipulated so that it would become the dominating wear process happening in a given knot. In the knots where the oxidation wear is desired, in the unfavourable conditions adhesive or abrasive wear might happen, which are less beneficial. Of course the trend is such that the intensity of the oxidation wear is as low as possible.

Factors influencing the process of oxidation wear:

- mechanical and physical-chemical properties of the surfaces of the interacting elements (they are formed by the suitable selection of the materials and surface processing); these properties influence the durability of the corrosive layer, which depends on its mechanical properties (the closer they are to the properties of the basic metal, the better) and on its thickness (there is an optimal value – too high and too low thickness decreases the durability);
- lubricant: too high chemical reactivity might intensify the wear process (usually the anti-wear and anti-seizing additives increase reactivity, on the other hand, these additives prevent adhesive wear), too low viscosity might create mixed friction (the speed of the destruction of the corrosive layer is significantly higher with mixed friction than with fluid friction);
- load, relative speed, the temperature of the elements and the vibrations (the increase of these properties intensifies the process of wear);
- presence of hard particles in the lubricant accelerates the destruction of the corrosive layer.

Surface fatigue is the process of wear happening as a result of periodical contact pressure impacting the surface during the friction of the interacting elements. Changing contact pressure on the surface causes the material fatigue and local loss of its integrity and development of micro-cracks, and then the material loss.

Surface fatigue occurs both during slide and rolling friction. During slide friction, the dynamic interaction of the micro-protrusions in the surfaces leads to the material fatigue. However, the fatigue processes in these cases are not the most important. But in the case of rolling friction, the fatigue often is the dominant surface wear process.

During rolling there is repetitive periodical pressure induced on the temporary connection points and usually this connection is highly condensed (small surface of the connection point), which causes high temporary pressure on the contact point. Because of the details of the process we distinguish two kinds of surface fatigue in rolling friction: spalling and pitting.

Wear through spalling is the process typical of rolling friction with no or inadequate lubrication. First micro-cracks appear in the places of the highest stress of the material, they might occur on the surface or under the surface. Typical of spalling is the expansion of the cracks along the surface or at a slight angle. It results in creation of relatively wide and flat flakes, which are then separated from the surface. Spalling is often accompanied by the oxidation process of the revealed material, which accelerates the destruction of the surface. Relative slide of the rolling parts also intensifies the wear process.

Spelling occurs for example in the units wheel-rail, poorly lubricated roller bearings and gears, also in the metallurgical cylinders.

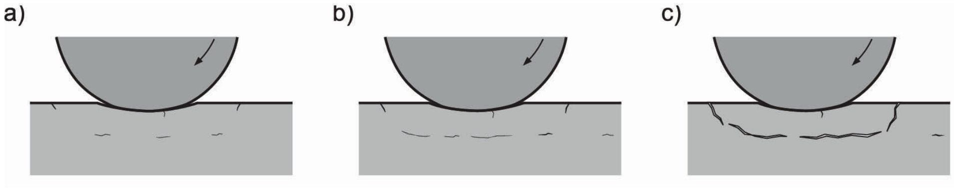


Fig. 2.5. *The development of spelling*

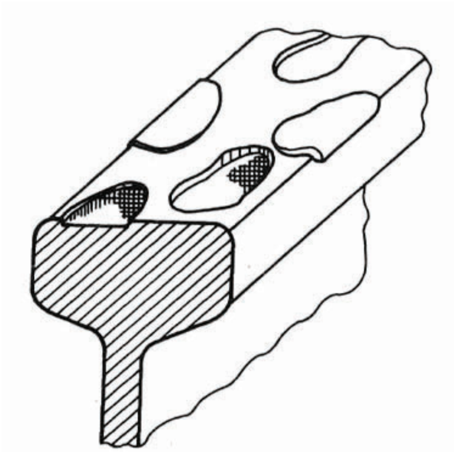


Fig. 2.6. *Schematic of the surface of the rail head damaged in spalling*

Pitting wear is typical of the rolling friction in the presence of lubrication. In the process of pitting there are three phases (Fig. 2.7): the appearance of the micro-cracks on the surface, 2) expansion of the cracks due to the wedging effect of the lubrication (oils with high adsorption ability decrease the surface energy and material cohesiveness, and thus accelerate wear), 3) pulling out the stressed fragments of the material, which are compressed and stretched (because of the adsorbing effect of the oil; improver additives usually increase the adsorptive ability of the oil).

Pitting is most common in the well-lubricated rolling bearings, cam drivers, gears, etc.

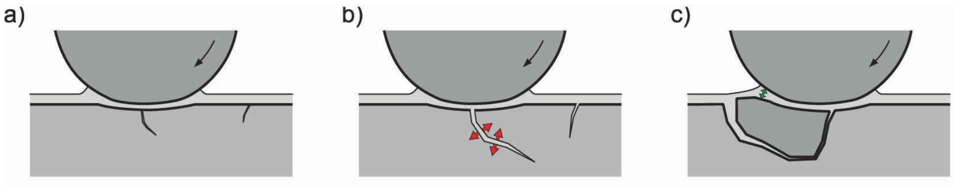


Figure. 2.7. *The development of pitting*

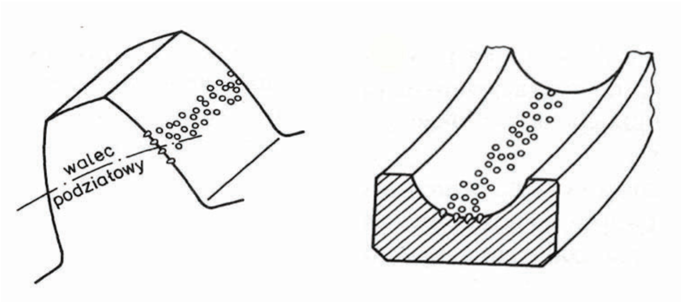


Fig. 2.8. *A schematic of the surfaces damaged by pitting: the side of the gear, track of the roller bearing.*

A characteristic feature of the fatigue surface wear is the appearance of the material loss only after reaching a specific number of periodical changes of pressure. Below this threshold the value of wear measured by the loss of material is equal to zero or very low. But in this phase, the increase is observed in the changes of the structure of the surface material. Above the critical number of the cycles the mass of the material loss usually grows quickly. The beginning of the material loss, caused by its fatigue, is assumed to be the end of the elements utility, especially in case of spalling.

The fatigue surface wear might be prevented by:

- selection of the interacting materials and suitable shaping of their surface (high resistance to fatigue, hardness, resistance to corrosion, proper tension in surface, high precision of the production and the roughness of the surface,
- supplying proper lubrication, among others the presence of the lubrication decreases the surface pressure and delays the appearance of the micro-cracks (first phase of pitting), the presence of lubrication might also slow down the corrosion, decreasing the speed of spalling,
- preventing the surface from overload, too high temperatures, vibrations and work in chemically aggressive environment.

Fretting, called also abrasive-corrosive wear, is the process of simultaneous abrasive and corrosive damage to the boundary-layer of the machine elements and constructions exposed to the vibrations and small relative movements. Wear through fretting occurs between the surfaces practically still in relation to each other (in macro scale). Small movement, usually in the range of micrometres (the amplitude might range from several nanometres to several millimetres), caused by the vibrations of the devices or by deformations related to the changing stresses influencing the elements, or by deformations related to the working movement of given unit. Relative motion of the interacting surfaces leads to mechanical severing of the mini-layers of the oxides from the surfaces of the elements and revealing the bare metal, which undergoes oxidation very quickly because of the increased reactivity of the surface caused by its deformations and contact tensions. Vibrating movements also cause the development of the fatigue processes in the surface, which may lead to the multiplication of the micro-cracks and the separation of the material particles. Separated products of the oxidation and other wear particles become an abradant that intensifies the destruction process. Small relative movements and constant connection of the interacting surfaces makes it difficult for the products of wear to leave the area of connection point. Because the wear products, which are mostly oxides, have higher capacity than the original material, it leads to the increase of the contact pressure and sometimes to additional deformations of the whole elements, e.g. in case of ropes it leads to their protrusion.

The types of connections between the machines and devices in which fretting occurs: different joints (screws, rivets, pin joints, splines, clevis fasteners, friction fit elements), working in static or with very low amplitude, rolling bearing and gears, switches, selected types of valves and regulators, springs of the suspension, ropes, etc.

The consequences of fretting are: the change of the interference fit which – in case of the joined connection – might directly or indirectly lead to the decrease or loss of the bearing capacity of connection, loss of hermetic tightness or jamming of the elements caused by the accumulation of the wear products between the interacting surfaces.

The wear through fretting might be limited by:

- suitable selection of the connected materials and the proper hardness and roughness of the surface layers,
- removing the possibility of the relative micro-movements of the touching elements, or decreasing the movements by building suitable construction knot,
- using lubrication that decreases friction and slows down the oxidation,
- preventing the connection from the oxygen and aggressive substances (less intensive corrosion), e.g. by painting, lubricating, sealing, etc.,
- suitable method of creating the connection (tensions of the surface layer occurring during the connection cause the increase in the surface energy and increase the chemical reactivity of the surface, leading to corrosive processes; sometimes it is possible to create compensating pressure in the surface layers by the suitable mechanical processing),
- complete disconnection of the connected surfaces by using appropriate layers or decreasing the friction force by using a wear-resistant layering, e.g. made of metals of low resistance to shearing (e.g. lead).

Non-tribological processes of wear

Non-tribological wear is one which occurs on surfaces of elements, which don't cooperate with other elements. Non-tribological wear consists of corrosive and erosive wear, including electroerosion and cavitation (Fig. 2.9).

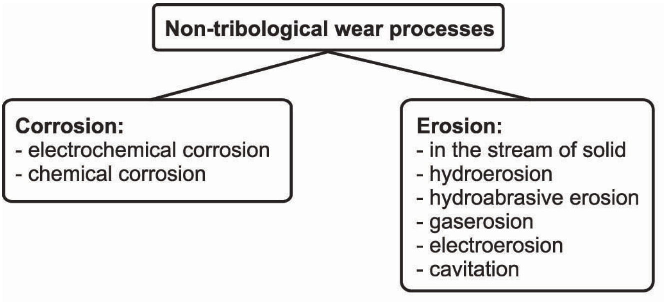


Fig. 2.9. *Processes of non-tribological wear*

Corrosion is a process of materials destruction under the influence of surrounding environment; corrosion occurs independently on the surface taking part in the process of friction or not. Dependently on conditions and kind of material, corrosive destruction may be caused mainly by chemical, electrochemical, physical-chemical or microbiological-chemical processes.

As regards metals, we can distinguish:

- chemical corrosion,
- and electrochemical corrosion.

Chemical corrosion consists in destruction of metals as a result of dry gases or liquids, which don't transmit electrical current, reacting on them. If a product of corrosion (this is mainly an oxide, but it may be also other chemical compound such as sulfide, nitride, carbide) creates a hermetic layer, permanently clinging to the metal, then this layer is the protection from further aggressive environment's interference and it stops the process of corrosion (passivating layer). If the products of corrosion don't create a hermetic layer or chip off, the metal undergoes a fast destruction. Usually chemical corrosion occur in high temperatures, e.g. during metallurgical processes or processes of welding. Then, there emerges a layer of oxides, called scale. One may prevent corrosion in such conditions by decreasing the aggressiveness of environment, including the use of covers of neutral gases. Also elements of machines and devices working in high temperatures, such as elements of furnaces, gas turbines, combustion engines etc. undergoes chemical corrosion. Resistance of elements to corrosion increases through a proper shaping of chemical composition of material (heat-resistant alloys) and the use of various protecting layers obtained by various methods (zincifying, phosphatizing, anodizing, painting etc.).

Electrochemical corrosion is connected with creating electrical micro- or macro-cells and it consists in destroying of materials as a result of electrical current transmission through the boundary of metal-electrolyte-metal and reactions of oxidizing occurring on the surfaces of a lower potential (anodes). The product of corrosion is usually an oxide of destructed metal, but also other chemical compounds, especially salts.

With regard to corrosion environment, one distinguishes the corrosions:

- atmospheric (factors deciding on the process: humidity, composition and concentration of chemical pollution, temperature, state and shape of surface),
- aquatic (factors deciding on the process: kind and concentration of dissolved mineral ingredients),
- earthy (factors deciding on the process: level of humidity and kind of soil, depth of element's location under the surface).

With regard to the kind of symptoms, one distinguishes the corrosions:

- even (even corrosion of the whole surface),
- pitting (occurring only in certain places in the form of stains or pits reaching sometimes deeply into material),
- intercrystalic (it proceeds on the boundary of metal's grain, reaching often deeply into material, which causes the decrease of its resistance and ductility).
- selective (dissolving of one of phases or ingredient of alloy under the influence of corrosive environment, e.g. diszincyfying of brass; as a result there may emerge a porous structure retaining the initial shape of element).

Electrochemical corrosion is a common phenomenon and it causes huge economical losses. That is why lots of attention is paid to the protection of metals from corrosion. There are various methods of counteracting this corrosion.

The first one is the use of constructional materials resistant to corrosion (on which there emerge passivating layers of oxides). The resistance is improved by insertion of proper alloy additions (chromium, silicone, aluminum, nickel, manganese) and heat or heat-chemical treatment.

The other one is the use of solutions decreasing the probability of corrosive cells emerging through:

- avoidance of direct connections of metals of different electrode potentials and preventing the so-called contact corrosion in that way (it occurs when metals of different nobility are in close contact, e.g. in connections: rivet, screw, welded – then, less noble metal, i.e. of lower electrode potential, becomes an anode and it undergoes corrosion); one prevents through materials selection (e.g. choice of material of which connection is made or with which it is covered) or through disconnection them with nonconductive material (the use of nonconductive pads, seals, dialectical lubricants);

- avoidance of non-even stresses and preventing the so-called stress corrosion in that way (non-even stresses in crystal net intensify corrosion, because the surface of metal is not energetically homogenous and there local cells emerge; the areas of bigger stresses, faulted become anodes on which the process of oxidizing occurs); natural stresses caused by technological processes (e.g. pushing on cool, welding) may be removed through proper heat or mechanical treatment (annealing, hammering); irregularity of stresses caused by external forces may be decreased through an appropriate design;
- avoidance of situation, in which construction is in the environment of differentiated features, because it leads to occurrence of cells, which are the result of different airing – on the surfaces, to which access of oxygen is better, occur cathodic reactions and deficiencies of metal appear close, where the access of oxygen is better; one should avoid i.a.: partial immersing or cumulation of water and other dusts in specified places on construction, local cumulation of residues in pipelines, pipelines setting, cables, reinforcements in ground of differentiated features as regards humidity, acidity or porosity, and also in the areas where stray currents may occur (e.g. under the electric traction).

The next method is the use of protecting layers. These may be:

- metallic layers (obtained through various methods, e.g. electrolytic, chemical, immersing), which are divided into cathodal layers, i.e. of nobler metal than the protected metal (such layer, in the case of metals not undergoing passivation, is effective under the condition of complete tightness – in the case of leakiness, there may occur intensive pitting corrosion, the cathodal layer provides effective protection of metals undergoing passivation, even in the case of its damage), anodic layers, i.e. of metal of lower electrode potential in the given environment (such layers provide protection even if leaky);
- non-metallic layers, including organic and non-organic ones, e.g. painting layers, oxide layers (obtained e.g. through the process of anodizing) and others, the layers may be one- or many-layered.

The next method is electrochemical protection consisting in using separate electrodes, placed in environment of corrosion, connected in one electrical circuit with protected element. One distinguishes the protections:

- cathodal, in which an external anode is attached (surface of protected metal becomes a cathode, owing to which reactions of oxidizing don't occur),
- and anodic, in which protected metal is an anode and on its surface occur reactions of oxidizing (this method, contrary to cathodic protection, is used rarely and only in the case when the protected metal undergoes passivization; e.g. some elements exposed to strongly oxidizing environment, such as containers for concentrated sulfuric acid).

There are two methods of obtaining electrochemical protection (the rules of this methods' working are the same in relation to cathodal and anodic protections; that is why they will be discussed below only in the example of cathodal protection, which is used definitely more often in practice):

- galvanic; in this method, exchangeable anode, called protector, has to have contact with protected metal and have lower potential than the metal in a given environment; in the time of protection, protectors (most often alloys of zinc or aluminium) undergoes corrosive wear; this method is used for protecting hulls of ships, ground-based, underground and port steel constructions, reinforcements in reinforced concrete constructions, containers, e.g. house warm water boilers etc.;
- electrolytic, in which an external source of voltage is used; in this method one uses persistent protecting anodes (alloys of iron with silicone, platinized or covered with metal oxide titan, graphite, copper,) connected with plus source of voltage and protected metal is connected with the minus source, the electrical circuit is closed with electrolyte (corrosive environment – soil, water); this method is used in the case of big constructions or if there are difficulties with obtaining appropriately big difference of potentials between protected material and anode (so when galvanic method is not effective), e.g. for protection of pipelines and big underwater containers, port constructions, mining platforms.

The next method of preventing corrosion is the use of corrosion inhibitors – chemical compounds inserted in corrosion environment, which cause emerging of adsorption protecting layer on the surface of material or they support the process of passivization. Corrosion inhibitors are added to engine oils, fuels, cooling and hydraulic liquids and so on, to water in closed circuits, e.g. heating ones etc.

Through activities undertaken in the phase of utilization and support, corrosive wear of elements of machines and constructions may be considerably limited. These actions should include: renewal of protecting layers, e.g. painting ones, modification of environment composition, including using of inhibitors, drying and cleaning of surfaces exposed to corrosion, maintaining systems of active electrochemical anti-corrosion protection in good condition, exchanging of protectors.

Erosion is a process of destruction of an element's boundary-layer as a result of particles of solids, liquids and gases of considerable kinetic energy or energy of electrical current reacting on it. Erosion occurs if there are big relative speeds between element of machine and surrounding environment, e.g. in flow machines (rocket and turbine engines nozzles, turbines and compressors' blades), cyclone filters, industrial installations, pipelines etc.

Depending on the conditions in which the process occurs, erosive wear may be divided into:

- erosive wear in the stream of solid's particles – the process has mechanical character and mechanisms of wear are similar to the ones discussed in the issue of abrasive wear, especially when angles of hit are small (tangentially towards the surface), then may occur scratching, cutting and chipping of irregularities etc.; when angles of hit are big, in the zone of collision occur brittle cracking (in the case of fragile materials) or cyclic elastic-plastic deformations, leading to reinforcing of surface and increasing of fragility, which next may lead to loss of material, after properly high energy and number of hits;
- hydroerosion, which is erosive wear in the stream of liquid – the process of destruction of surface layer as the result of hitting or friction of stream of liquid with a high kinetic energy, the process of destruction is almost always a result of simultaneous reactions of corrosive processes;
- hydroabrasive wear, which is erosive wear in the stream of liquid containing particles of solid – solid's particles act like an abrasive, so the effects are the sum of erosion and hydroerosion;
- gas erosion, which is erosive wear in the stream of gases or steams – the process occurs when speeds are very high, e.g. the movement of rocket in dense layers of atmosphere, or when gases have high temperature, e.g. hot flue gases of rocket engines; the process has mechanical-thermal character: flowing and shearing of material under the influence of aerodynamic forces, exfoliation, blowing off liquid material by the stream of gases;
- electroerosive wear, which is erosion connected with the flow of current – as the result of a high strength currant flow in the area of contact, leap of sparks or discharge of electricity, there occur very high local heating of material, causing partial melting, melting or even evaporation of a metal;
- cavitational wear – the process of surface destroying in the result of mechanical and corrosive reactions of flowing liquid, in which the phenomenon of cavitation occurs; cavitation, which is an immediate phase change of liquid from the liquid phase into the gas phase, occurs in the areas where the pressure of liquid drops below boiling pressure (most often as a result of local speedup, e.g. in the places of flow constriction or on the surfaces of turbines blades); when the liquid leaves the area of fast flow, gas bubbles implode, which creates shock waves; if the implosion occurs close to walls, mechanical destruction of surface occurs, most often in the form of deep pits; cavitational wear occurs in shipping screws, turbines' blades, valves, slide bearings and other elements of machines and devices.

Erosive wear usually doesn't have purely mechanical character, but this is a result of simultaneous erosive and corrosive (erosive corrosion) reactions. Erosive wear of corrosive layers accelerates corrosion, and on the other hand corrosion makes erosion easier, because products of corrosion are usually less resistant to erosion than native material. So-called flow accelerated corrosion (FAC) is also usually counted among erosive-corrosive wear, however, removal of protecting layer in this case is caused rather by its dissolving by fast flowing liquid, not mechanical hydroerosion.

Erosive wear is counteracted by:

- the use of proper materials and parameters of surface layer; most often a big hardness and smoothness of surface are beneficial; resistance of material to electroerosive wear is higher when temperature of melting, heat conductivity, module of elongated elasticity are higher and when the linear expandability is lower;
- decreasing of reactions causing erosion, including: filtration of air and liquid, constructing of devices in the way so that flows speeds are as low as possible, preventing cavitation by proper designing of canals preventing from immediate drop of static pressure of the flowing liquid and the use of liquid of a small inclination to cavitation and maintaining its low temperature as far as it is possible; preventing electroerosion through increase of electric flow surface and a proper design of contactors.

