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MEASUREMENTS AND LIMITS OF THE MACHINE WEAR MARGIN OF PRODUCTION SYSTEMS

Key words

Machine operability, functional unit wear margin measurements, the identification of wear margin.

Abstract

The article points out the need to describe the relationship between the quality of the company and the quality of the machine as an item of a company production system. In terms of description, existing measurements and limit values of the wear margin of production system machines are recognized as insufficiently developed. It has been shown that, based on the concept of *quality*, it is possible to decompose the desired quality characteristics of a company to get the desired measurements of machine characteristics and the machine functional unit. It is also possible to define the term *machine wear margin* and *machine functional unit wear margin*. The author identifies measurements of functional unit characteristics that make up the manufactured (real) wear margin and points out the need for finding substitute measurements of the actual wear margin. The algorithm is given for the identification of wear margin and the types of relationships between the excitation and response of the functional unit node. The author presents the basic models of the nodes and discusses the purpose of their development and use in the identification of machine wear margin.

Introduction

Production systems in a company are used for the manufacture of products or the provision of services. Products or services are a means to achieve the principal aim of an enterprise, which is to bring profit to its shareholders. The prerequisite for making a profit is to produce goods or services of acceptable quality. The adequate quality of product or service, among other factors, depends on the adequate quality of the basic components of the production system, particularly machines. The quality of machines is formed in their design and manufacture, and it is retained in operation and maintenance. The costs of machine quality add to the overall costs of the company, which significantly affects company profits. Therefore, it is necessary to optimize the cost of machine quality. There are attempts to describe the complicated relationship between business objectives and the quality of machines using the concept of machine wear margin. The problems to be solved are the measurements and limit values of the machine wear margin of a production system.

1. The desired and actual measurements of machine characteristics

The rich literature in the field of company management, company asset management, the operation of technical items, including diagnostics, maintenance, repair and identification of machine components and machine manufacturing technology, creates a need to systematize that knowledge to form a coherent system enabling management − from item material management to company management. *Quality* may be the basic term of this systematization.

According to ISO standards [1], the quality of a product is “general characteristics and properties of the product and service that determine the ability of a product or service to satisfy stated or anticipated needs”, and the requirements for the characteristics of the product are set out in a document called *product specifications*. In work [2], the author introduced the concepts of *company quality* and *the quality of the production system* and, based on the literature, summarized the main characteristics of quality. The relationships between the qualities of a company, production systems, and products are shown in Figure 1.

Since the company itself determines the desired values of its characteristics and the main elements of the production system are machines. According to the previous considerations of this author [2, 3, 4], the characteristics of machine quality and the measured values of these characteristics (Fig. 2) should result from the decomposition of the characteristics and the desired measured values of production system characteristics. Machines as items of the production system are products of other production systems. The life cycle of the product − a machine of the production system in the social market economy − consists of the design, manufacture, operation, and disposal. Actual characteristics and values of the measured values of the characteristics of the machine are determined during the development phase (design) of the machine as a product, while the desired measured values of machine characteristics should result from the desired characteristics of company quality.

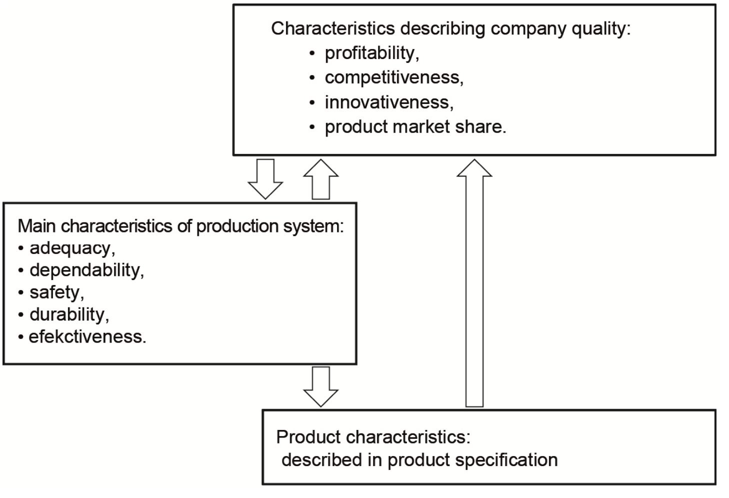

Fig. 1. The relationship between the quality of the company, the production system, and products