2.4. Course and measures of wear

Measures of machines elements wear serve for quantitative evaluation of the process of wear, or the wear – being its result.

In practice, thickness of separated or deformed boundary-layer or volume or mass of separated material are determined. These values are specified on the basis of precise geometrical measurements of elements or the measurements of mass. Sometimes the influence of wear processes on surface's roughness and its bearing capacity, and physical features, e.g. hardness are also evaluated.

Absolute measures of wear may be:

- linear wear – thickness of separated or deformed boundary-layer,
- volume wear – volume of separated material,
- mass wear – mass of separated material.

For evaluation of the process of wear the intensity (rate) of wear is used, which is absolute wear related to generalized time. The generalized time may be: calendar time, friction time, friction distance, work of distance or others.

The process of wear in time may be:

- stabilized – if the intensity of wear is constant,
- unstabilized – if the intensity of wear is changeable.

Intensity of wear depends on the type of friction and many other discussed before factors. However, as regards quality, courses of wear in function of time are characterized by certain regularities, independently on the intensity of wear. In the case of surfaces taking part in slide friction three typical periods can be distinguished (Fig. 2.10):

- period of run-in,
- period of stabilized wear,
- period of accelerated, emergency wear.

In the first period of friction joint operation, called the run-in period, the process of wear is unstabilized. This period is relatively short, but very important for proper work of the joint, because super finish and fitting of cooperating surfaces occur in there. That is why loss of material is quite intensive. In the end of this period, real surface of contact of mating parts increases, the intensity of wear decreases and state of tensions and deformations in boundary-layers stabilize.

The second period includes normal work of machine's elements and it is characterized by almost constant intensity of wear. Intensity of wear in this phase and time of its duration decide on element's life.

The third period begins in the moment of disrupting of normal wear as a result of the loss of required features of boundary-layer or exceeding the permissible clearance of cooperating parts. Intensity of wear begins to increase. The further operation is not advisable in these conditions, because it leads to destructive, emergency wear.

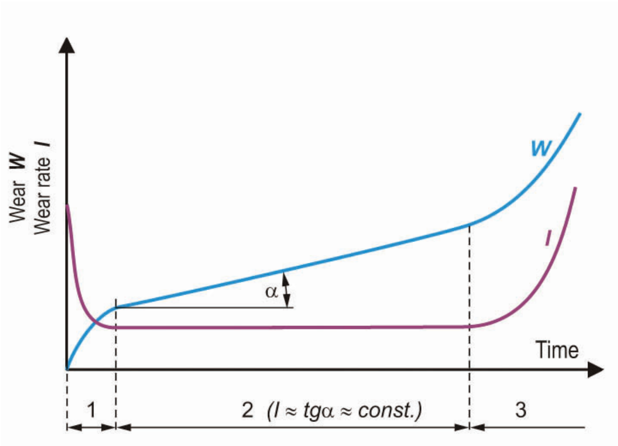


Fig. 2.10. *Typical course of tribological wear: 1 – run-in period, 2 – period of normal, stabilized wear, 3 – period of accelerated wear*

Other courses of wear in time are also encountered (Fig. 2.11). These courses may be typical of certain conditions of work and kinds of wear, or they may be caused by design or operation mistakes, e.g. improper running-in of a joint. A different course is e.g. typical in the case of wear of parts working in conditions of rolling friction. Changes occurring in the period of run-in and normal wear, caused by pressing of boundary-layer are very small. Accumulation of fatigue in the boundary-layer leads to the beginning of the process of first pieces of material chipping off (pitting, spalling), which is the beginning of mass, emergency wear.

The lengths of particular periods of wear and wear intensity depend on:

- design features of mating parts, shape of their surface, load, kind of lubrication, kind of used materials,
- technological features of mating parts: type of final treatment, quality of heat or thermo-chemical treatment, surface roughness, quality of the assembly,
- operation characteristics: proper use, maintenance, service between repairs.

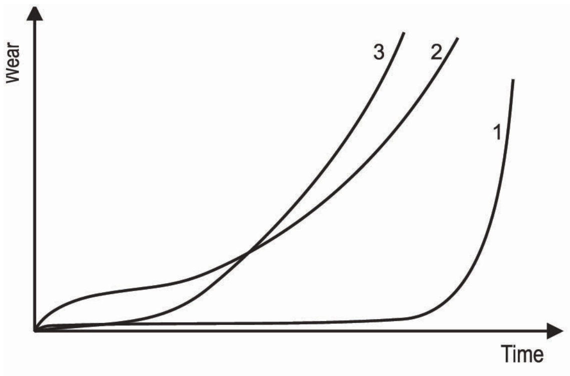


Fig. 2.11. *Various courses of wear: 1 – typical for fatigue wear while rolling friction, 2 – with a very short period of stabilized wear, 3 – with increasing intensity of wear*

3. Lubricants

3.1. Basic functions and properties of the lubricating oils

The main objectives of each of the lubricating oil is to obtain fluid friction between elements of kinematic pairs of lubricated machines. Separation of cooperating elements with oil film – oil film prevents friction wear of the lubricated parts. Fluid friction resistance is thousandths particles of a normal force loading the grating pair, (in the case of dry friction these are it is usually tenths particles of a normal force). Thus, an additional effect of lubrication is a radical reduction of resistances and mechanical losses.

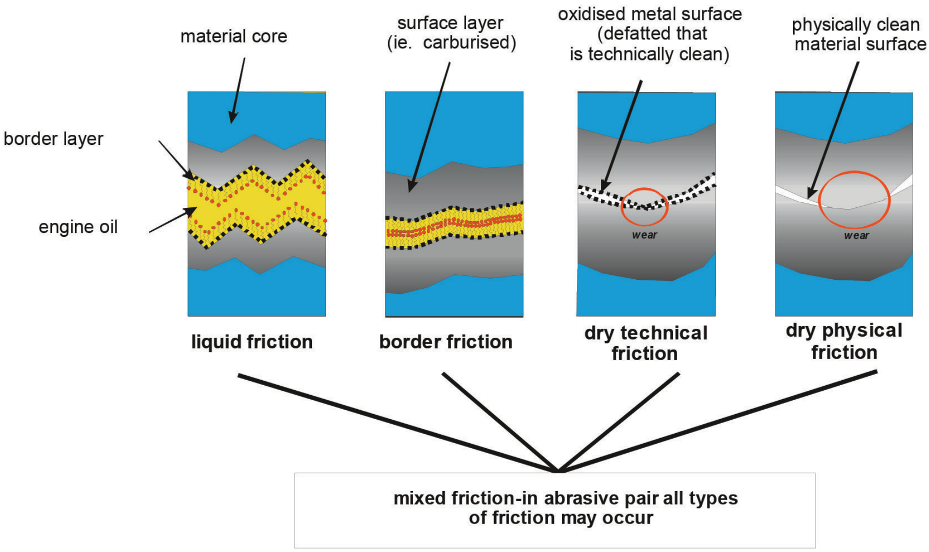


Fig. 3.1. *Types of friction at the lubricated machinery nodes*

Molecules of oil of polar properties form a thin film attached with adsorption forces on the surface of the lubricated elements. This layer is called the boundary layer. In situations when there is a deficiency of oil between the elements and there is no possibility to produce a film of oil components can be separated only by boundary layer. It occurs e.g. during the start-up of engines – in these conditions protective capacity of oil depends mainly on the “resistance” of the boundary layer. Frictional wear occurs when between the elements of kinematic pairs dry friction occurs, due to the breaking of the boundary layer.

Besides the functions protecting from wear and decrease of movement resistances, oil serves a few more important functions:

- it is a cooling factor for hot elements of machines
- an element for damping of vibrations and hits between the elements, which helps to reduce noise,
- protects the lubricated surfaces from corrosive effects of environment in which they work,
- flushes exploitation products from the space between the lubricated elements and cleans lubricated surfaces

Splitting of the lubricated surfaces with oil film is connected with forming of proper value of hydrodynamic pressure in the oil supplied to the lubricated kinematic pair. If the value of hydrodynamic pressure exceeds the pressures appearing in the node of friction, then only liquid friction occurs in it. The value of hydrodynamic pressure ($p_{hydrodynamic}$) is directly proportional to the relative speed of the lubricated surfaces (v) and to viscosity of oil (η) and inversely proportional to the size (h) of the oil gap (commonly referred to as loose between lubricated parts).

$$p_{hydrodynamic} \approx \frac{\eta \cdot v}{h}$$

The value h – is formed structurally and substantially and should not undergo significant changes over the period of the oil usage. The velocity v depends on the parameters of the lubricated device, e.g. on engine’s speed and it varies along with it. Dynamic viscosity η is the property of the oil.

Properties of lubricants

Viscosity

Viscosity is the most important physicochemical property characterizing lubricating oils. On the viscosity directly depend: maintenance of fluid friction in majority of lubricated nodes of friction, the amount of losses of energy needed to overcome the frictional forces, the size of the flow resistances through the oil trunks and oil filters, cooling efficiency and seals of cooperating parts, removal of impurities while flowing through the filter.

The viscosity can be defined as the ability of transferring shear stresses through a fluid film, manifesting in resistance while moving the liquid films. Viscosity plays an important role in the process of hydrodynamic lubrication: the higher viscosity, the higher is hydrodynamic pressure in the joint gap. From the mathematical point of view viscosity is defined as the Newton's formula, which regards the force needed to move weightless plate surface of the area A moving on the fluid layer of the thickness *h* with the speed *V* (Fig. 3.2):

$$F = \eta \cdot A \cdot \frac{dV}{dh}$$

Shear stress causing the fluid to move the films will be:

$$\tau = \frac{F}{A} = \eta \cdot \frac{dV}{dh}$$

The coordinate η is called the coordinate of viscosity or shortly viscosity (dynamic or absolute). The unit of dynamic viscosity is [Pa·s]. In the calculations connected with the speed of viscous liquids flow of lubricating oils, one uses kinematic viscosity. It is the dynamic viscosity relative to the density:

$$\nu = \frac{\eta}{\rho}$$

The unit of kinematic viscosity is:

$$1\frac{m^2}{s} = 10^6 \frac{mm^2}{s}$$

If the viscosity depends on the condition parameters (pressure and temperature), and does not depend on the velocity *dV/dh*, Newtonian fluids are talked about. Most liquids including lubricating oils, are Newtonian liquids. In contrast, liquids of the viscosity dependent also on *dV/dh*, are the nonnewtonian liquids. An example of non-Newtonian fluids are greases.

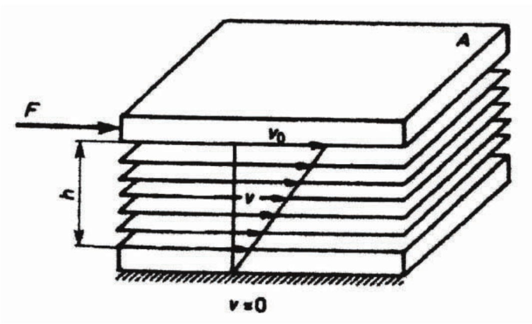


Fig. 3.2. *Illustration of Newtonian viscosity formula*

Examples of changes in engine oils viscosity depending on temperature are shown in the Figure 3.3.

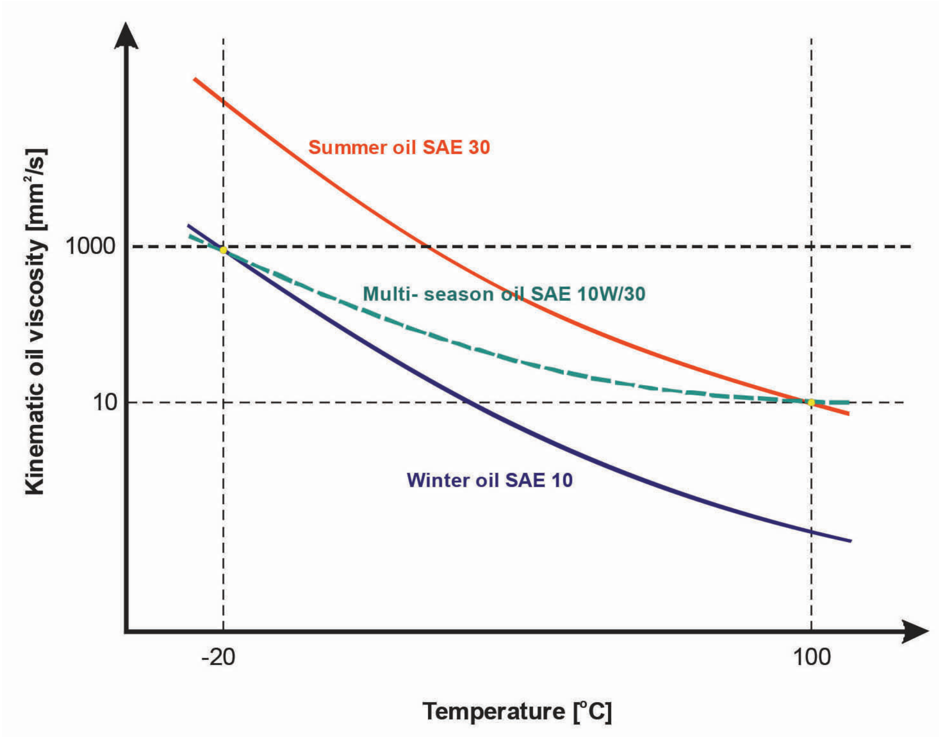


Fig. 3.3. *Changing the viscosity of various engine oils depending on the temperature*

A strong dependence of the viscosity of oils on temperature results mainly from the properties of oil bases (of the main component of the oil). To evaluate the effect of temperature on the viscosity value, oil viscosity index is used. The viscosity rate (abbreviated as VI): is calculated from oil viscosity marked at two temperatures: 40 °C and 100 °C. Viscosity index is a dimensionless unit. The higher viscosity, the lower change of viscosity along with temperature is. The viscosity index (Viscosity Index) is calculated on the basis of the formula: $VI = \frac{L-U}{L-H} \times 100$. In which:

L – kinematic viscosity in 40 °C of pattern oil of the series L (of the viscosity index = 0) having in the temperature 100 °C the same kinematic viscosity as examined oil, *U* – is the kinematic viscosity in the temperature 40 °C of examined oil, *H* – kinematic viscosity in the temperature 40 °C of pattern oil of the series H of VI = 100, having in the temperature 100 °C the same viscosity as examined oil.

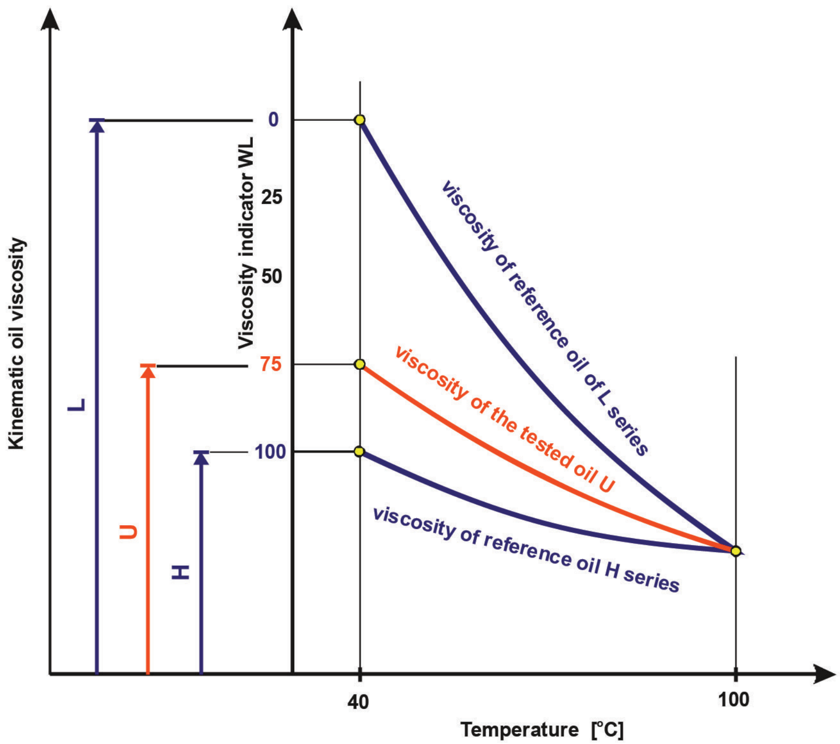


Fig. 3.4. *Marking of viscosity index according to PN-79/C-04013*

Greasiness

As it was mentioned, the primary task is to produce a lubricating oil film separating the surfaces of cooperating components. If the oil film undergoes discontinuation, fluid friction is replaced by the boundary friction. Boundary friction means that the role of the oil film is taken over by the adsorbed on the element's surface oil molecules creating the boundary layer. On the adhesion force, with which oil molecules are held at the metal surface, depends the size of load that can be moved by the boundary layer. The higher are the forces needed to break the absorbed boundary layer of oil from the lubricated element, the oil-lubricated surface is better protected from wear.

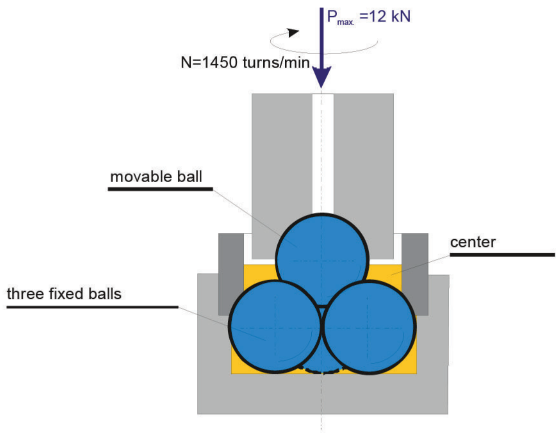
The discussed lubricating oils property is called lubricity and is defined as the ability of permanent adhesion of oil molecules to lubricated surfaces and creation of permanent friction-reducing layers on these surfaces (in conditions of semi-liquid friction). One should remember that there is no relationship between oil viscosity and its lubricity. The lubricity is primarily determined by the content of polar compounds, e.g. organic acids (depending on chemical composition of the oil). Also the chemical composition of the nobling additives package is important (including detergents and friction modifiers). Organic acids included in the oil base have an acid residue with a minus charge, which as a result of electrical interactions is attracted by the plus ions of lubricated metal. Improvement of lubricity of oils is obtained also by adding anti-wear additives, which are compounds of sulfur, chlorine or phosphorous. Lubricity of oils is evaluated with the use of so-called friction machines. There are many varieties and types of these machines. All of them have in the structure properly shaped friction node working under variable (adjustable) load. This node is lubricated with examined lubricant (oil) during the tests. The variety of loads and tribological contacts used in friction machines causes that the results obtained in them can be compared only in relation to the type of machine. The obtained in this way evaluation of oils lubricity has only comparative character. For evaluation of lubricity most often used are: four-ball machine, machine Falex (used mainly in the USA), Timken machine, the machine using the combination of needle-drive (pin of disk). This list is not exhaustive for all types of friction machines, e.g. for lubricity research of gear oils, one uses other types of machines mapping the work of gears, e.g. FZG machine.

The most common type of friction machine is a four-ball machine. Friction node is the point contact of four normalized steel balls with the diameter of 11.2 mm. Three of them are unmoved in a holder, the fourth one is held in rotary at a constant speed (1450 rev / min) spindle and it is pressed against them, with adjustable force (max. 12 kN). Frictional contact of balls is immersed in the examined oil. Normalized test cycle includes trials lasting 10 or 60 seconds. Evaluation of lubricity of tested oils consists in:

- comparison of load at which welding (adhesive friction) of balls is made,
- comparison of the biggest non-rubbing load,
- comparison of rubbing load,
- comparison of the size of wear scar under a constant load at the time of the testing trial,
- comparison of changes of moment of friction while increasing the load.

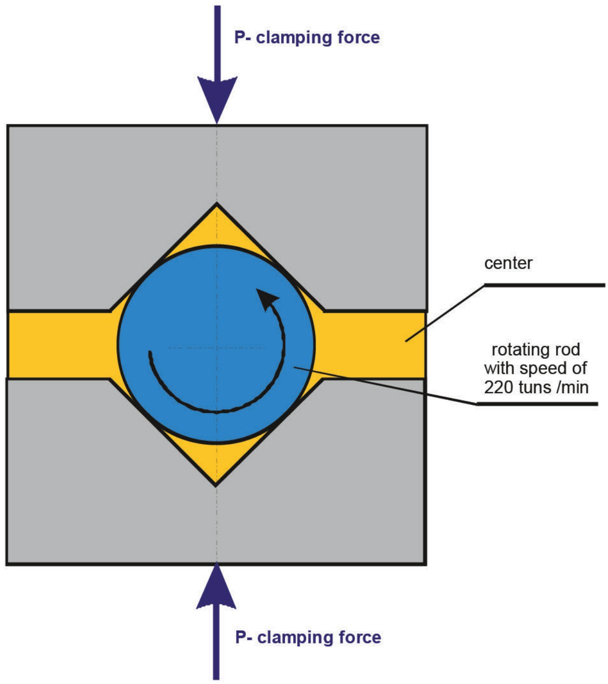
Detailed guidelines of lubricity tests are given in the norm PN-76/C-04147.

a)



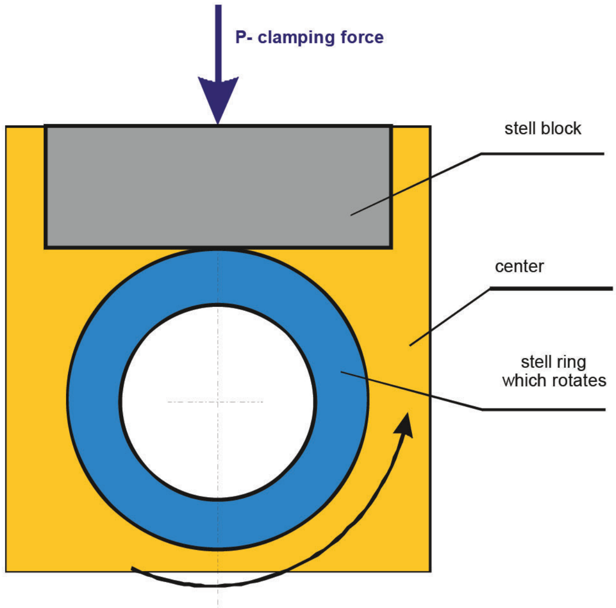
$P_{max.}$ =12 kN
N=1450 turns/min
movable ball
center
three fixed balls

b)



P- clamping force
center
rotating rod
with speed of
220 tuns /min
P- clamping force

c)



d)

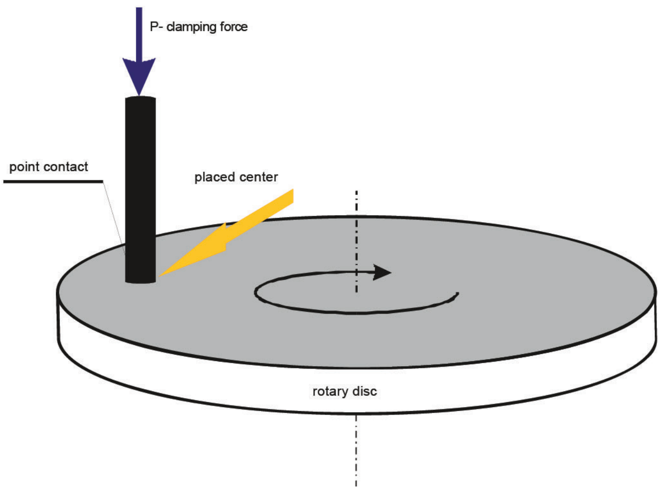


Fig. 3.5. *Rubbing combination of friction machines: a) four-balls, b) Falex, c)Timken, d) „pin of disk"*

Resistance to oxidizing

Lubricating oils, especially engine oils work in specific conditions. The average temperature of the oil in sump oil does not usually exceed 100 °C, but in contact with hot engine parts a thin layer of oil film is heated even up to several times higher temperature. Hot oil is gradually oxidized easily in the presence of oxygen (air). This phenomenon occurs most strongly in the subsurface, hot oil layers, the visible effect is embedded in the form of a brown raid on the metal surface oxidation products. Paraffin and olefin hydrocarbons undergo oxidizing most easily. The first products of oxidation of oil are peroxides – unstable oxygen compounds, which are next transformed into fatty acids and hydroacids. Also aldehydes, ketones and alcohols are formed. The final result of oxidation is the appearance of deposits in oils, such as lakes, tars and esters of hydroacids. The speed of oxidation increases along with temperature. In room temperature it is small and the oil can be stored for a long time. At temperatures of about 70 °C, so at the ones which occur in oil sump of the engine and uncooled gears, the speed of oxidation is relatively large. In contrast, at the temperature 95÷115 °C it increases repeatedly. In order to increase the oxidation resistance of oil the substances which absorb oxygen are added to it , not allowing oxygen to react with oil molecules for some time. These substances are oxidation inhibitors (amines, phenols and phosphates).

Increasing the time between oil changes requires the oil being immune to this negative phenomenon. There are several tests for comparative assessment of the susceptibility of oil to oxidation. The first one is the so-called test of prolonged oxidation. Some of metals (such as copper, iron) used in engines development have a catalytic effect on oil – in the presence of high temperatures oxidation reactions are accelerated. The test shows how oils react to combination of temperature and catalytically favorable to oxidation metals. The oil in a vessel, in contact with the conventional metals used in the development of engine (iron, copper, aluminum, lead) is heated to 190 °C for 40 hours. The measure of resistance is change of the oil viscosity here. Oxidation resistance of thin layers of oil may also be evaluated in the test "frying pan". The oil is heated in a flat container in the temperature of 230 °C for 90 minutes. The color of the cooled oil is the subject of evaluation. Oils which do not alter the color and texture are resistant to oxidation. Dark oils, nearly reminding of the consistency of slurry does not have sufficient resistance to oxidation. Another test is the test of extended evaporation made on Selby-Noack device. It allows to assess the intensity of oil evaporation under a high temperature. During the test, the oil is heated in a crucible for 5 hours at the temperature of 240 °C when constant discharge of steam. The subject of evaluation is weight loss of oil. It's worth remembering that heating of oil is always done in a water or sand bath – a direct contact of vessel with oil, element or heating factor is unacceptable.

Other physicochemical characteristics of oils

- Density is a property used for calculating the oil weight into volume. It is not a specific feature differentiating oils between each other, it is given with regard to marketing issues.
- Temperature of flowing – lowest temperature at which the oil is still a liquid. It should not be confused with the lowest temperature at which oil can be used, but rather the temperature at which it can be poured or pumped. Below this temperature, oil changes into the solid state. Temperature of flowing for oils fluctuates between -25 °C and -35 °C, for synthetic oils it is below -40 °C. The measuring principle is shown in the Figure 3.6. In the case of engine oils, the so-called temperature of pomping is marked – temperature at which pump oil gear can already start giving oil to the entire oil trunk of engine.

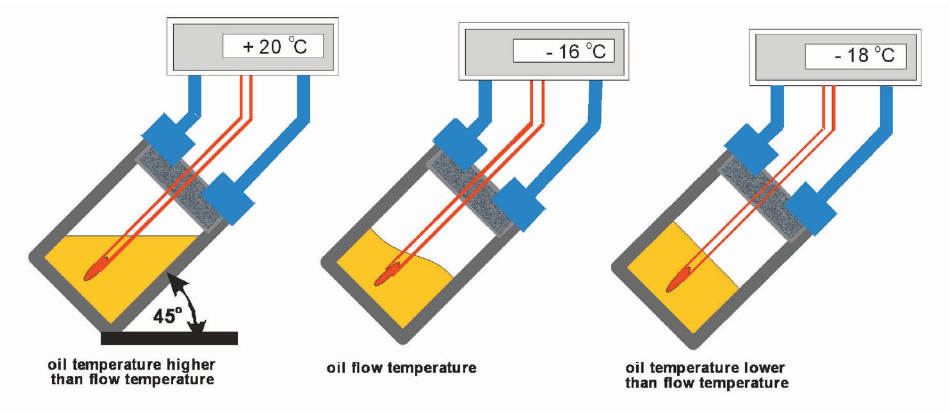


Fig. 3.6. *Marking of temperatures of oils' flowing*

- Solidifying point is the temperature at which the oil loses its fluidity to such extent that after tilting of tube with test oil of 45° its meniscus will not move within one minute (Fig. 3.7).
- Flash point. Producers provide this temperature marked in two ways: a) in an open crucible, marked in Marcusson's device, b) in crucible we'll close it in the Pensky Martens's device. The first way practically corresponds to the oil vapor ignition conditions in an open air, the other corresponds to conditions of ignition of vapors inside of the crankcase of engine. From a chemical point of view, this temperature proves the presence of low-boiling components in oil. For example, a decrease in the ignition temperature of the oil exploited in the engine proves unambiguously entering of fuel into oil. Engine oils should not be exploited when flash point in closed crucible falls below 190 °C.

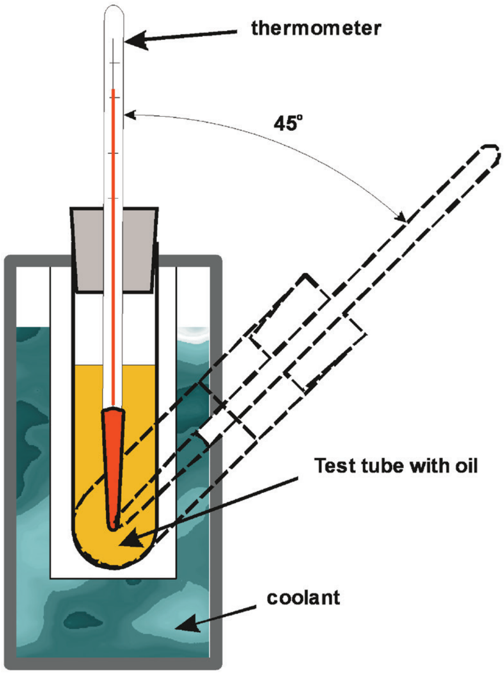


Fig. 3.7. *Marking of solidifying point*

- Base number (TBN- Total Base Number) specifies the ability of oil to maintain engine cleanliness and to neutralize acidic combustion products. The given number is equivalent to the neutralization of acids which have 1 gram of oil, expressed in milligrams of potassium hydroxide KOH. Fresh engine oils have TBN in the range of 2.5 mg KOH / g to 15.0 mg KOH / g. One should assume the principle of the worse fuel (higher sulfur content in fuel), a higher TBN the used engine oil should have. The base number is used for evaluation of engine oils.

3.2. Classifications of engine oils

SAE and API

Viscosity classification SAE J306MAR85 is characterized by six classes of “winter” oils 0W, 5W, 10W, 15W, 20W, 25W and six classes of “summer” oils 20, 30, 40, 50, 60. This classification is widespread throughout the world, and this is one of the basic criteria used in evaluation of the oil usefulness. With a rough approximation it can be stated that the viscosity of the oil at 1000 C corresponds to the average viscosity of the oil during normal engine wear. The criteria of division are as follows:

- maximum viscosity which can be achieved by an oil at a minus temperature, for “winter” oils: By convention, as the limiting value of the temperature at which no problems with starting the engine (oil reaches the viscosity of 3500 cP (centipoints),
- boundary pumpable temperature at which the oil reaches the viscosity of 30 000 cP and becomes longer pumpable,
- a minimum viscosity at the temperature of 100 °C for “summer” classes,
- maximal viscosity at the temperature of 100 °C,
- minimal viscosity at the temperature of 150 °C and of cutting load (HTHS).

(Full range of numerical values for J300MAR93 SAE viscosity classification is given in the table no 3.7). All-season oils must meet the conditions relating to the “winter” and the “summer” parts. One also cannot exclude the possibility of using oils belonging to winter classes in the summer, or vice versa. In the composition of engine oils nobling additives occur, formulated into packets. The nobling additives are compounds which can often be chemically active in relation to one another. Therefore, while mixing oils, one should take this aspect into account. Currently, major producers care to use in oils the packets of additives which are unreactive with packets of other leading producers.

Tabela 3.7. *Viscosity classification of engine oils (SAE J300MAR93)*

Viscosity class SAE	Viscosity (in cP) at the temperature (°C), maksimum		Viscosity in 100 °C (cSt)		Viscosity HTHS[1] 150°C,10 sec^{-1} minimum
	structural	pumpability	min	max	
0W	3250 w – 30	30000 w -35	3,8		
5W	3500 w -25	30000 w -30	3,8		
10W	3500 w -20	30000 w -25	4,1		
15W	3500 w -15	30000 w -20	5,6		
20W	4500 w -10	30000 w -15	5,6		
25W	6000 w -5	30000 w -10	9,3		
20			5,6	<9,3	2,6
30			9,3	<12,5	2,9
40			12,5	<16,3	2,9[2]
50			16,3	<21,9	3,7
60			21,9	<26,1	3,7

[1] HTS – viscosity at high temperatures and high cutting tensions
[2] for the oils OW/40, 5W/40, 10W/40
[3] for the oils 15 W, 20W, 25W i 40

On the complexity of packets depend other oil properties determining its quality. To determine the level of oil quality one uses the quality classification in accordance with API (American Petroleum Institute, USA).

API quality classification divides oils into two groups labeled as:

- S (Service) – for engines with spark ignition,
- C (Commercial) – for diesel engines.

Classes of oils are marked with two-letter code. In the first group one distinguishes the quality classes: SA, SB, SC, SD, SE, SF, SG, SH, SJ; SL. In the second one: CA, CB, CC, CD, CD-II, CF i CF-4(CG-4), CF-2, CH-4, CI-4. The next letter in the alphabet is a higher class of richer set of additions. The described classifications are best known classifications of engine oils in the world.

European classification ACEA

ACEA (European Automobile Manufacturers Association) has all leading European manufacturers of passenger cars, vans, trucks and buses. They produce ten million vehicles per year in total. The used development practices often set new standards in terms of safety, environmental protection from motor burdens and technology – including engine oils.

Development of traction engine determined with concern for natural environment. Known in the past designers' strive to increase the wear endurance of engine has been replaced by the struggle for effective and sustained reduction of not only toxic emissions, but also the overall negative impact of the vehicle on the environment. In this scope, all new engine constructions are integrated with external exhaust treatment systems and are characterized by long periods between oil exchanges (amounting approximately 20 thousand km for car engines and up to 120 thousand km of mileage of truck engines).

New ACEA engine oils classifications, binding since December 2009, aim to keep European car manufacturers in the world class forefront setting trends in the field of environmental protection against negative influences of motorization industry. This classification has replaced the classification introduced in 2004. The changes concern: requirements for selected parameters oils, researches and tests conduction and the creation of new categories of oils (E9).

The specificity of the European classification of motor oils (ACEA) consists mainly in the fact that the place of oil in the classification is determined by its usefulness in chosen type of engine. The basis of classification is therefore adjustment of the oil to a level of modernity of engine – so this is a qualitative classification. Structural changes imply the development of classification of produced engines. It was assumed that after the introduction of new classifications, all engine oils available in commerce must comply with them. One distinguishes four types of oils:

- ❑ A – oils for gasoline engines,
- ❑ B – oils for diesel engines used in cars,

- ❑ C – oils for diesel engines used in cars, equipped with particulate filters used in cars,
- ❑ E – oils for engines of vans, trucks and buses with diesel.

For each letter denoting the purpose of oil a number representing the level of quality is added – the category of oil. Next numbers indicate the year of realization of category and they are intended for manufacturers of engines and vehicles – they inform what parameters or tests an oil meets. The numbers of year are the marking of update of technical requirements for oil of a given category (e.g. introduction of a new type of engine for testing of oil – in A1 / B1 08 the engine VW TDI was introduced instead of the VW ICTD). The update of oil within the same category should meet the previous requirements, if not, the oil belongs to a new category within the same class. Given in the ACEA classification typical uses of oils have the orientational character – the final choice of a specific engine oil is the responsibility of vehicle manufacturers. It results from the fact that even the oils of higher categories do not always have to meet the same requirements as the oils of lower categories within a single grade. An example of oil marking by the ACEA classification is shown in the Figure 3.8.

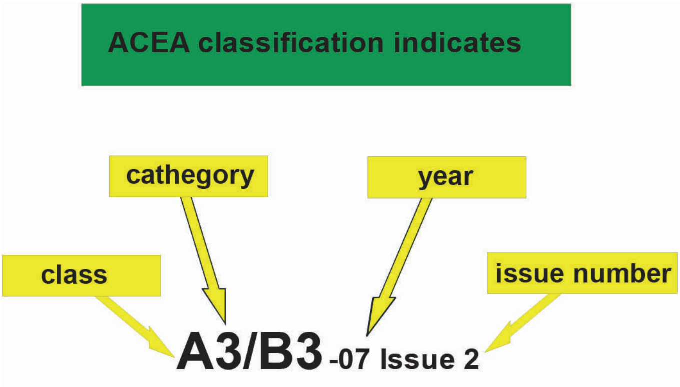


Fig. 3.8. *The scheme of engine oil marking by the ACEA classification*

The current classification of ACEA binding since 22 December 2009 divides all produced oils into three classes:

A/B – oils for ZI and ZS engines used in cars

***A1/B1* – all-season oils of prolonged period between exchanges** destined for gasoline and small diesel engines of minimal viscosity of to 2.6 [mPa • s] (milipascaloseconds) at high temperatures, for the oils of class xW / 20 and minimal viscosity of 2.9 to 3.5 [mPa • s] for the other viscosity classes of oils.

A3/B3 – all-season oils of low viscosity destined for powerful gasoline engines and small diesel engines with extended periods between oils exchanges.

A3/B4 – all-season oils for powerful gasoline and diesel engines with direct fuel injection, used also as oils of class A3 / B3. A4 class was reserved for future engines with fuel injection.

A5/B5 – all-season oils with low viscosity at high temperatures (minimum of 2.9 to 3.5 [mPa • s]) with extended periods of exchanges, destined for powerful gasoline and diesel engines. Unlike the previous classes, they provide economy of fuel in measurement engine higher than 2.5% in relation to the reference oil 15W / 40.

C – oils for passenger cars engines equipped with exhaust cleaning systems (solid particulate filters – DPF or three-way catalysts – TWC)

C1 – all-season oils of SAPS type (with reduced sulfur and phosphorus content – sulphated ashes content less than 0.5%) and low viscosity at high temperatures to a minimum of 2.9 [mPa • s]. HTHS oils (oils with high resistance to viscosity changes by cutting at high temperatures), destined for gasoline and diesel engines equipped with a catalytic converter or DPF filter. Oils destined for older types of engines are not suitable for the use in newer types of engines because of different than in the other SAPS (sulfur and phosphorus) oils boundaries.

C2 – all-season oils destined for powerful gasoline and diesel engines equipped with exhaust clearing systems (solid particulate filters – DPF, three-way catalysts – TWC) of low viscosity at high temperatures – HTHS (minimum to 2.9 [mPa • s] – meeting the requirements of Peugeot). With regard to the sulphated ash content of to 0.8%, similarly to the former ones, they are not suitable for the use in some types of engines.

C3 – all-season oils destined for powerful engines equipped with DPF and TWC, of low viscosity at high temperatures HTHS (minimum to 3.5 [mPa • s] – meet the requirements of Daimler and BMW). Sulfated ash content to 0.8% causes that they cannot be used in some types of engines.

C4 – oils recommended for powerful gasoline and diesel engines equipped with a DPF filters and TWC catalysts, requiring low content of sulfur and phosphorus (SAPS) and high viscosity at high temperatures to a minimum of 3.5 [mPa • s] allow to extend the period of wear (life) of soot filters and catalysts.

E – oils for diesel engines of trucks and buses

E4 – stable all-season oils providing excellent control of pistons cleanliness, low exploitations of the engine elements and high solubility of carbon black. Recommended for engines that meet the emission standards: Euro I, II, III, IV and V. Designed for engines working in very difficult conditions and allowing for extending of periods between exchanges of oil, according to the manufacturer's instructions. Suitable for engines without DPF filters and some engines with EGR systems and SCR – selective reduction of NOx.

E6 – all-season oils providing excellent piston cleanliness, high solubility of carbon black and low wear. Recommended for engines that meet the emission standards from Euro I to Euro V, working in very difficult conditions with significantly extended periods between oil exchange. Designed also for engines equipped with exhaust cleaning systems including the DPF solid particulate filters and selective reduction SCR systems or EGR systems of exhaust recirculation. The use of E6 class oils for engines with DPF should be connected with the use of diesel oil with low sulfur content (up to 50 ppm).

E7 – all-season oils providing high purity and low wear of engine components. Designed for heavy duty vehicles operating in harsh conditions, with extended periods between oil changes, meeting the emission standards of Euro I to Euro V, not equipped with DPF filters. Especially recommended for most engines with SCR or EGR systems.

E9 – oils effectively protecting the engine against wear and ensuring low amount of deposits (high purity). Especially recommended for heavy duty diesel engines equipped with DPF filters. E9 class' oils provide increased stability of DPF filters in combination with the use of fuel with low sulfur content (less than 50 ppm). Oils can also be used in all engines that comply with the Euro I to Euro V norms equipped with EGR or SCR systems.

new ACEA classifications have been developed in cooperation with the manufacturers of oils and engines. The introduced uses have orientational character, and about the selection of the particular oil for the engine manufacturer decides (responsible for eventual negative consequences of its use). Therefore, in this classification in the description of each category of oil it is recommended to consult the suitability of individual engine oil according to manual instructions issued by the producer. To sum up: the modern oil becomes more and more individually-matched structural component of the engine.

Evaluation belonging of oil to a proper class of quality

Evaluation of oil's belonging to a proper category is made on the basis of the results of laboratory tests and engine tests of oil. All tests should be carried out in accordance with the conditions set by EELQMS (European Quality Management System Motor Oils). EELQMS has been developed mutually by ACEA and ATIEL (Association of European Producers of Industrial Lubricants). All producers of engine oils, using ACEA classification, are the members of ATIEL and are required to comply with the rules of testing the oils, laid down by the oil research EELQMS. In addition, producers must have the cerificate of Quality Management System ISO 9001 or 9002 and make a declaration proving the compliance of led by them oils researches with requirements of EELQMS. This compliance concerns: procedures, equipment, and research methods – this ensures reproducibility of results obtained in different laboratories.