The design of a machine involves the preparation of machine specifications in the form of construction and manufacturing documentation. The specifications identify the following:

- The ranges of the measured values of the characteristics describing the machine load;
- The desired ranges of the measured values of the characteristics of the structural materials of elements;
- The desired ranges of the measured values of the characteristics of machine components (macrostructure, shape dimensions of the elements);
- The desired ranges of the measured values of the characteristics of built-in assemblies and components (e.g., backlash, pretension of bolts, press fit, tightness, unbalance, etc.); and,
- The desired ranges of the measured values of the characteristics of working fluids (e.g. oil viscosity).

It is assumed that, if all of the measurements have values from the corresponding desired range, then the item as a whole will obtain the desired characteristics with values falling within the desired range.

The characteristic values rendered during the manufacture of the machine change as a result of wear due to machine operation. The effects of wear are included in the characteristics describing the production system. These characteristics do not appear directly in machine specifications. Not all of the machine characteristics are subject to change. For convenience, in further considerations, the term *machine wear margin* will be used.

2. Measurements of machine wear margin

Wear margin refers to a working machine. There are many definitions of *wear margin* [5, 6]. For the purposes of these considerations, *machine wear margin* is defined as a set of the measurements of characteristics whose values

- result from the manufacture of the machine,
- decrease due to wear during machine use, and
- can be restored through repair or maintenance.

In the literature, wear margin and associated costs are presented as a function of the machine life cycle phases. Wear margin is formed in the design and manufacture phases, is reduced in the operation phase, and is liquidated in the recycling phase (Fig. 2). Operation is the longest phase of the life cycle of the machine and consists of cyclically repeated phases of use and maintenance, namely repair (maintenance where the use is stopped) or additionally, in the form of maintenance and/or repairs without stopping use. Problems in making use of machine wear margin arise because of the following:

- Machine specifications lack on-line measurable characteristics that directly describe the wear margin of the machine, and
- The number of characteristics necessary to describe machine wear margin is large.

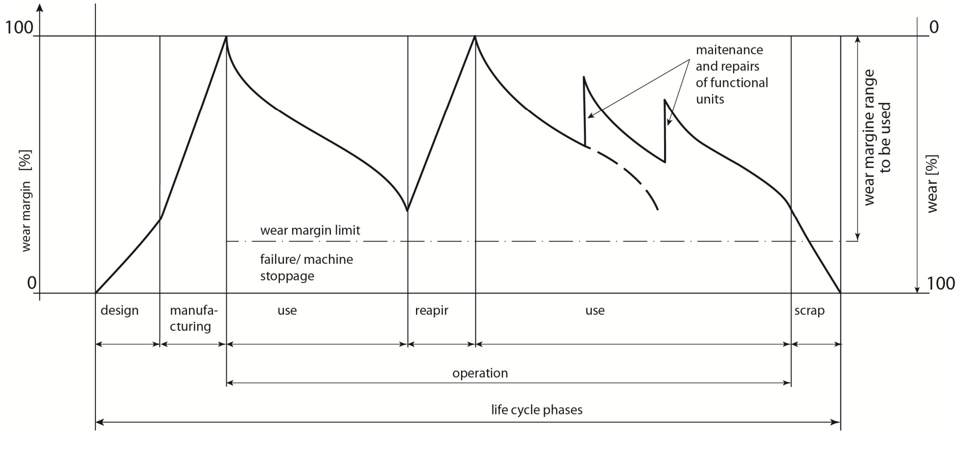

Fig. 2. Phases of the life cycle of a machine and its wear margin as a function of operating time