Laboratory tests of the oil properties within formulation of its category include:

1. measurement of viscosity at selected temperatures,

2. determination of the oil resistance to cutting by measuring the decrease of viscosity after 30 cycles of cutting realized through squeeze of 170-ml sample of the oil through a calibrated opening at the temperature of 100 °C,
3. specifying of the oil resistance to cutting at high temperatures (150 °C) by measuring the decrease of viscosity,
4. measurement of weight loss of oil by evaporation at 250 °C in the time of one hour, the so-called Noack's test,
5. marking of the base number TBN,
6. marking of sulfated ash content,
7. marking of the chemical elements such as: sulfur, phosphor and chlorine,
8. marking of the oil compatibility, and elastomers (rubbers) used in engine seals,
9. evaluation of resistance to foaming of oil at different temperatures,
10. oils resistance to oxidization (for the oils of class E),
11. evaluation of the corrosive reaction of oil on the non-ferrous metals (for oils of the class E).

The used engine tests include the evaluation of:

1. tendency of oil to the casserole piston rings during operation at high temperatures,
2. tendency of oil to create lakes and deposits on the piston skirt,
3. oil exploitation by engine during 72-hour test,
4. tendency of oil to create deposits at low temperatures,
5. impact of oil on wear of roll's bearing and cylinder liners of selected types of engines,
6. the impact of oil on fuel exploitation (this is an indirect method of assessing the degree of reduction of the frictional resistance of the engine by oil),
7. the ability of oil absorption and maintaining the dispersion of carbon black.

In the Figures 3.9 the growth of requirements for diesel class A1 / B1 associated with the introduction of a new ACEA classification is presented. Figure 3.10 illustrates the differences in requirements for class E oils of different categories.

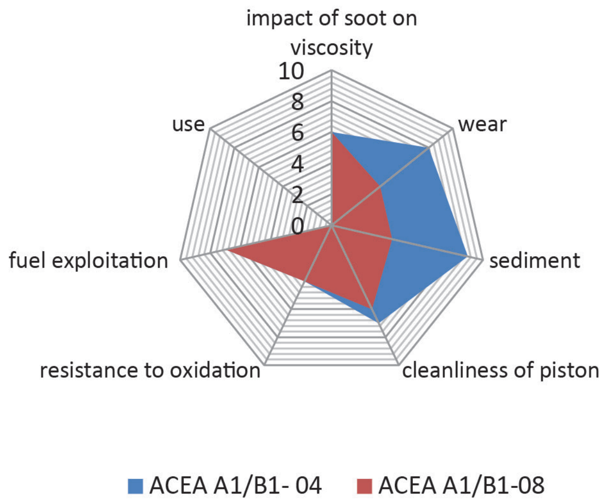


Fig. 3.9. *An example of the growth of selected requirements of the new ACEA A1 / B1 classification from 2008 in relation to the requirements of A1 / B1 classification from 2004 [developed on the basis of ACEA materials]*

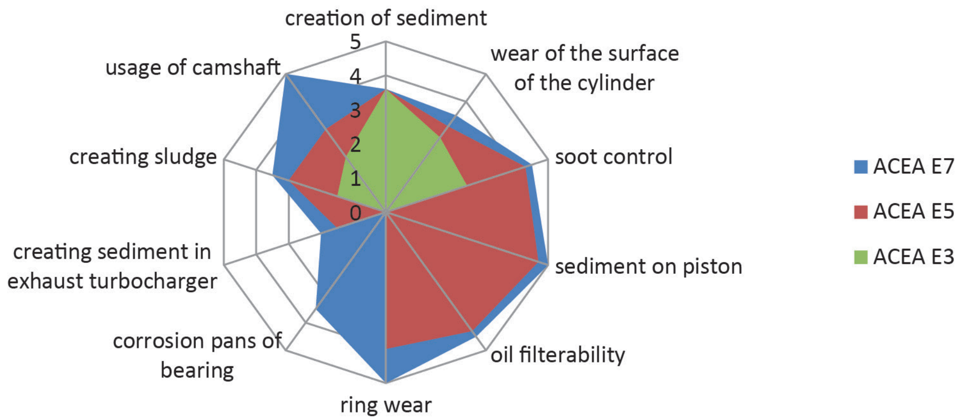


Fig. 3.10. *Requirements for engine oils for heavy-loaded ZS diesel engines according to currently valid ACEA classification*

Global classification

Global Classification of Engine Oils – Global DHD – developed mutually by ACEA, JAMA, EMA, is to help in unambiguous specification of requirements for all engine oils and in marking of uniform methods of testing them.

Restrictions within the limit of toxic compounds emissions by internal combustion engines and globalization of car market caused that all the leading manufacturers of engines and vehicles take action to meet the required standards.

These operations include changes in the development of engines and their exhaust systems (which are commonly used recirculation systems, DPF filters and SCR systems). For efficient and reliable work of systems can within the prescribed time of exploitation, the use of fuel with a low sulfur and engine oils of the Low SAPS class content is required.

Producers use their own tests and requirements adjusted to the conditions of engine's work in the context of the specific oil allowance to its production (the conditions of conducting engine researches of oils are different depending on the producer). With this regard, there was a kind of pat – DPF engines pose different requirements for oils than SCR engines; that is why one cannot define common requirements for all engine oils and specify uniform methods of oils testing. Global classification developed mutually by: the ACEA (European Automobile Manufacturers Association), EMA (Engine Manufacturers Association) and the JAMA (Japanese Automobile Manufacturers Association) is to form the basis for resolving the emergent impasse.

As part of creation of the Global Classification of Motor Oils, two classifications developed: Global DHD-1 and DLD-1 Global, DLD-2, DLD-3. The first Global DHD-1 was presented as a project yet in December 2006. It includes lubricating oils for heavy duty diesel engines (HDD – Heavy Duty Diesels) – used in trucks. The other one is the oil destined for the lubrication of small diesel engines (light duty), used in cars and vans. Both of the enumerated classifications serve for evaluation of the quality of oil.

DHD-1 specification includes oils used in the engines produced since 1998 and later. These oils also meet the requirements of older structures and can be used in them.

3.3. Operational degradation processes of the lubricating oils on the example of an engine oil

During exploitation, oil is subjected to a series of physical and chemical interactions that cause changes in its properties. The most important of these are:

- temperature,
- pressure,
- presence of chemically active gases – oxygen and carbon oxide,
- oil dilution with unburned and not evaporated fuel,
- the presence of water vapor and compounds emergent as a result of the combustion of fuel and oil.

Besides the physical and chemical interactions, also the amount and type of impurities contained in the whole mass of oil determine the changes of lubricating properties of exploited oil. Production and distribution impurities content and is usually negligible. A decisive role in reduction of the lubricating properties of the oil plays the exploitation pollution. The most important one is solid pollution. In order to reduce the amount of it in lubrication systems oil filters are used. The main source of solid impurities of engine oil are:

- products of friction exploitation of engine kinematic pairs,
- products of corrosion of engine's elements,
- products of chemical degradation of oil and incomplete combustion of fuel i.e.: soots and deposits,
- external impurities entering into engine.

A visible effect of physico-chemical interactions are carbon deposits and lakes that can be observed after a long exploitation of the engine without oil change. To prevent degradation, compounds forming the packet of nobling additions are added to the oil. The formation of lakes and carbon deposits is prevented by detergents and dispersants. The primary function is to prevent the agglomeration of detergent deposits such as soot particles, carbon deposits, dirt, abrasive products. They also prevent the formation of deposits of coking in the grooves of the piston rings on the piston skirt and cylinder surface. Dispersants, in turn, does not allow the coagulation and maintain insoluble contaminant particles in dispersion, allowing by this to remove them in the filtration process. The content of these compounds in oil is limited and decreases with time of exploitation. The same thing happens to other compounds forming oil additive package.

In order to make description of engine oil degradation processes easier, we may divide them into two groups. The first is degradation of the nobling additives, the second one is degradation of only oil base.

Degradation of the compounds which noble the oil is partly a process regarded while its composition, since these compounds extend the time of oil exploitation in engine, inhibiting the other non-enumerated and useless processes such as acidification, oxidation or change in viscosity of oil. Oils of upper classes are usually larger in the package of such additives, hence there is a possibility of prolonged use in the engine. Degradation of nobling compounds are chemical processes that may be intensified by:

- exceeded increase of oil's temperature of about 130÷140 °C,
- passage of fuel oil or coolant liquid,
- catalytic reactions of some metals, e.g. copper

In exploitation, this means that even a brief overheating of the oil is equivalent to the long-term use. If the oil worked at excessively for some reason at high temperatures, one should therefore think about reducing the time of exploitation in the engine.

The entry of coolant oil is usually called engine failure. In contrast, the appearance of the fuel oil is a process that occurs periodically in engines fueled with liquid fuels (gasoline, diesel). When starting the engine to the work area of the cylinder, fuel delivery is usually increased (boot). Incomplete combustion which is accompanied by the first rotation of the crankshaft causes that on cylinder liner oil film is mixes with the fuel boundary layer. This reduces the local conditions of lubrication, and it leads to increase fuel content in the oil.

An important factor degrading the oil (both nobling additives and the oil base) is the occurrence of water in oil. This occurs most intensively during the winter season while operation of unheated engine. The exhaust gas penetrating into the crankcase as a result of blows, has a considerable amount of water vapor that condenses on the cold inner surface of the engine. This can easily be seen in the form of oil-water emulsion forming in winter on the oil filler cap.

Degradation of oil base is connected mainly with the processes of:

- evaporation of lighter hydrocarbon fractions (this is the main reason for the loss of oil composed on mineral based)
- cracking (under high temperature decomposition of hydrocarbons forming a base for hydrocarbons of shorter carbon chains may occur, which next are easier to evaporate)
- oxidizing and cooking.

Mineral oil bases undergo degradation more easily than synthetic bases. The process also affects the degradation of the kind of fuel. Liquid fuels (as previously mentioned), get into the oil and dilute oil base and dissolves in it impurities such as lacquers and pitch. Visually, this manifests in dimming – dirty oil. Gaseous fuels (LPG and CNG) do not cause such phenomena and, consequently, their impact on oil is a little different. Lack of fuel dilution and dissolution by contamination appear as a bright (only slightly tinted) color of the used oil. Higher temperatures, however, causes the intensification of cracking processes and evaporation of lighter fractions, the effect of which is increase of the oil viscosity. Degradation of engine oil is the oil properties change exceeding the permissible boundary values. Table 3.8 shows examples of boundary values of selected properties of the oil. The quoted values have orientation character.

Table 3.8. *Boundary values of changes of chosen properties of engine oils*

Property	Boundary change of value	Source
Kinematic viscosity measured in temp. 100 [°C]	Decrease higher than 25% of the value for fresh oil or increase of 15÷18 [mm^2/s]	BN-79/0535-46
	For the oil of SAE class 40 11,5÷16,5 [mm^2/s]	[1]
	Increase 20% decrease 40 %	[2]
	Increase 35% decrease 25%	[3]
Temperature of ignition [°C]	Not lower than 175 in closed crucible	BN-79/0535-46
	Not lower than 170 in open crucible	[1, 3]
	Not lower than 180 in open crucible	[2]

Property	Boundary change of value	Source
Base number [mg KOH/g]	Decrease of not more than 70%	BN-79/0535-46
	0,6 for diesel oil with sulfur content up to 0,2%	[1]
	1, for diesel oil with sulfur content up to 0,5%	[1]
	Decrease not more than 70%	[2, 5]
	Min. 1÷1,5 dependently on the kind of oil	[3]
Water content	Below 0,2%	BN-79/0535-46
	Below 0,05%	[1]
Fuel content	Max. 5%	[3]
Lubricity	Decrease of parameters' values 25%	[2]

Assessment of the degree of degradation of engine oil

Assessment of the oil degradation degree can be done by analyzing the physicochemical and functional properties of the oil. The operating conditions may be:

- color – allows to assess the contents of produced in exploitation asphalt and tar substances dissolved in oil,
- smell – allows to assess the content of fuel and degree of oxidation oil.

The other properties may be evaluated only in laboratory conditions, these are:

- kinematic viscosity – the size of the changes allows for an overall assessment of the degree of oil degradation,
- WL viscosity index – its decline indicates an increase in the influence of temperature on the change in oil viscosity,
- density – density changes indicate chemical transformations occurring throughout the mass of oil,
- flashpoint – the lowest temperature at which the heated oil gives off enough steam that it forms with air a flammable mixture, on the approach of the flame. Its reduction is caused primarily by the advent of lighter fractions of hydrocarbos – it may be an indirect measure of the amount of fuel dissolved in the oil,
- base number – its decrease proves the acidity of oil, e.g. with compounds of sulfur,
- Water content into oil due to the earlier mentioned thermodynamic transformations (the water content can be made by hydrie-oil or so-called test on creaking water).

A full assessment of the degree of degradation in oil use is not possible only on the basis of its appearance and smell. It requires the conduction of several laboratory tests to determine the parametered physical-chemical and functional changes of oil's properties:

- the basic parameter that specifies the usefulness of oil for lubrication of engine is viscosity. The assessment of allowable changes in viscosity should include the following: measurements of viscosity at selected temperatures, specification of changes of viscosity index.
- the second parameter, the value of which determines the possibility of further oil exploitation is temperature of ignition. The decrease below the permissible values means that it is possible to ignite oil vapor in the engine crankcase oil- this should not be used any longer.

3.4. Gear oils

Oils for manual transmissions MTF (Manual Transmission Fluid)

The concept of the classic manual transmission currently includes several different development solutions:

- gear boxes with friction synchronizers made of copper alloys,
- gear boxes with friction synchronizers rings made of other materials that copper alloys,
- gear boxes without synchronizers – electrically steered with sets of brakes regulating the speed of cogwheel.

Similarly to the case of engine oils, the fundamental parameter characterizing the gear oils is viscosity. Since the gear oil works mainly by producing grease film between surfaces of cooperating cogs and during this work it undergoes a very high pressure, its viscosity is definitely higher than the viscosity of engine oils. Nobling additions content prevent wear (AW) and friction between the rubbing surfaces (EP). The processes of exploitation destruction of oil include mainly impurities with the products of friction of the cooperating surfaces and exhaustion of counter-exploitation and counter-friction nobling additions. The change of viscosity connected with zi and evaporation of oil bases is less significant here than in the case of engine oils. The included gear oils work in more comfortable conditions than engine oils, that is why they are much more persistent as regards exploitation. Gear oils serve the same functions as engine oils. However, their concrete prosperities are dependent on the type of gear in which they are to be used.

Adjustment of gear oils includes, similarly to the other lubricating oils, viscosity and quality features. Viscosity classification of gear oils SAE includes 4 classes (70W, 75W, 80W, 85W) of winter oil and 7 classes of summer oil (80, 85, 90, 110, 140, 190, 250). The adjustment of viscosity class of oil depends on climate conditions and construction of the gear (e.g. the oils of 70W class allows to keep fluidity at temperatures to about 55 °C). Quality classification (API) divides the gear oil into 6 groups (from GL-1 to GL-6). In practice, most often used in cars oils are currently the oils GL-4, GL-5 and GL-6. Adjusting the oil as regards quality, one should remember to not use GL-5 oils consisting of anti-rubbing additions EP for synchronized gears. This concerns above all gear boxes with synchronizers made of copper alloys, in which producer advises to use only the oils of class GL-4. EP additions may cause chemical corrosion of synchronizers and at the same time make proper work impossible. These additions increases their viscosity under the influence of high pressure (pushes) – this prevent friction of of surfaces of the co-operating elements. The increase of viscosity is here almost linear and it undergoes doubling by 0,35 MPa. EP compounds may react with copper which is the cause of strong decrease of friction coordinate. This phenomenon doesn't allow to use them in oils destined for boxes equipped with rubbing synchronizers made of copper alloys. Producers of gear boxes usually inform explicitly about the necessity of not using the oils containing the EP additions by recommending of using the oils of GL-4 class, deprived of these additions.

GL-5 oils consisting of EP additions are especially recommended for heavily loaded gears of circle-arched or hypoid cogs in which small rotary speeds occur. One may say that these are typical oils for drive-axles and major gears. The oils of GL-6 class allows to work with huge pressures and huge rotary speeds, protecting the surfaces of cogs from rubbing, exploitation, even if the oil works in the conditions of boundary friction. Adjusting the oil, it is advisable to use the procedures places on the websites of producers of oils – we'll avoid eventual exploitation problems.

Oils for automatic gear boxes ATF (Automatic Transmission Fluid)

Automatic gear boxes is a set of a couple of cooperating subgroups: hydrokinetic gear, set of clutches and brakes, planetary gears and set of steering valves. Each of the enumerated elements has different requirements in relation to the medium with which it works. Sets of valves and the hydrokinetic gear require relatively low and constant viscosity of oil in the whole scope of temperatures of working (-60 °C – 50 °C). That is why such oils have to possess a very high index of viscosity (VR) and a very high temperature of flowing. In order to keep the features on an unchanged level, they cannot undergo aging which induces the use of anti-oxidization additions packet. A little different requirements has the set of clutches and brakes and planetary gears. On the one hand, sets of frictional elements have to provide friction, on the other hand these elements cannot undergo exploitation. The necessity of individual adjustment of oil composition to the gear box, the use of sets of precise filtration of oil, removing the products of exploitation and impurity. Additionally, ATF oils cannot undergo foaming while moving through a complex hydraulic steering set because it makes its proper work completely impossible.

Oils for two-clutch gear boxes DCT (Dual Clutch Transmission)

Two-clutch gear boxes designed for car racings have the advantages of manual and automatic box. There is lack of typical for classic gears moment of unclutching – disconnection of engine from the drive set of a vehicle. Mechanical set of the gear consists of two middle clutches, one of which cooperates with rollings switching the even gears, and the other one which switches odd rollings. Switching of gears occurs ultimately on both of rollings – this is why the phenomenon of clutches' shields sliding occurs. It shortens radically the time of gears shifts in relation to manual gear box from 0,4 sec to about 0,02 sec. The rotary moment is here transmitted from the engine to wheels all the time. At the same time, in comparison with classic automatic gear box, a driver has the possibility of free choice of gears which helps to decrease the exploitation of fuel. The basic flaw of two-clutching set is slide of clutches. The slide is accompanied by giving off heat and exploitation processes. There are three groups of constructional solutions for such gear boxes:

- boxes with wet clutches working in mutual oil bath with the group of gears,
- boxes with wet clutches working in own oil bath (the group of gears is covered with other oil),
- boxes with dry clutches.

The fewest problems with oil adjustment for box possess the owners of two-clutch boxes with dry clutches – here, classic oils destined for manual boxes are sufficient. Boxes equipped with wet clutches require oils of low viscosity which decrease the losses caused by resistances which are made by oil to rotating clutches. Such set easily gives out the heat produced whle clutch's slide in comparison to dry clutches. Oils destined for this type of boxes has to have both features of classic gear oils and oils for automatic boxes, thus they should:

- have low viscosity in the whole scope of working temperature (like ATF oils),
- provide the protection of cog gears and synchronizers (like MTF oils),
- have high resistance to oxidizing at high temperatures (like ATF oils),
- have to possess high resistance to foaming (as ATF oils).

3.5. Utilization and toxicity problems of the lubricating oils

Modern lubricating oils are the mixtures of various chemical compounds i.a. esters, carboxylic acids, silicones, fluorosilicones, synthetic hydrocarbons, chlorohydrocarbons and fluorohydrocarbons. One should remember that the more technologically advanced is the oil, the more differentiated its chemical composition is. The increase of active substances content (additions) causes that the oil poses a bigger threat to environment. Car oils, with regard to a specific way of exploitation, poses such threat not only after finishing their exploitation, but also during the storage, transport and usage in vehicle. Of course, the level of toxicity of these oils is always different. Considering the level of threat, all oils (not only the ones used in motorization) are divided into four classes:

- ***Class 0*** – these are highly-purified plant and mineral oils, undergoing relatively easily biodegradation. Oils of this class are used in pharmacy and in production of cosmetics. In 90s trials of formulations of biodegradable engine oils was undertaken, but there wasn't any decision about their mass production,
- ***Class 1*** – these are pure base oils. Harmful substances here are mainly aromatic and non-saturated hydrocarbons,
- ***Class 2*** – these are all lubricating oils consisting of nobling additions. The dangerous are here some nobling additions consisting of chlorine, phosphor, sulfur, barium,
- ***Class 3*** – these are overworked oils. Such oils, besides the compound creating packet of additions or the products of their change, consist of many impurities coming from exploitation of engine's elements (zinc, tin, chromium, copper, iron) and products of reactions of oil with fuel. There occur also: heavy aromatic hydrocarbons. Multi-annular aromatic hydrocarbons are regarded as carcinogen substances. Their occurrence is an effect of reaction of high temperatures: first, pyrolysis (thermal damage) occurs, and then pyrosynthesis (joining) of hydrocarbon structures. These compounds increase a negative reaction of oil on human and on environment.

Recycling of lubricating oils

The concept of recycling means a regain consisting in repeated processing of substances in the productive process aiming at getting of substances or material of initial or other destination. In relation to engine oils, recycling is realized mainly by:

- the use of oil as boiler fuel,
- rerafination of oil aiming at repeated getting of a new oil base or cracking (which is thermal or catalytic dissolution of hydrocarbons included in oil into hydrocarbons of shorter carbon chains),
- purifying of oil in order to retain its initial properties.

3.6. Plastic lubricants

Composition and properties of plastic lubricants

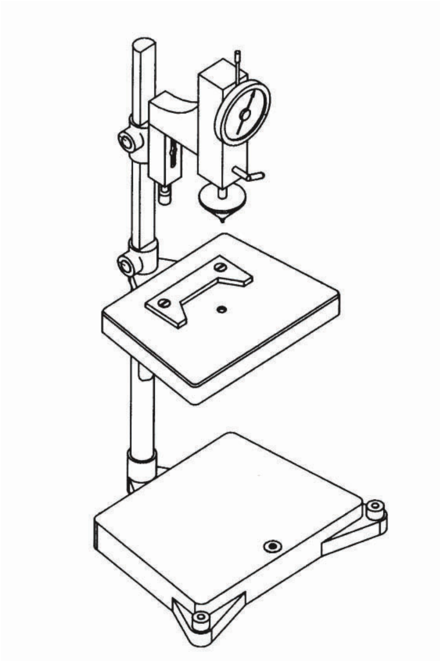
Each plastic lubricating oil is a mixture of two phases: fluid – which is grease along with nobling additions (about 70-90%) and the constant – which is concentrator (about 5-30%) and an eventual addition of solid lubricating substance, e.g.

graphite (0-5%). The concentrator is bearing structure for grease – comparative to the structure of sponge soaked with water. While cutting of the structure of concentrator during the movement of lubricated elements, the oil condensed in it flows out, similarly as the water from squeezed sponge. The amount of grease squeezed from the structure is dependent on the speed of concentrator's deformation speed. This property causes that viscosity of greases is dependent on not only temperature, but also on the gradient of speed of its structure cutting (that is why plastic greases are nonnewtonian lubricating substances). By low mutual speeds of relocations of greased elements, the grease is characterized by high viscosity resulting from the structure of concentrator and a small amount of squeezed oil. In the case when the speed undergoes increase, the increased amount of squeezed oil causes the decrease of viscosity. This property causes that plastic grease is suitable for greasing the elements moving with high and low speeds by small and big loads, providing the production of greasing film in such differentiated conditions.

The properties of greases are strongly connected with their composition. Boundary of flowing depends on the kind of used concentrator. It is a boundary tension by which the viscosity of grease decreases immediately as a result of complete squeeze of grease oil from the concentrator. If the concentrator connects strong adhesive reaction with molecule of oil, the boundary of flow increases. Such situation has place in the case of lithium greases for rolling bearings. The opposite situation is used in half-fluid greases. The remained properties dependent on the kind of used concentrator are: consistency (measured with the number of penetrations), temperature of dropping and resistance to water reaction.

Consistency of greases specify their resistance to tensions working (greases of higher class of consistency possess a higher boundary of flowing). Classes of consistency are specified on the basis of the so-called number of penetration (according to NLGI- *National Lubricating Grease Institut)*. Number of penetrations is the depth of infiltration of normalized cone of the mass 150 g in the grease in the time of 5 seconds at the temperature of 25°C, expressed in tenth parts of millimeter (Fig. 3.11). Because the consistency of grease depends not only on temperature, the kind and amount of concentrator, but also on the intensity and time of grease's clotting, the measures are conducted on fresh grease (in sale package) and after kneading it in normalized vessel. On the basis of number of penetrations 10 classes of consistency were distinguished (table no 3.9).

a)



b)

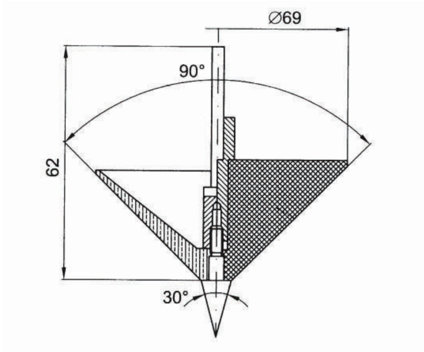


Fig. 3.11. *a) Penetrometer, b) penetrating cone*

Table 3.9. *The division of greases by classes of consistency and scope of uses correspondent to them*

Class of consistency	State	Number of penetrations according to NLGI- DIN ISO 2137	Scope of uses
000	very fluid	445-475	gears
00	fluid	400-430	
0	half-fluid	355-385	
1	very soft	310-340	rolling and sliding bearings
2	soft	265-295	
3	middle	220-250	
4	dense	175-205	conservation
5	very dense	130-160	
6	hard	85-115	special uses
7	very hard	less than 75	

Temperature of dropping is the lowest temperature at which first drop of oil leaks out from the grease inserted in a normalized vessel. Emission of oil proves dissolving of the connection oil-concentrator. The temperature of dropping allows to specify boundary temperature of the use grease. The majority of producers gives the boundary temperatures of the use of grease of about dozen or so degrees lower than the temperature of dropping. It results from the fact that during heating of grease occur:

- increase of dissolvability of concentrator in oil (it concerns primarily the greases based on soap concentrators),
- dissolution of the structure of soap's "net",
- decrease of oil viscosity.

This complex of phenomena causes that the grease heated to the temperature of dropping is not able to produce an effective grease film.

The enumerated properties belong to the group of rheological properties (they show relations which occur between tensions, viscosity and deformation of structure of grease in the time).

The other group of properties of greases are the ones which specify their stability – these are:

- mechanical stability – it specifies the resistance of gear to the changes of viscosity and consistency under the influence of operating mechanical forces. The smaller are changes of viscosity and number of penetrations of working grease, the mechanical stability is higher. This property specifies the usefulness of grease for greasing the elements undergoing the big tensions of e.g. rolling bearings;
- thermal stability – it specifies changes of properties under the influence of high temperature;
- resistance to water's operating – it depends mainly on the kind of concentrator, the used oil and consistency of grease. It specifies the resistance of grease to water which flushes the grease from the greased connection. (Researches are conducted on an open bearing, on whose rolling elements water stream of constant volume of flow and constant temperature is directed – the amount of grease flushed in that way is evaluated).

The enumerated properties of greases belong to the most important ones, besides the important are: colloidal permanence (ability to keep the colloidal state in the time of exploitation and storage – colloidal dissolution of grease manifests in emission of liquid phase), chemical permanence (resistance to the changes under the influence of oxidizing processes occurring during the work and storage), exploitation permanence (ability to produce effectively protecting from tribological exploitation grease film) and ability of protection of greased elements from corrosion.

The presented properties of greases causes that they have a couple of valuable advantages:

- possibility of work in unsealed friction nodes (ability to keep on vertical surfaces),
- no necessity of using the devices providing grease or their simple composition,
- higher than in the case of oil resistance to impurities (by the ability of producing thick layer on greased surfaces),
- possibility to relocate bigger loads (in relation to oil) – thicker layer of oil conditions elastohydrodynamical greasing.

Classifications of greases

Classification based on consistency

Greases can be classified according to the above described consistency class (NLGI classification), as well as a thickener and an oil type used. The NLGI classification (National Lubricating Greases Institute) divides greases into 9 classes of consistency and determines their application. Liquid greases are essentially used for lubricating transmissions and sliding sleeves, while greases with a soft and medium consistency are used as bearing lubricants. Hard greases are intended for special application- mainly as technological lubricants.

Classification of greases due to the type of oil used

Taking account of the basic component of greases- oil, they can be divided into groups according to an oil type used. This division of greases is significant when mixing greases in use is necessary.

Table 3.10. *The miscibility of oils most frequently used in plastic greases according to the types of base oil; (+) miscible , (–) immiscible)*

Oil type	Mineral	Synthetic hydrocarbon	Polyglycol	Ester	Silicone
Mineral	+	+	–	+	–
Synthetic hydrocarbon	+	+	–	+	–
Polyglycol	–	–	+	–	–
Ester	+	+	–	+	–
Silicone	–	–	–	–	+

Classification of greases due to the nature of a thickener

It is the oldest and the most common type of grease classification which specifies five basic groups of greases:

1. Greases based on soap thickeners (including greases based on simple to complex soaps). These include lithium, calcium, aluminium, and sodium greases. Lithium greases (based on 12-hydroxystearate and lithium stearate) constitute the dominant group of greases on the world-wide market. They have more than 51% grease market share and dominate in applications, among other things, as greases for rolling and sliding bearings (often called universal greases). All greases with a thickener based on simple soaps are characterized by dropping points which are lower than those in greases based on complex soaps. Simple soaps are salts of organic acids, e.g. lithium stearates, calcium stearates, etc. Complex soaps are mixtures of salts of at least two acids, e.g. stearic and acetic. They form a more complex structure of a thickener, which facilitates growth of the dropping point of a grease. Thus, complex greases can be used in higher temperatures than greases based on simple soaps (which is presented in Table 3.11).

Table 3.11. *Comparison of selected properties of greases based on simple and complex soap thickeners as well as a mineral oil basis*

A thickener type	The temperature range of grease application [°C]	Dropping point [°C]
Lithium simple	–35 - 130	170 - 200
Lithium complex	–30 - 150	240
Calcium simple	–30 - 50	80 - 100
Calcium complex	–30 - 140	240
Aluminium simple	–20 - 70	120
Aluminium complex	–30 - 160	260
Sodium simple	–30 - 100	150 - 190
Sodium complex	–30 - 130	220

2. Greases based on mixed thickeners which are most often a mixture of soaps and inorganic thickeners. These greases are to combine specific properties of particular thickeners.
3. Greases based on hydrocarbon thickeners, such as paraffins, ceresins or waxes. There are mainly protective greases; a typical example of this group is industrial grade petroleum jelly.
4. Greases based on inorganic thickeners: bentonites or silica. These thickeners are infusible and can be used in very high temperatures, even above 200 °C without fear of grease leak. Bentonite thickening agents are received from bentonite clay

with a layered crystalline lattice that can absorb large quantities of liquids. This process can be compared to saturating clay with water. Silica thickening agents are aggregates (polymers) of silicon dioxide SiO_2.
5. Greases based on polymer thickeners. Its most important group is composed of polyurea greases. They are characterized by the ability to endure high temperatures, even up to 180 °C, as well as high mechanical and chemical stability. Polyurea thickeners are also water-resistant. Similarly to lithium greases (universal), polyurea greases have a wide range of other applications. They are particularly useful for the single lubricating of high-speed rolling bearings.

The type of a thickening agent is one of the main factors determining grease properties. It also has a decisive influence on the miscibility of greases, which is presented in Table 3.12.

Table 3.12. *The miscibility of greases according to the type of a thickening agent; (+) miscible, (–) immiscible, (+/–) miscibility limited to certain proportions*

A grease type									
Lilithium simple									
Lithium hydrostearic									+
Lithium complex								+	+
Lithium-calcium hydrostearic							+	+	+
Calcium simple						+/–	+	+/–	+
Calcium hydrostearic					+	+	+	+	+
Calcium complex				+/–	+/–	–	+	–	+/–
Aluminium colmplex			–	+	–	–	+	–	–
Polyurea		–	+	–	–	–	–	–	–
Bentonite	–	–	+/–	+	+	–	–	–	+/–

Classification of greases according to their application

Taking account of application, greases can be divided in to the following groups:

- greases reducing friction and the coefficient of friction, the so-called anti-friction greases,
- maintenance greases preventing corrosion,
- greases increasing the coefficient of friction, the so-called friction greases,
- anti-friction and maintenance greases,
- sealing greases,
- special greases.

The function of plastic greases

Enhancing additives and their function

Enhancing additives used in plastic greases can be divided into: stabilizers, corrosion and oxidation inhibitors, as well as lubricating and adhesive additives. When in use, stabilizers and oxidation inhibitors allow maintaining unchanged properties of a grease. Corrosion inhibitors and adhesive additives help keep lubricated surfaces from oxidizing and allow for their better moistening with grease particles. Lubricating additives include compounds such as AW (anti-wear), EP (extreme pressure), and friction modifiers. AW compounds are anti-wear substances. They include: graphite, molybdenum disulfide, wolfram disulfide, boron nitride, and polar compounds with long carbon chains. The former have a layered structure. Subsequent layers of their crystalline lattice can easily separate from one another, thanks to which these substances form a solid lubricating film after being applied on surfaces in frictional contact (Fig. 3.12 and 3.13). EP compounds belong to the group of anti-seizing additives. Seizing is a process that occurs when pressures between lubricated surfaces cause that oil substance is squeezed out of the contact area between the surfaces. There appears, then, direct frictional contact between the surfaces as well as their frictional joint (welding). EP additives present in a plastic grease form a layer permanently adhering to the surface of metal. They react with metal when friction surfaces are heavily loaded. A newly formed compound is easily coagulated, which prevents lubricated surfaces from being joined (Fig. 3.14). EP additives most often include compounds of zinc, sulphur, phosphorus, or chlorine. EP additives application requires knowledge of their mechanism of action, since a compound that forms an EP additive should be appropriately matched to a lubricated metal. Additives based on compounds of sulphur easily react with copper alloys, and phosphorus-based compounds with aluminium alloys. The shift of pairs metal-additive will not generate expected benefits (anti-seizing protection). It should also be remembered that using a grease with an EP additive may be inadvisable if there must be friction between lubricated elements during operation. There can appear difficulties in achieving a permanent wearing reaction due to an EP additive and its function. When an excessive friction value (pressure) appears, the active additive will cause elements to slide. AW and EP additives are used in greases designed for lubricating heavily loaded elements.

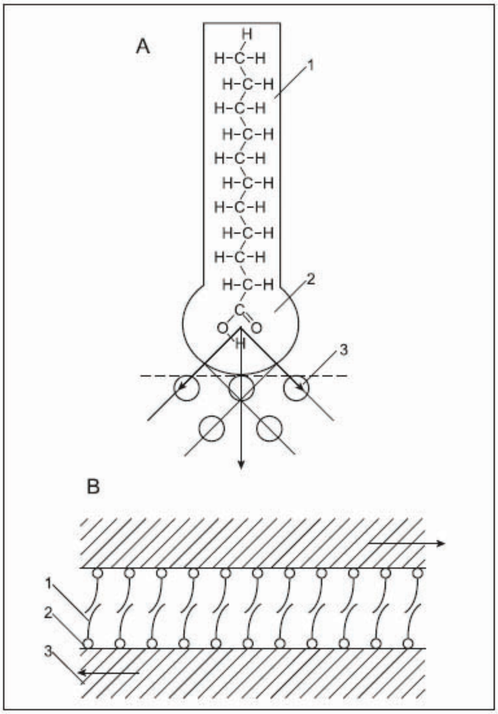


Fig. 3.12. *The mechanism of action of AW additives; A- the polar additive molecule absorbed on the surface, B- „ molecule tails" restricting the possibility of direct contact metal-metal (1- the „tail" of a molecule, 2- the polar „end" of a molecule, 3- the surface of metal*

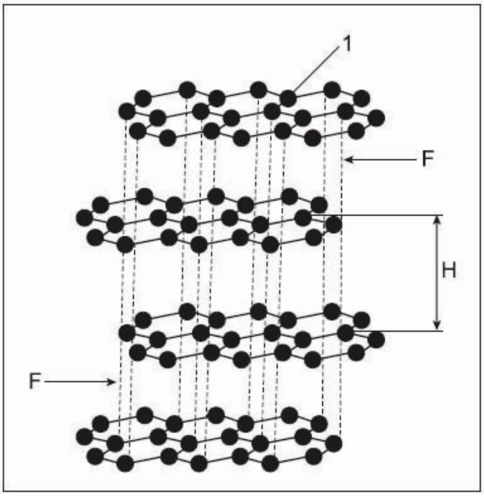


Fig. 3.13. *An additive with a layered structure- graphite; 1- carbon atoms, F- forces causing "the cutting-off" of the graphite layers, H- distance between the layers*

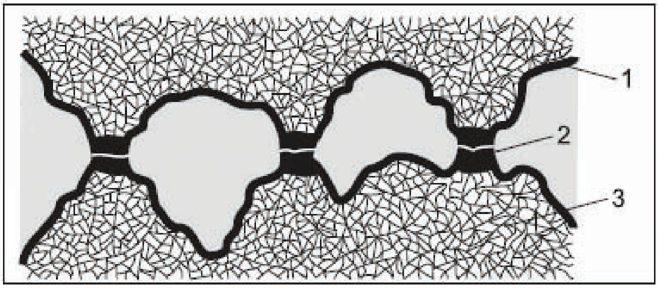


Fig. 3.14. *The mechanism of action of EP additives; 1- a layer of an EP additive sticking to the surface of metal, 2- metal-metal interface, 3- metal*

AW and EP additives are effective and function only at high pressures. The use of plastic greases requires that lubricated surfaces should be protected against wear in different conditions, also at moderate pressure values and lower speeds of mutual movement of the lubricated surfaces. In order to ensure protection of the lubricated surfaces in such conditions, plastic greases are enriched with compounds called friction modifiers. Their effect is similar to that of AW and EP additives, however, it can be observed when friction contact is much weakly loaded. Friction modifiers use various physical phenomena, adsorption processes and chemical reactions in the area of fraction contact. Friction modifiers that use physical phenomena include: molybdenum disulphide, metallic copper dispersion, PTFE-Teflon, fluorinated graphite; these compounds function as AW additives, except that they do not require high pressures. It can be said that they cover a surface with a thin layer and behave like weak AW additives. Friction modifiers that use adsorption phenomena include: carboxylic acids with long carbon chains and their esters, ethers, amines, and amides. These are compounds with a polar structure "sticking" to clear metallic surfaces. Another group of friction modifiers is composed of compounds that form protective layers on lubricated surfaces as a result of tribochemical reactions. Examples of such compounds include: phosphoric acid esters or sulphuric fatty acids.

The mechanism of elastohydrodynamic lubrication

The basic aim of lubrication is to substitute dry friction with liquid friction. It allows reducing radically the resistance to motion of cooperating components with negligible wear values of their surfaces. Liquid friction may appear when cooperating surfaces are totally separated with a layer of a lubricant: oil or grease. In the case of oils this is usually hydrodynamic lubrication. Lubricating oils are treated as Newtonian fluids. The condition of complete separation of lubricated surfaces by a lubricating film is its appropriate value of hydrodynamic pressure. One deals with hydrodynamic lubrication when a lubricant is a liquid (Fig. 3.15).

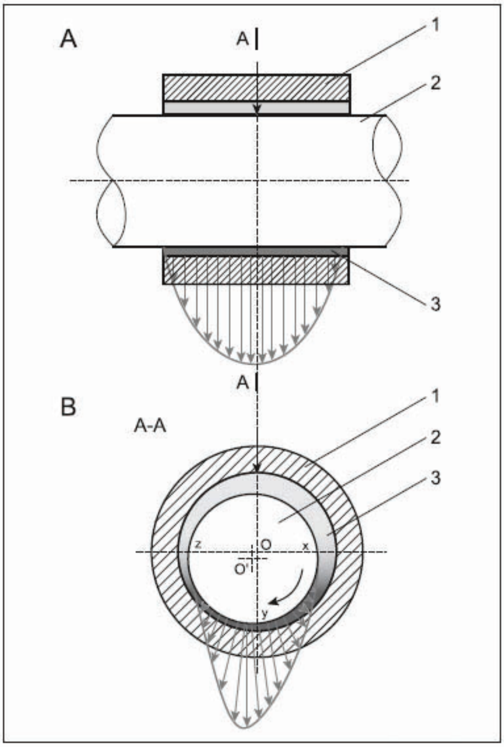


Fig. 3.15. *The mechanism of hydrodynamic lubricating; A- the longitudinal section of a slide bearing, B- the cross section of a slide bearing, 1- a bearing shell, 2- a shaft, 3- a lubricant*

In the case of plastic greases, the mechanism of forming an oil wedge is slightly different. Under pressure, grease "changes" from solid to liquid. This "transformation" influences its viscosity. The viscosity of plastic greases strongly depends on stress (deformation) which the grease is exposed to. In the case of greases this is elastohydrodynamic lubrication (Fig. 3.16). The mechanism of forming an oil wedge in elastohydrodynamic lubrication is similar to the mechanism in hydrodynamic lubrication. However, high viscosity allowing grease to be treated as solid enables the effective separation of friction surfaces even at small values of oil clearances and the relative speed of friction surfaces. Liquid friction occurs in the case of oil clearances merely four times bigger than an average roughness of lubricated surfaces. Pressures in elastohydrodynamic films are also substantially higher than pressures in hydrodynamic oil films. In the central contact area of working elements, the pressure in grease balances Hertz's pressure points. Thus, grease in use causes elastic deformations of lubricated elements. Due to deformations in the outlet of an oil clearance, there appears a narrowing, while the value of elastohydrodynamic pressures rapidly increases, exceeding Hertz's maximum stress that appears when elements are not lubricated.

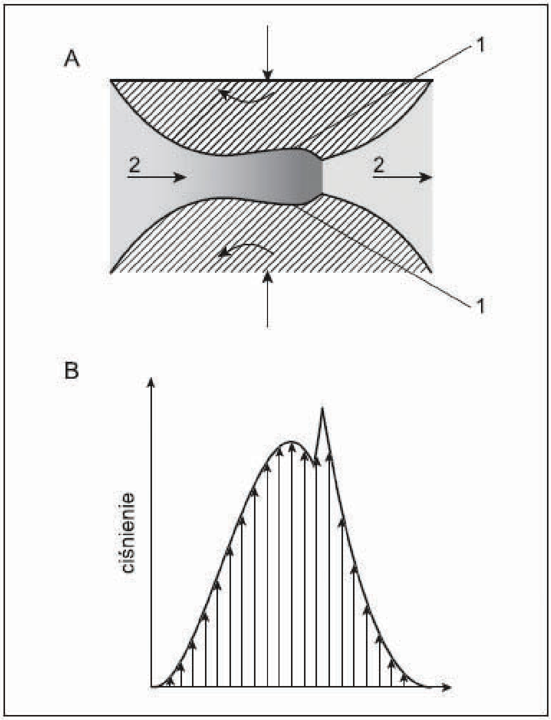


Fig. 3.16. *Pressure distribution in an elastohydrodynamic film; A – rotating rollers, B – pressure distribution in conjunction with friction; 1 – the place of elastic deformation, 2 – a lubricant*

4. The basics of machine diagnostics

4.1. Introduction

Machine diagnostics is a set of means and methods used for assessing the technical condition of machines. The objectives of machine diagnostics include:

- diagnosis – determining a current technical condition,
- genesis – determining reasons for a current condition,
- prognosis– determining a time horizon of a change of technical condition in future.

The technical condition of a device is directly determined by its characteristics. These include e.g.: geometric dimensions, trajectories of element movement, material stress, etc. In order to measure the above quantities so that the condition of a machine can be assessed, in most cases the machine must be turned off or even dismantled. The technical condition is, however, reflected in the quality of work processes of machines such as: power, maximum speed, or energy efficiency. In the case of technological machines, e.g. machine tools, a product quality test can be performed to obtain assessment of the quality of a machine. Carriers of the condition of a machine also include the so-called residual processes – accompanying work processes which unintentionally accompany machine operations. Residual processes include thermal, frictional, electrical, and vibroacoustic processes. Their usage provides an opportunity to assess the technical condition of a machine in use without dismantling it, and often even without contact. The residual process test belongs to the group of passive methods. There is also a group of diagnostic methods which requires the usage of a special stimulus, e.g. light, an ultrasonic wave, a magnetic field, etc. in order to obtain a diagnostic signal. These methods are described as stimulus methods. The possibilities of machine conditions tests with passive methods are presented by means of a schematic diagram of information and energy flow in Fig. 4.1 Table 4.1 shows a review of diagnostic methods most frequently used, as well as their basic application fields and limitations.

Further in this chapter only two diagnostic methods will be discussed in more detail; vibroacoustic and thermal diagnostics. They belong to passive methods, most frequently used, and also allowing the technical condition of a machine to be assessed.

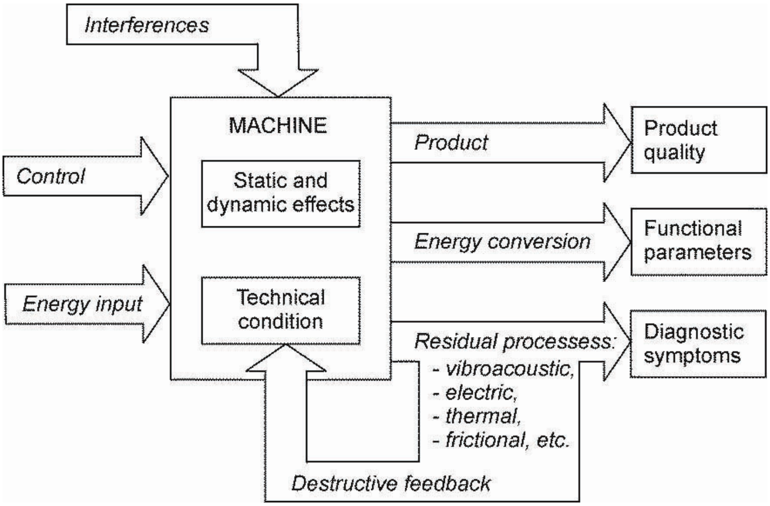


Fig. 4.1. *The machine as a system with a flow of information and energy, as well as methods of its observation*

Table 4.1. *The review of diagnostic methods of machine condition and development*

<table>
<tr><th colspan="2">The group and the name of a method</th><th>Nature</th><th>A field of application</th><th>Limitations</th></tr>
<tr><td rowspan="3">Visual</td><td>Endoscopic</td><td>Optical examination through a lens system or an optical fibre cable</td><td rowspan="3">Static elements of machines and developments</td><td rowspan="3">Only surface defects, direct access necessary</td></tr>
<tr><td>Holographic</td><td>Reconstruction of a wave front from a 3-dimensional diffraction Figure</td></tr>
<tr><td>Colour or fluorescent penetration</td><td>Delving into defects of visible or fluorescing chemicals</td></tr>
<tr><td rowspan="2">Magnetic</td><td>Powder</td><td>Concentration of ferro-powder in the areas of defects and damage</td><td>Static elements of machines made of ferromagnetic materials</td><td>One-millimetre defects</td></tr>
<tr><td>Eddy current</td><td>A change of amplitude and current phase in the defect area</td><td>Static elements of machines made of conductive materials</td><td></td></tr>
</table>

The group and the name of a method		Nature	A field of application	Limitations
Radiographic	X-ray	Attenuation, reflection and dispersion resulting from radiation.	Static elements of machines and constructions	Expensive and heavy instru-mentation, safe access necessary. Volumetric defects, the minimum size of a defect 2-4 mm
	Isotopic			
	Neutron			
Product consumption tests	Filtering cartridges	Filtered and centrifuged lubricating oil (pressure liq-uid)- obtaining rest products for quantity analyses	Machines in use after taking a sample of oil	Difficulties in locating failures
	Magnetic plugs	Capturing large magnetic rest molecules in oil (pressure liquid)	Machines in use after changing a plug	Do. only large molecules of materials
	Ferrography	Do. (molecules of all sizes)	Machines in use after taking a sample of oil	Difficulties in locating failures
	Oil spectral analysis	Spectographic analysis of small molecules after burning		Expensive instrumentation
	Particle counting	Current molecule counting in the lubrication system (hydraulic)	Machines in use, current reading	Expensive and difficult installation
Thermal	Thermogra-phy	Analysis of an infrared image	Elements of machines and installations that warm up. Non-contact tests	Direct access required (visibility)
	Thermometry	Spot-measurement of temperature	Bearing housings, power machine frames	Difficult installation, high thermal inertia

The group and the name of a method		Nature	A field of application	Limitations
Vibroacoustic	Vibration	Analysis of vibration connected with the functioning of a machine (components)	Machines (components) in use. Possible non-contact tests	No significant limitations
	Noise	Do. noise analysis		Possible interferences
	Medium pulsation	Analysis of medium pulsation in working spaces of a machine	Turbo-machines (engines, compressors, etc.)	Difficult access to the measurement area
	Acoustic emission	Reception and analysis of acoustic waves in material generated by natural development of micro-damage	Elements of machines (developments) under working load	Expensive instrumentation
	Ultrasonic	Deadening, dispersion, reflection, a phase shift, acoustic wave resonance	Static elements of machines and developments	Direct contact required

The utilitarian aim of machine diagnostics is linking observable symptoms with drawing conclusions about the technical condition of a machine. Realization of this aim concerns:

- measuring physical quantities that provide information about the condition of a machine,
- isolating useful components from a signal through selection, filtration, etc.,
- drawing diagnostic conclusions, that is linking observed symptoms with the condition of a machine.

The last task that consists in linking observed symptoms with the condition of a machine requires a diagnostic model to be created. The diagnostic model is cause-effect relation between the condition of an object and diagnostic parameters, damage-oriented, reflecting a changeable technical condition of the object examined. It is usually an mathematical description (analytical, graphical, logical) which takes account of connections between object characteristics and its condition. It contains a set of diagnostic data as well as information about condition, including a diagnostic relation that enables a diagnosis to be made.

A diagnostic model of an object is, then, a tool for an description of the object and its behaviour in various conditions by means of a diagnostic relation between the sets of condition characteristics and symptoms.

4.2. Diagnostic signals

Definition and classification of signals

A diagnostic signal (dependent on the condition of an object) is any tangible medium, most often the course of a physical quantity, that provides information about the condition of the object observed to be conveyed. The most frequently used signals are those expressed as a function of time $f(t)$ or a function of a position in space $f(x, y, z)$. In general, only some signal characteristics convey information (they are conditioned by a conveyed message). These are the so-called active signal characteristics (symptoms). Other characteristics are called noises. A classification of signals has been presented in Fig. 4.2.

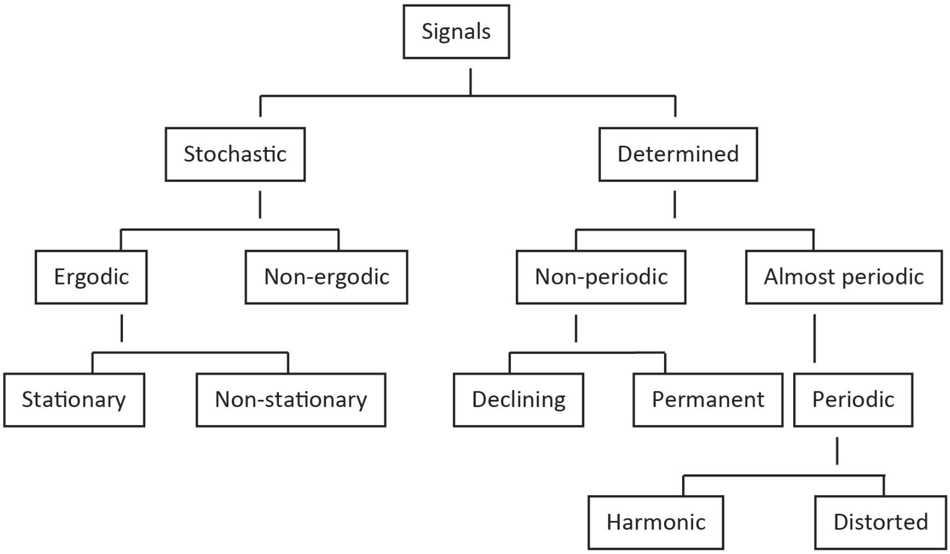


Fig. 4.2. *Classification of signals*

A stochastic signal is a signal whose values are random variables at any moment. On the basis of a statement on ergodic signals that is important for practical calculation, averaging after the infinite set of values of random variables at a particular moment can be replaced with averaging after the infinite set of realizations of random variables in successive time periods. In practice, stochastic stationary signals (with time-invariant random parameters) are ergodic signals. For these signals, all moments, including an expected value and variance, can be counted on the basis of time series.

Stationary signals are those whose statistical characteristics (the average rectified value, the root mean square, a function of correlation) are not functions of time (are not dependent on the choice of initial moment). Signals that do not match the above definition are called **non-stationary signals**. Examples of non-stationary signals have been presented in Fig. 4.3.

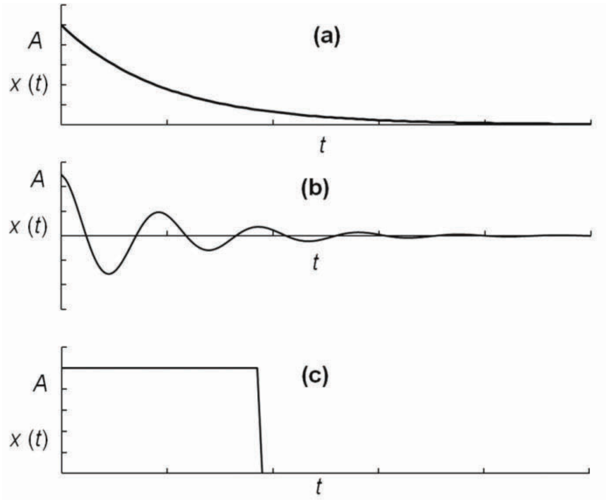


Fig. 4.3. *Non-stationary signals*

A **deterministic** signal is a signal whose value is unequivocally determined by means of precise mathematical relations at any time (on the basis of fundamental laws or a number of observations). Determined signals can be divided into periodic (almost periodic) and non-periodic. **Harmonic** signals play a very important role among periodic signals. These can be described via the following equation:

$$x(t) = A\ \sin(\omega t + \theta\_0)\ , \qquad (4.1)$$

where: *A* is an amplitude, ω – pulsation, a θ_0 – an initial phase. There is a relationship between pulsation and the frequency of a signal: ω=2 π ʃ.

Ideal harmonic signals practically do not exist. Even signals often regarded as pure sinusoidal variables (e.g. voltage) are, in fact, distorted by interferences and components with frequencies other than the basic one. Signals composed of components with more than one frequency are called **polyharmonic** signals. An example of a polyharmonic signal has been presented in Fig. 4.4.

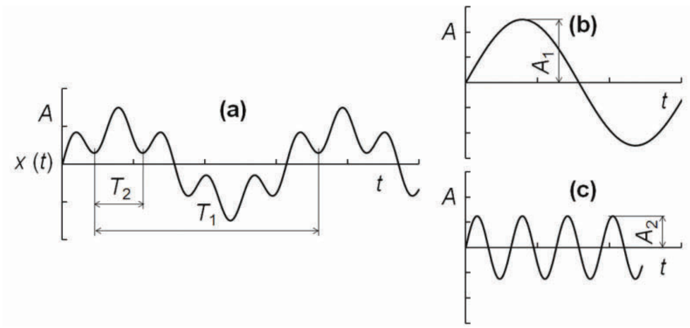


Fig. 4.4. *A polyharmonic signal and its components*

However, it should be noted that not all polyharmonic signals are periodic. A signal will be periodic only if the quotients of all possible frequency pairs are rational numbers. Otherwise, it is an **almost periodic** signal.

Real dynamic signals generated by technical objects usually contain determined as well as random components.

Parameters of signals

The observation of diagnostic signal values with the aid of human senses is possible only when they are slowly-variable signals (e.g. ambient air temperature). However, most signals generated by machines belong to fast-variable signals, an observation of which goes beyond human abilities. Therefore, time-averaged quantities are used in observation. The basic parameters of harmonic and dynamic signals have been presented in Fig. 4.5.

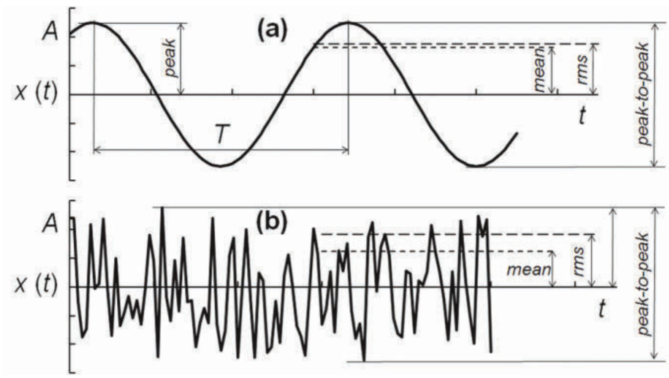


Fig. 4.5. *Parameters of harmonic (a) and real dynamic signals (b)*

A mean value of a signal is defined in the following way:

$$x_{mean} = \frac{1}{T}\int_0^t x(t)\,\mathrm{d}t \;, \qquad (4.2)$$

where: T is a period for a harmonic signal. If the signal is sinusoidal, the average value is 0 by definition, but it can be calculated for a half of the period (as shown in Fig. 4.5) or from an absolute value. In the case of realization of a dynamic process presented in Fig. 4.5b it is impossible to specify a period. Therefore, averaging is performed in particular time *T*.

A commonly used quantity characteristic to a signal amplitude is the root mean square (rms) value, computed in the following way:

$$x_{rms} = \sqrt{\frac{1}{T}\int_0^t \left[x(t)\right]^2 \mathrm{d}t} \;, \qquad (4.3)$$

The rms value is an energy measure of a signal. The interpretation of the rms value for alternating current is as follows: the rms value of alternating current is such a value of direct current that has an identical heat effect as alternating current.

However, the averaging of signals in time makes many of their properties impossible to interpret. A diagnostic signal usually consists of a number of frequency components characteristic to specific processes, the functioning of individual elements or particular damage. Therefore, a frequency analysis of signals proves to be useful in machine diagnostics which allows amplitudes in particular frequency bands to be isolated. Such an analysis can be done by means of filters with various frequencies, or calculations based on an analysis of registered time series. In practice, a Fast Fourier Transform is used most often in a frequency analysis.

4.3. Vibroacoustic diagnostics

The sources of vibroacoustic signals

Every technical device in use which has moveable elements or in which there is a media flow is accompanied by generating vibrations and noise emission connected with them. Sound and vibration phenomena reflect the most significant physical processes that take place in machines. The movement of the mass centre of an object, e.g. as a result of unbalance, is connected with a fictitious force which "tried to move" the whole machine. Consequently, it generates vibrations with the same frequency as that of the moving centre of the mass. Vibrations caused by factious forces are present in every machine. Fig. 4.6 presents a diagram of vibrations that are generated by a lack of the balancing of a rotating element.

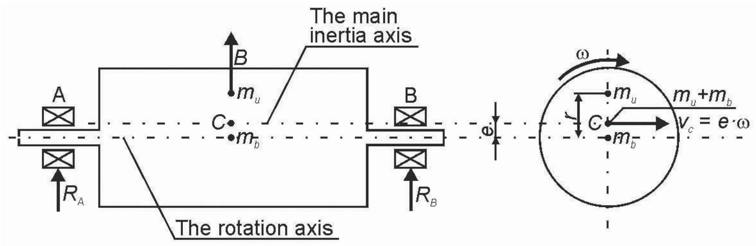


Fig. 4.6. *A diagram of vibrations generated by a lack of balancing.*

A fictitious force resulting from a lack of balancing is:

$$B = m_u r \omega_0^2 \quad , \qquad (4.4)$$

or

$$B = (m_u + m_b) e \omega_0^2 \quad , \quad (4.5)$$

where symbols are present in Fig. 4.6, and e stands for impropriate unbalancing which is expressed with an equation:

$$e = \frac{m_u r}{m_u + m_b} \quad , \qquad (4.6)$$

Other common sound and vibration phenomena are connected with clearances between machine elements. When in use, they are colliding, a result of which are impulsive vibrations and clanking of all kinds. An example of inappropriately installed machine being a source of noise and vibration has been presented in Fig. 4.7.

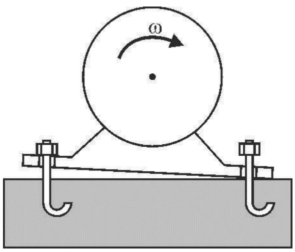


Fig. 4.7. *An example of inappropriately installed machine which causes noise and vibration*

A characteristic feature of most machines is the cyclical nature of their work. On account of that it is possible to identify a source of vibrations through associating the moment in which a vibration occurred with the kinetics of the machine. In turbo-machines, important information is provided by an analysis of medium pulsation achieved, for example, by measuring pressure in working volumes.

Vibration quantities

Vibration diagnostics of machines and their elements is based on measurement and recording of vibration signals generated by machines in use. Initial vibroacoustic signals are specific mechanical quantities describing motion. The quantities measured in diagnostics are as follows:

- the movement of vibrations– a vector quantity specifying a position of the point of an object towards the position of this point in a state of dynamic balance, while the end of the vector is in current position of the point,
- the speed of vibrations– a vector quantity, a derivative of vibrations towards time,
- the acceleration of vibrations – a vector quantity, a derivative of the speed of vibrations towards time.

Vibration measurements

To enable recording of signals, they should be first converted to electrical quantities. Both contact and non-contact methods are used for vibroacoustic measurements. Contact measurement convertors most often measure acceleration and are called accelerometers. A concept of the mechanical system of an accelerometer is the same in every case. An element with specific mass is connected with the main body by means of a force converter which is proportional to acceleration. Differences between particular accelerometer solutions come down to the application of different force convertors. A measurement element of piezoelectric accelerometers is most often made of quartz or polycrystalline ceramics- materials which show an opposite piezoelectric effect. A piezoelectric accelerometer without an internal electric system has a loading output with high impedance. There are also accelerometers with a voltage output with low impedance which are connected with a charge amplifier. An example of the mechanical construction of an accelerometer has been presented in Fig. 4.8.

a) b)

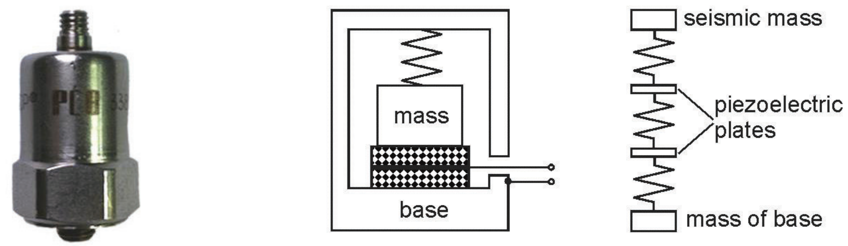


Fig. 4.8. *A view (a) and an internal construction of a piezoelectric accelerometer (b)*

Acoustic quantities

A sound wave generated by a source of sounds travels in an acoustic field in accordance with the law of wave movement. Various acoustic quantities are used for a sound description. Volume in a particular point of the acoustic field is an average acoustic power carried by a surface unit perpendicular to the direction of wave movement. Since pressure is a relation of power to a surface, and velocity is a relation of a way to time, the volume of a flat acoustic wave can be expressed by pressure p and sound speed c:

$$I = \frac{p^2}{\rho c} \cdot \qquad (4.7)$$

A unit of volume is a watt per a square metre.

Acoustic power is an amount of energy emitted in time to an environment. There is a relationship between acoustic power W and volume I:

$$W = \oint_s I \mathrm{d}s \cdot \qquad (4.8)$$

Sine a range of acoustic quantities is extensive, a relative logarithmic measuring scale has been introduced. Acoustic quantities expressed in this way have their own values of reference. The most frequently used quantity is a level of acoustic pressure:

$$L_p = 10 \log \frac{p^2}{p_{odn}^2} = 20 \log \frac{p}{p_{odn}} \quad , \qquad (4.9)$$

where the pressure of reference is a conventional auditory threshold and amounts to $20 \cdot 10^{-6}$ Pa.

Acoustic measurements

Measuring sensors used in acoustic diagnostics are microphones, or electro-acoustic convertors. Their task is to process energy of an acoustic wave to electric energy. However, energy processing is not direct and takes place by means of mechanical energy.

Microphones are usually adjusted to the measurement of pressure or a pressure gradient. Pressure microphones most often consist of a closed can; one of its walls is a diaphragm. Fast shifts of pressure cause movements of diaphragm. Gradient microphones measure a difference in points of the acoustic field close to them, that is they measure the pressure gradient.

Various phenomena are used in order to convert diaphragm movements to electric energy. Taking account of a way of conversion, microphones can be divided into:

- contact (carbon),
- dynamic (magnetic with a moveable coil),
- electromagnetic,
- condenser,
- piezoelectric.

Fig. 4.9 presents the construction of dynamic and condenser microphones.

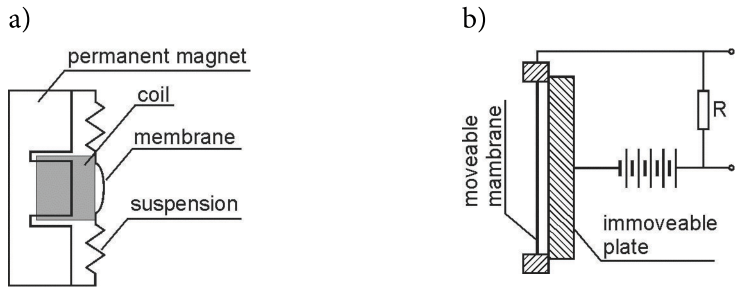


Fig. 4.9. *The construction of dynamic (a) and condenser (b) microphones*

4.3.1. Assessment of the technical condition of a machine with vibroacoustic diagnostics

Vibroacoustic diagnostics is used in many branches of engineering. Due to the simplicity of measurements and resistance to background interferences, measurements of the acceleration of vibration are most frequently used. Diagnostics can be carried out either online with permanently installed sensors of vibrations and constant monitoring of the condition of a machine, or off-line with periodic measurements.

Vibroacoustic diagnostics works very well in assessing the technical condition of rolling bearings. During the exploitation of bearings, a level of noise and vibrations rises. On the basis of experimental data, the permissible level of vibrations of a particular central unit can be established in order to prevent catastrophic damage. Fig. 4.10 presents examples of the level of vibrations of rolling bearings in various conditions which is dependent on the rotation speed.

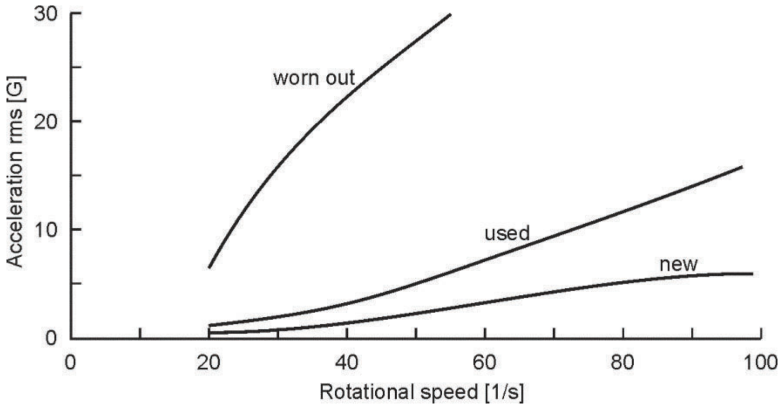


Fig. 4.10. *The rms values of vibrations of three bearings as a function of the rotary speed of an internal race: a new bearing, a bearing used for a short time, a bearing for replacement*

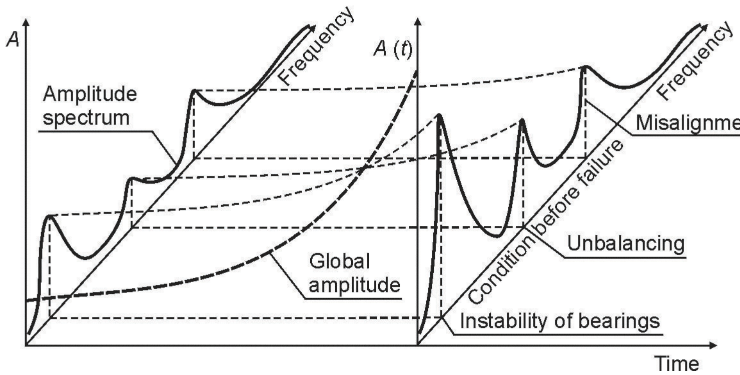


Fig. 4.11. *A graphic interpretation of a frequency analysis application for assessment of the condition of a machine along with identification of a source of faultiness*

In the case of more complex machines, vibrations observed can occur in different central bodies. However, the nature of cooperation of elements and their speeds will determine characteristic frequencies of vibrations generated by the machine. In this case, a frequency analysis and an observation of the development of vibrations in characteristic frequency wavebands prove to be useful. A concept of vibration diagnostics using a spectral analysis for failure identification has been presented in Fig. 4.11.

4.4. Thermal diagnostics

Thermal diagnostics application

Heat generation accompanies every machine in use that processes energy, since all energy losses are associated with heat generation. An important heat source in machines are friction processes. Increased motion resistance of cooperating elements caused by exploitation, an increased load or inappropriate lubricating make friction centres warm up. In turn, a high temperature of cooperating elements decreases durability and the strength of materials. A described positive feedback between a cause and effect results in inevitable damage to cooperating pairs. The above description proves that thermal diagnostics of machines is significant. If cooperating elements warm up excessively, it indicates that a particular mechanism of the machine is faulty.

Generating heat in heat machines is not a residual process, but a working process. Measurements of temperature in selected parts of heating and cooling devices or other energy convertors are the most important elements of systems used for monitoring the condition of the machine. They are also essential in monitoring technological processes in the iron and steel industry or polymer material processing.

Thermal diagnostics is also of great significance in the case of electric machines. Apart from detecting typical mechanical defects, e.g. defects of the rolling bearings of engines, it enables detection of electric defects. Damage to electric current conductors is usually connected with changes of the temperature of machine elements, which may be used for defect locating.

Temperature measurements

Methods of the measuring of temperature can be divided into two main groups: contact and non-contact measurements. The former use measuring sensors which must be located in the medium, the temperature of which is being measured. Therefore, temperature sensors interfere in the structure of the medium examined, influencing a heat exchange, and thereby a value of the temperature measured. Contact sensors belong to invasive sensors.

The number of types of contact temperature sensors used is as high as the number of physical and chemical phenomena connected with temperature. Temperature sensors can be generally divided into electric and nonelectric ones. The former group will not be discussed, since diagnostic applications use the measurement and registration systems of electric quantities, therefore, electric sensors are more comfortable in use. Basic types of electric sensors include:

- resistance thermometers:
  - metal,
  - thermistors,
  - silicon resistance sensors;
- thermoelectric thermometers,
- semiconductor thermometers.

Materials used in production of **metal resistance sensors** should be characterized by a high temperature coefficient and linear dependence of resistance on temperature. In order to achieve a long-term stability of metrological parameters in time, materials used in production of sensors cannot corrode. Materials that meet these requirements are copper, nickel and platinum. The linear characteristics of a sensor as a function of temperature T is described by the following equation:

$$R=R_0\ (1+\alpha\ T), \qquad (4.10)$$

where: R_0 is the resistance of the sensor in temperature 0 °C, and α stands for a temperature coefficient which is $4.26 \cdot 10^{-3}$ °C^{-1} for copper, $6.17 \cdot 10^{-3}$ °C^{-1} for nickel, and $3.85 \cdot 10^{-3}$ °C^{-1} for platinum. Platinum is the most frequently used material in production of industrial sensors. Resistance values R_0 have been normalized and amount to 100, 500 orb 1000 Ω.

Thermistors are semiconducting sensors, resistance of which may increase or decrease along with temperature. In practice, the most frequently used sensors are those with a negative temperature coefficient (NTC). The resistance of a thermistor can be described as follows:

$$R = A\ e^{B/T}\ , \qquad (4.11)$$

where A and B are material constants. The values of a temperature coefficient of thermistors are provided for a temperature of 25 °C and they are 10 times higher than those for metal sensors.

Due to their nonlinear properties, thermistors are not frequently used in industrial applications. However, they are very popular in the automotive industry. An example of the characteristics of a thermistor used for measuring a temperature of engine cooling liquid has been presented in Fig. 4.12.

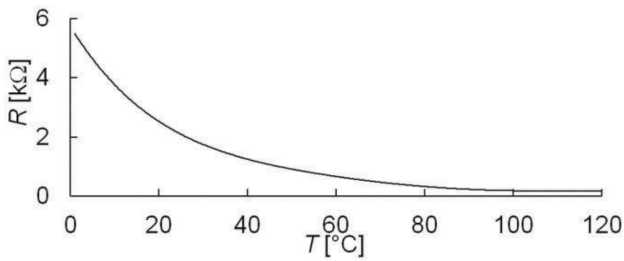


Fig. 4.12. *Characteristics of the NTC thermistor*

The operating principle of thermoelectric sensors is based on Seebeck's effect. It results from the crystalline structure of metals. If there appear a temperature gradient along the conductor, a heat flow occurs. This, in turn, triggers a movement of electron clouds, which produces an electromotive force at the ends. Thermoelectric sensors are built by connecting materials that differ in electromotive forces. If one creates a circuit by means of various conductors, as in Fig. 4.13, and the connectors of various materials are at different temperatures, such a circuit will produce a thermoelectric force proportional to a difference between the temperatures of both the connectors.

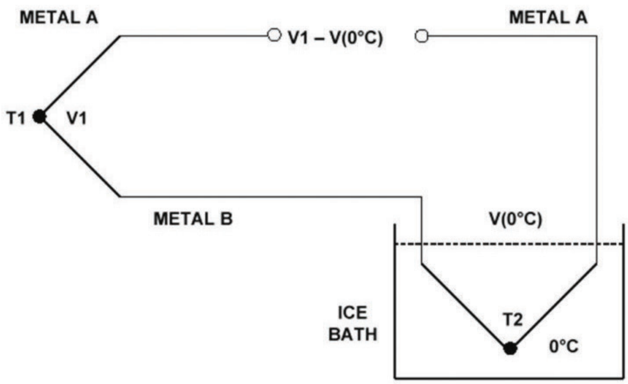


Fig. 4.13. *The operating principle of a thermocouple*

Typical material connections used in industrial applications as well as their symbols have been normalized. Thermocouple types are chosen depending on environmental conditions and ranges of temperature. Descriptions of basic thermocouples have been presented in Table 4.2.

Table 4.2 *Materials, Seebeck coefficients and markings of typical thermopairs*

Materials	Measurement range [°C]	Sensitivity [μV/°C]	ANSI marking
Pt 6% / Rhodium – Pt 30% Rhodium	38-1800	7,7	B
Tungsten 5% / Ren – Tungsten 26% / Ren	0-2300	16	C
Chromel – Constantan	0-982	76	E
Iron – Constantan	0-960	55	J
Chromel – Alumel	-184-1260	39	K
Pt 13% Rhodium – Platinum	0-1593	11,7	R
Pt 10% Rhodium – Platinum	0-1538	10,4	S
Cu – Constantan	-184-400	45	T

Contrary to the contact sensors, **non-contact sensors** (pyrometers) do not interfere with structure of the examined medium. Non-contact sensors use the dependence of intensity and distribution of electromagnetic spectral radiation of the opaque bodies. Distribution of radiation as a function of wavelengths is described by the Planck's law. Radiation power density of the black body with a temperature of T, as a function of Λ wavelength is:

$$L_{cc}\left(\Lambda,T\right)=\frac{2\pi \mathrm{hc}_0^2}{\Lambda^5\left(e^{\mathrm{hc}_0/\Lambda \mathrm{k}T}-1\right)} \qquad (4.12)$$

where: c_0 is the speed of light in vacuum, h – Planck constant, k – Boltzmann constant. Figure 4.14 shows the graphical interpretation of the Planck's law and Wien's displacement law

$$\Lambda_{max}=\frac{2898}{T}\mu\mathrm{m}\cdot\mathrm{K} \quad , \qquad (4.13)$$

indicating maximum position of the emission for the given temperature.

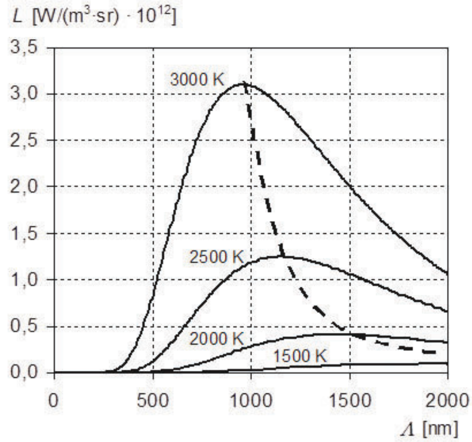


Fig. 4.14. *Black body's emission in a function of wavelength for different temperatures and graphical interpretation of Wien's displacement law*

Most frequently for the temperature measurement, a two-colour pyrometry is used, which uses the ratio of radiation power in two wavelengths Λ_1 and Λ_2. After simplification of 4.12 expression, the temperature formula takes the following form:

$$T = \frac{\dfrac{hc_0}{k}\left(\dfrac{1}{\Lambda_1} - \dfrac{1}{\Lambda_2}\right)}{\ln\left(\dfrac{L_2}{L_1}\right) + \ln\left(\dfrac{\varepsilon_1}{\varepsilon_2}\right) + 5\ln\left(\dfrac{\Lambda_2}{\Lambda_1}\right)} \qquad (4.14)$$

In equation 4.14, additionally the body's emissivity ε_1 and ε_2 has been introduced at selected wavelengths.

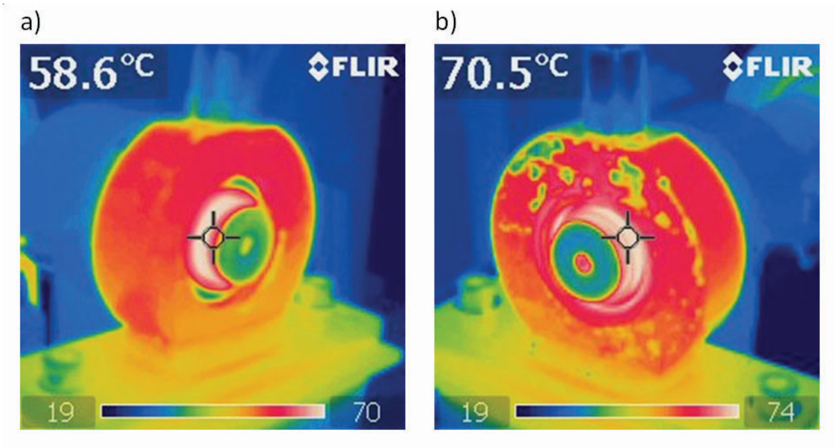


Fig. 4.15. *Thermographic images of the new (a) and used (b) rolling bearing housing after the same amount of work*

Pyrometric measurements can be performed as point measurements or the temperature distribution fields can be obtained. The second type of measurements is called thermography and the images are obtained using thermal imaging cameras that operate in the mid-infrared range. Example thermographic images of the new and significantly used rolling bearing housing are shown in fig. 4.15.

Besides the obvious advantages of non-contact methods, their basic disadvantage is the fact that only the measurements on the body's surfaces are possible. Also, pyrometry is not applicable to the temperature measurements of the gases.

5. Placing on the market or putting into service

The machines can be placed on the market or put into service, if with proper installing, maintenance and use as intended or in conditions, which may be predicted, they do not endanger the safety and health of people and domestic animals, or the property and environment, and they comply with the relevant provisions of Ordinance of the Minister of Economy, dated 21 October 2008, on the essential requirements for machines.

This ordinance implements Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on machinery, so called Machinery Directive. This directive is the so called new approach directive.

5.1. New approach to the harmonisation of technical regulations

Decision to introduce new approach to harmonisation of the technical regulations was made by the European Community states in 1985. This decision was a response to defects of the old system, currently called the Old Approach. The Old Approach Directives contained detailed technical requirements, which had to be met by the products. Due to technical progress, they had to be constantly updated. However, due to the bureaucratic inertia and long time execution of legislation procedures, the changes of regulations contained in Old Approach Directive were not fast enough. Furthermore, the use of these directives was not compulsory, and member states had no obligation to withdraw their own regulations, even if they were incompatible with the directive. As a result, the directives not only started to be an inhibition of technical development, but they also did not eliminate the barriers in the movement of goods (free movement of goods, services, capital and people is the fundamental assumption of the European Union), because in different countries could exist different requirements regarding the same product.

The purpose of introducing new approach directives was not only to ensure that only safe products would to be place on the market and that the regulations wouldn't inhibit the technical progress, but also to eliminate obstacles in the trade of goods on the member states markets through harmonisation of products requirements in the scope of safety. This has been complemented by so called Global Approach, which aimed to harmonise the assessment procedure of product conformity with directive requirements. The provisions contained in the directives of new/global approach are binding for the member states and should be implemented into the legal system of each country, and all incompatible regulations must be removed.

The essence of so called New Approach to harmonisation of technical regulations in the European Union comes down to a few basic rules:

- the subject of harmonisation are only the rules related to safety, health and environmental protection, so called essential requirements,
- the directives contain only essential requirements, while technical details are contained in the relevant European standards EN, the application of which is voluntary,
- a product that meets requirements of the directives and bear the CE marking (some directives do not predict CE marking) has the right to be placed on the market of any EU member state.

New Approach Directives contain only the general requirements regarding the safety of the products placed on the market, called the essential requirements in the scope of protection of health and safety. The essential requirements are formulated in the form of features, which should characterize the product or objectives, which must be achieved during its design and manufacture. They do not include the description of specific technical solutions, which should be used to achieve these objectives or features, leaving the manufacturer the freedom to choose the solution. Technical details can be specified in the relevant harmonised standards with individual essential requirements, however the use of these standards is, in principle, voluntary. The manufacturer may achieve the specified objectives and product's feature determined by essential requirements, by using solutions provided in the harmonised standards or in any other manner, freely selected by the manufacturer. Such principles do not impose the same solutions to all manufacturers and do not limit creativity, therefore they do not inhibit the technical progress.

However, the use of harmonised standards usually provides the manufacturers with some privileges. First of all, the right to use the so called presumption of conformity – it is presumed that the product manufactured in accordance with harmonised standard meets the essential requirements in the scope of protection of health and safety, covered by such standard. In addition, in the case of some directives, including machinery directive, the use of harmonised standards may allow for the selection of assessment procedure of conformity with essential requirements, which is not participated by the notified body. The list of standards harmonised with individual directives is published in the Official Journal of the European Union and it is periodically updated.

Most directives of the new approach require that a product, before placing on the market, must be marked with CE marking, which symbolizes the product's conformity with requirements of the new approach directives. Placing of the CE marking on the products constitutes the manufacturer's declaration, or his authorized representative, that the product meets all essential requirements, which apply to this product, and that appropriate procedures of the conformity assessment have been fulfilled.

Before placing the product on the market, the manufacturer must therefore carry out the appropriate assessment procedure of conformity, predicted in the directive. In accordance with the Global Approach, such assessment should be recognized in all EU states. Decision 768/2008/EC of the European Parliament and of the Council distinguishes 8 basic modules (marked with letters A to H) and 8 variants of these modules, which can be used in the assessment procedures of the conformity. The modules concern the different stages of product manufacture (designing, prototype, manufacturing) and differ in the manner of assessment (documentation inspection, prototype examination, inspection of the implementation quality control) and the entity that conducts this assessment (manufacturer, notified body). Individual directives, taking into account the specifics of the product to which they relate, determine which modules can be used in the conformity assessment procedure. Some directives predict several possible assessment procedures, depending on the product and the manner of achieving the fulfilment of essential requirements, and sometimes they also provide the manufacturer with the possibility of selecting the procedure.

Most of the modules predict the participation of a third party i.e. independent of the manufacturer and the recipient of the product, in the process of product conformity assessment with the essential requirements. Third party in order to be included in the conformity assessment procedure, preceding the labelling of the product with CE marking, must be a notified body i.e. it must be on the list of such bodies, which is included in the Official Journal of the European Union. Notified bodies are appointed by individual member states after ensuring that they meet certain requirements, in particular that they:

- have properly qualified staff and appropriated technical equipment in the scope of performance of conformity assessment,
- are impartial and independent, including financially,
- maintain confidentially and have civil liability insurance.

In Poland, the Ministry of Economy is responsible for submitting bodies to the European Commission. Before submitting, a given body, which may be an institute, laboratory, public company or private company, must be accredited by the Polish Centre for Accreditation and obtain authorization of the appropriate minister. In the notification process, the body is assigned with a unique number, and determined are the products categories and conformity assessment modules, to which the body has been designated. Member states are required to monitor whether the bodies meets the requirements. When it is found that the body no longer meets the criteria or seriously fails to fulfil its obligations, the state must immediately withdraw the notification. Manufacturer while carrying out the conformity assessment procedure has the right to choose any notified body from any country.

Currently, in the European Union there are over 30 new approach directives and the new ones are continuously issued. They are replacing the old approach directives, which are withdrawn, and they regulate new areas. It should be noted that the old approach directives are still valid. It's particularly the case, where harmonisation of requirements has already occurred earlier in all member states or in the areas where it's hard to formulate the essential requirements and there's a need to provide specific requirements. Old approach directives are valid in such sectors as: automotive, pharmaceutical, food.

New approach directives have a common structure, including the articles determining:

- scope of their applicability,
- conditions for placing products on the market and putting into service, as well as the principles of freedom of movement,
- conditions for presumption of conformity and rules for standards harmonisation,
- conformity assessment procedures and labelling with CE marking,
- responsibilities of the member states, including in the scope of market surveillance and notification of bodies, as well as other provisions.

Annexes to directives specify:

- essential requirements concerning health and safety,
- content of CE conformity declaration,
- detailed descriptions of conformity assessment procedures,
- minimal criteria, which member states should take into account during notification of the bodies.

5.2. Obligations of the manufacturer

Actions that should be undertaken by the manufacturer before placing product on the market will be discussed on the example of the machinery directive. It should be remembered that the presented description was aimed to provide the essence of the issues and it does not contain details and legal nuances, which the reader can find in the relevant legislation.

Before placing the machine on the market or putting it into service, the manufacturer or its authorized representative:

a) ensures that the machine meets the relevant essential requirements in the scope of protection of health and safety,

b) ensures that the technical documentation is available,
c) provides, in particular, necessary information, such as instructions,
d) carries out appropriate conformity assessment procedures,
e) prepares EC conformity declaration and ensures that it has been attached to the machine,
f) places CE marking.

Verification of compliance with the essential requirements

Manufacturer must determine to which directive/directives its machine is subject to, what essential requirements apply to it, as well as how to design and manufacture a machine to meet all requirements.

Determining directive to which the product is subject

All directives define the scope of their applicability. Not all machines are subject to machinery directive. This directive excludes among others: air, water and rail means of transportation, road vehicles, agricultural and forestry tractors, trailers, electrically powered household appliances, electric motors, etc. On the other hand, the directive includes devices that are not machines, such as: separately sold safety elements, chains, lines and other lifting accessories, removable devices of the mechanical powertrain etc.

In the case of machines or other products subject to the machinery directive, for which the hazards defined in Annex I of this directive (Annex I contain Essential requirements in the scope of protection of health and safety) are covered by other directives in more detailed manner, the machinery directive does not apply in regard to such hazards. In regard to such hazards, the product must meet the essential requirements determined in directives, in which these issues are defined in more detailed manner. In regard to the machines, such directives may be, among others: Low Voltage Directive (LVD) – 2006/95/EC (from 2016 it will be replaced by new directive 2014/35/EU), Simple Pressure Vessels Directive (SPVD) – 2009/105/EC, Lifts Directive – 95/16/EC (from 2016 it will be replaced by new directive 2014/33/EU), Electromagnetic Compatibility Directive (EMC) – 2004/108/EC.

It should be remembered that if some product is not subject to any directive, than it's subject to the Directive 2001/95/EC on general product safety, which establishes a general obligation of placement of only safe products on the market.

Designing of safe machine

Manufacturer already at the design stage should identify the hazards associated with his product, assess the risk and, if necessary, take steps aimed at lowering the risk, so that the product would meet all applicable essential requirements in the scope of protection of health and safety. In the Annex I of Machinery Directive containing the essential requirements, the comprehensive safety rules have been determined, which say that the machine must be designed and constructed in such manner that it is fitted for fulfilling its function and can be operated, adjusted and maintained without putting persons at risk during carrying out of these activities in the predicted conditions, but also with taking into account its improper use, which can be reasonably foreseen. Undertaken measures must be aimed at eliminating all risk throughout the assumed lifetime period of the machine, including its transport, assembly, disassembly, disabling and scrapping.

According to the rules of comprehensive safety, the manufacturer throughout the process of obtaining a safe product must carry out actions in accordance with the following order:

- eliminate or minimize risks, as far as it's possible, by designing and constructing machine that is safe in its design itself. This means that a manufacturer should select, when only possible, such manner of machine operation, work processes execution, which do not cause hazards e.g. by using: low voltages, temperatures, harmless fluids, etc.; moving parts that due to the form of movement or affecting forces do not constitute hazard, and otherwise put them beyond the reach of people e.g. inside the housing; such machine shapes, including edges, which do not cause injury,
- take necessary protective measures in relation to risk, which can't be eliminated e.g. by using covers or other protective devices, appropriate control systems e.g. the ones that require continuous support during enabling of unsafe functions,
- inform users about the residual risks due to any shortcomings in adopted protective measures; indicate whether any particular training is necessary and determine the needs for using measures of personal protection; carry this out by placement of various warnings, symbols on the machine and providing appropriate information in the instructions attached to the machine.

Manufacturer searching for solutions allowing the machine to meet essential requirements in the scope of protection of health and safety may use harmonised standards. The use of solutions provided in the standards allows for the use of presumption of conformity. Manufacturer doesn't have to use these standards, but then he needs to demonstrate (in technical documentation) that his product complies with the essential requirements. The manufacturer even if he decides not to use the harmonised standards should get to know them, because they provide current technical solutions and determine the adopted level of reference for the given safety aspects.

Technical documentation

The manufacturer must prepare technical documentation, in which he demonstrates that the machine meets the requirements of directives. It must include design, development and operation of the machine in a scope necessary for this assessment. Therefore, this documentation does not have to include detailed figures or any other detailed information about the subassemblies used for manufacture of this machine, unless such information is necessary during the checking of conformity with the essential requirements. This documentation must be prepared in at least one of the European Community's languages (with the exception of instructions – see below) and must be made available for review by the relevant state authorities for at least 10 years from the date of machine manufacture or, in the case of serial production, from the manufacture date of last unit.

In accordance with the Machinery Directive, technical documentation includes:

- general description of the machine,
- assembly drawing, control circuits schemes, descriptions and explanations necessary for understanding the operation of the machine,
- detailed drawings, along with the attached calculations, tests results, certificates, etc. necessary for checking the machine conformity with the essential requirements,
- risk assessment documentation presenting the used procedure, including:
  i) list of essential requirements in the scope of protection of health and safety, which apply to the machine,
  ii) description of preventive measures implemented in order to eliminate identified hazards or to reduce risk, and in appropriate cases, indication of residual risks associated with the machine,
- used standards and other technical specifications, indicating essential requirements in the scope of protection of health and safety, covered by these standards,
- all technical reports providing the results of all tests conducted either by the manufacturer or by the body selected by the manufacturer or by its authorized representative,
- copy of the machine instructions,
- in appropriate cases, declaration of inclusion of partly completed machinery and relevant assembly instructions of such machinery and copy of EC conformity declaration of the machinery or other products incorporated into the machine,
- copy of EC conformity declaration,
- in the case of serial production, internal measures that will be undertaken in order to ensure conformity of the machine with the directive requirements.

Instructions

In the EU, it is assumed that the purchaser does not need to have elementary knowledge about the product and the manufacturer's obligation is not only to provide a good product, but also to provide information allowing its safe use. It is carried out by placing appropriate information and warnings on the product, and by providing instructions along with the product. Each machine placed on the market or put into service in the EU must have instructions attached, which scope and form should be consistent with the machinery directive.

The scope of information provided in the instructions should enable identification of the machine and its safe use. Instructions should provide all possible stages of machine's operation and handling (e.g. assembly, use, adjustment, etc.), in which the hazards may occur and the manner of proceedings in order to avoid or minimize this hazard.

Instructions should be written in one of the European Community's languages. All machines should be equipped with the instructions in language of the country, in which the machine will be placed on the market or put into service and in instructions in the original language. As an exception, the maintenance instructions intended for the specialized personnel employed by the manufacturer or its authorized representative may be written only in one of the EC's language, understood by that personnel.

In the case of machines intended for the use by non-professional users, the general level of education and intellectual capacity that can be reasonably expected from such users must be taken into account.

According to the Machinery Directive all machines should be accompanied by instructions, containing at least the information, if applicable:

- name and address of the manufacturer or his authorized representative,
- marking of the machine, which has been placed on the machine itself, excluding the serial number,
- EC conformity declaration or a document presenting its content,
- general description of the machine,
- drawings, schemes, descriptions and explanations necessary for the use, maintenance and repair of the machine, and for checking the correctness of its operation,
- description of the workstation or workstations, which may be occupied by operators,
- description of the machine use as intended,
- warnings concerning prohibited manners of machine use, which, as experience shows, can take place,
- assembly, installation and connection instructions, containing drawings, schemes and fixing manners and determination of chassis or installation, on which the machine is to be mounted,

- instructions regarding installation and assembly, which are aimed at reducing noise or vibration,
- instructions regarding putting into service, as well as use of the machine and, if it is necessary, instructions regarding the training of operators,
- information regarding residual risk, existing despite the use of safe development in the design itself, precautionary measures and additional protective measures,
- instructions concerning protective measures that must be undertaken by the user, in appropriate cases, in combination with provision of personal protection measures,
- essential characteristics of tools, which can be used in the machine,
- conditions, in which the machine meets the stability requirements during use, transportation, assembly, disassembly, testing or foreseeable failures,
- instructions aimed at ensuring that transport, moving and storage would be carried out safely, providing the mass of the machine and its individual parts, if they are usually transported separately,
- method of operation used in the case of accident or failure; if there's a probability of blocking, a method used in order to carry our safe unblocking of the device,
- description of adjustment and maintenance actions, which should be carried out by the user and preventive maintenance measures that must be followed,
- instructions enabling safe carrying out of the adjustment and maintenance, including protective measures, which must be undertaken during these activities,
- specifications of the spare parts, which are supposed to be used, if they have an impact on the health and safety of operators,
- information regarding the noise emission and, in the case of hand-held machines and/or operated with hand, information regarding the vibrations,
- information concerning the emitted radiation affecting the operation and exposed persons, when the machine can emit non-ionizing radiation, which may cause harm to persons, in particular persons with implanted active or inactive medical devices.

Practically, the instructions usually consist of the following elements:

- information about the product, including identification information and technical specification (among others: name, machine marking, technical parameters, information concerning noise emission and vibrations, addresses of: manufacturer, importer, service),
- operating instructions (among others: intended use, acceptable operating conditions, prohibited manners of using, scope of activities which must be carried out before each start of operation, manner of safe use as intended, etc.),

- maintenance instructions (among others: lubrication, adjustments, assessment of condition, repairs),
- if necessary, assembly, transport, storage instructions, etc.

The manufacturer has the right to determine that certain activities, particularly inspections, repairs and adjustments can be performed only by him or by authorized service centres. In such case, the instructions provided for the user can't cover the scope of these activities.

Conformity assessment procedures

In order to certify conformity of the machine with machinery directive regulations, the manufacturer or his authorized representative must use one of the following conformity assessment procedures:

1. In the case when machine is not listed in Annex IV, the conformity assessment procedure combined with internal inspection of machine manufacture must be carried out (described in Annex VIII of the Directive).
2. In the case when machine is listed in Annex IV and has been manufactured in accordance with the harmonised standards and provided that those standards cover all relevant essential requirements in the scope of protection of health and safety, one of the following procedures must be used:
   a) conformity assessment procedure combined with internal inspection of machine manufacture, described in Annex VIII,
   b) procedure of EC type-examination, described in Annex IX, along with the internal inspection of machine manufacture, described in Annex VIII, article 3,
   c) full quality assurance procedure described in annex X.
3. In the case when machine is listed in Annex IV and it hasn't been manufactured in accordance with the harmonised standards or it has been only partially manufactured in accordance with such standards, or if the harmonised standards do not cover all significant essential requirements in the scope of protection of health and safety, or when no harmonised standards exist for the given machine, one of the following procedures must be used:
   a) procedure of EC type-examination, described in Annex IX, along with the internal inspection of machine manufacture, described in Annex VIII, article 3,
   b) full quality assurance procedure described in annex X.

As it's clear from the above, all products subject to the Machinery Directive have been divided into two groups: listed and not listed in Annex IV. Listed in this annex are the machines and other devices that may create particularly high hazards. Among others, the following have been considered to be such: circular saws, planers and some others machine tools with manual feed or with feed of processed objects, portable chainsaws for woodworking, some machines for underground works, lifts for vehicle service.

If the product is not listed in Annex IV (it's the vast majority of the products subject to the directive) or it is, but it has been completely manufactured in accordance with harmonised standards, the manufacturer can carry out ***conformity assessment procedure combined with internal inspection of the machine manufacture***. It's a procedure that does not require the participation of notified body. According to this procedure, the manufacturer must develop technical documentation demonstrating conformity of the product with essential requirements and he must undertake all necessary measures so that the manufacturing process will ensure the conformity of manufactured machine with this documentation and directive requirements.

If the machine is listed in annex IV and it has not been fully manufactured in accordance with harmonised standard, the conformity assessment process must be carried out with participation of notified body. The manufacturer can choose one of the two procedures.

According to ***procedure of EC type-examination combined with internal inspection of machine manufacture***, the manufacturer supplies to the notified bodes, selected by himself, one unit of the machine, called the type sample, along with technical documentation. Notified body conducts examination of the documentation and supplied machine. If the given type meets the requirements of the directive, the notified body issues EC type-examination certificate to the manufacturer. At the manufacturing stage, the manufacturer must undertake all necessary steps, which will ensure the conformity of the manufactured machines with technical documentation and requirements of the directive. EC type-examination certificate is valid for five years. At the request of the manufacturer, the notified body renews certificate for another such period, after it confirms that the certificate remains valid, taking into account the current state of technical knowledge. It should be emphasized that the notified body has the ongoing responsibility to inform the manufacturer about all significant changes, which could affect the validity of the certificate, and the manufacturer has the ongoing responsibility to ensure that the machine corresponds to the current state of technical knowledge. Notified body shall withdraw the certificated if it has expired. The manufacturer is obliged to stop placing the given machine on the market in the case of expiration of EC type-examination certificate.

To carry out conformity assessment of the machines manufactured with the use of ***full quality assurance system***, the manufacturer must have approved quality system in regard to design, manufacturing, final inspection and tests of the machine. Quality system must ensure the conformity of the machine with regulations of the directive. All elements, requirements and regulations adopted by the manufacturer must be documented in systematic and orderly manner, in the form of measures, procedures and written instructions. Documentation of the quality system must enable a consistent interpretation of procedural and quality measures, such as quality programs, quality plans and quality manuals. Approval of the system is conducted by notified body selected by the manufacturer, after carrying out its assessment. Manufacturer is obliged to fulfil obligations arising from the approved quality system and to ensure that it will remain appropriate and effective. Notified body is obliged to monitor whether the manufacturer properly fulfils the obligations arising from the approved quality system. Reassessment of the quality system should be carried out every three years. For this purpose, the notified body carries out periodic audits. Notified body may also make unannounced visits to the manufacturer.

In the case of products listed in annex IV and fully manufactured in accordance with harmonised standards, the manufacturer may, although not have to, choose the procedure, which is participated by the notified body. Usually, it's more expensive and longer procedure, but the manufacturer obtains a much greater assurance that his product is compliant with all applicable directives. Procedure of full quality assurance is usually more beneficial than procedure of EC type-examination, in the case of manufacturers that manufacture many different machine models of the given category, listed in Annex VI and/or frequently introduce modifications to these machines.

Declaration of conformity and CE marking

New Approach Directive usually require from the manufacturer to issue EC Declaration of Conformity, in which he declares that the product complies with the essential requirements. Some directives require that the EC Declaration of Conformity must be attached to the product (e.g. Machinery Directive). In other cases, it must be made available for the market surveillance authorities at their request.

Content of EC Declaration of Conformity is defined separately in each of the directives, but in principle, it should include the following elements:

- name and address of the manufacturer (or his authorized representative),
- full name and address of person having place of residence or headquarters in EC, authorized to prepare technical documentation,
- description and identification data of the product (functions, trade name, type, model number, etc.),
- clear statement that the product meets all relevant provisions of the machinery directive, and in appropriate cases, a similar sentence containing declaration about the conformity with other EC directives or relevant provisions, which the machine must meet,
- name, address and identification number of the notified unit, if it has been involved in the conformity assessment procedure,

- harmonised standards (or/and other standards), with which the product is compliant,
- issuing place and date of declaration, as well as identity and signature of the person authorized to prepare declaration on behalf of the manufacturer.

After the singing of declaration of conformity, the manufacturer may label the machine with CE marking. Please note that if the product is subject to the directive, which requires the use of CE marking, then it can't be placed on the market or put into service without such marking. On the other hand, CE marking can't be used on products, for which it's not provided by any new approach directive. Graphic form and place of marking placement are determined by the individual directives. According to machinery directive, CE marking must be placed on the machine in visible, legible and durable manner, in the immediate vicinity of the manufacturer's name, using the same technique. In addition, in the case of using full quality assurance procedure, after the CE marking, there must be placed identification number of the notified body.

There's a presumption that the products on which the CE marking has been placed, fulfil all requirements contained in the relevant directives. As a result, the member states may not prohibit, restrict or hinder the placing on the market or putting into service, in their territory, products with CE marking, unless the provisions concerning the marking have been used in the improper manner.

Responsibility of the manufacturer

Manufacturer must remember that he bears full responsibility for his product. In addition to the consequences arising from the orders of market surveillance authorities, which the manufacturer must undertake in regard to his product non-conforming with the requirements (see below), the person placing such product on the market is subject to high fine or even imprisonment (in the case of intentional placing on the market the product that does not meet the safety requirements). Moreover, the manufacturer must take into account the claims of individuals affected by the use of his products, based on the provisions of civil law (manufacturer is responsible for his product on the base of risk, not guilt).

5.3. Market surveillance

Member states are required to conduct surveillance of the market for the purpose of protecting the society from products posing a threat to the life and health of people and/or, in appropriate cases, property and environment. Please note that the surveillance is also intended for protecting the interests of manufacturers, ensuring the same conditions of market operation to all manufacturers (not allowing the dishonest manufacturers to "save" on the product's safety or on the tests associated with conformity assessment).

In Poland, the market surveillance system is the responsibility of the President of the Office of Competition and Consumer Protection who is supported by a number of specialized authorities, such as: Trade Inspection, National Labour Inspectorate, Inspectorate for Environmental Protection, Office of Rail Transport, construction supervision authorities, etc.

In the case of establishing that the product does not meet the essential requirements or it is labelled incorrectly in regard to the requirements, the specialized authority shall initiate administrative proceedings. Usually, at first the manufacturer is obliged to voluntarily remove the non-conformity. Only in the case of lack of cooperation on the part of person responsible for the product, the coercive measures provided by law are used. The undertaken measures should be compliant with the principle of proportionality i.e. they must be adequate to the type of threat posed by the product and the range of non-conformity. Specialized authorities have at their disposal a variety of measures: from the order to withdraw the product from the market, and also its repurchase from the users, to the order to inform the consumers or users of the product about the identified non-conformities and the order to achieve the compliance of the product.

Product, along with the information about the type of non-conformity, used measures and dangers it may cause, can be entered into the generally available register of products not compliant with the essential requirements, run by the Office of Competition and Consumer Protection. Member State is obliged to notify the Commission and other Member States about every such measure and the reasons for such decision. It should be noted that the non-conformity may be a result of shortcomings in harmonised standards, which the manufacturer has correctly applied in regard to his product. In such case, the procedure for disputing a harmonised standard is initiated, which may result in the withdrawal of the reference to the given standard in the Official Journal of the European Union.

5.4. Summary

Before placing on the market or putting into service within the European Union, the machine or other product must be subjected to the conformity assessment procedure, provided for in the directive, which applies to it. The purpose of this procedure is to assess conformity of the product with essential requirements of the directive.

One of the most important principles of the New Approach to harmonisation of technical regulations is to limit the legal requirements to the essential requirements, fulfilment of which is required by the public interest. These essential requirements primarily relate to the protection of health and safety of the users (consumers and employees), and sometimes they cover other important issues e.g. protection of property or environment.

Labelling of the product with CE marking on the basis of conformity assessment carried out by the manufacturer, on one hand simplifies and accelerates the process of approving the product for placing on the market, on the other hand it completely transfers to the manufacturer the responsibility for the product's features and possible consequences of damages resulting from the lack of fulfilment of the essential requirements.

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