Due to the large number of characteristics necessary to describe wear margin, it is desirable to determine substitute measurements − measurements that can be determined from measurable values of the characteristics of built-in elements, working fluids, load, and relative motion. The literature provides examples of measurements that can be considered as measurements of the wear margin of *machine functional units*. Therefore, the proposed solution may be the term *wear margin of machine functional unit*, justified as follows:

- The wear margin of a machine is the resultant of the individual wear margins of functional units of that machine.
- The existence of functional units in a machine performing specific partial functions means that the degradation rate of the wear margins of individual functional units may be different and may require a separate remedial action.
- Combining machines into sets is done by connecting elements of selected functional units. New functional units are created, which are not included in the machine specifications.

The necessary condition for using the wear margin of functional units is the decomposition of the desired values of characteristic measurements of the machine into the desired values of wear margin measurements of functional units D_{ij} (Fig. 3). Actions affecting the wear margin of a functional unit are activities within machine maintenance.

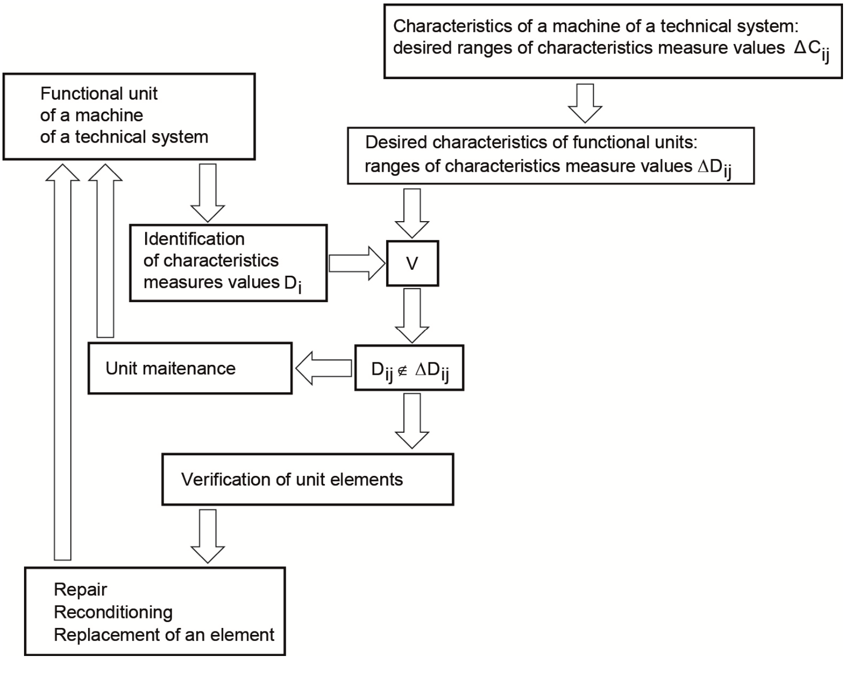

Fig. 3. The maintenance of functional units of machines [2]

3. Diagnostic signals of functional units

Direct measurement of the values of wear margin measurements of functional units is usually not possible. One needs to make an indirect measurement using signals emitted by elements of the functional unit. A relevant algorithm for the identification of the wear margin of the functional unit is shown in Figure 4.

The elements of a functional unit form the so-called nodes. A functional unit may be represented as the sum of the nodes, but the same element of the functional unit may be incorporated into several nodes. In the simplest case, a functional unit may form one node. Three basic models of functional unit nodes can be distinguished by the following (Fig. 5):

1) Two solids are separated by a fluid: The fluid is affected by a hydrodynamic load that excites and determines the movement of the fluid relative to the solids, Fig. 5A.
2) Two solids are separated by a fluid in which phenomena occur typical of fluid mechanics (hydrodynamics, aerodynamics, rheology): One of the bodies, in addition to mechanical load, may be affected by magnetic, electric, or thermal loads. A mechanical load excites and determines the relative motion of solids (Fig. 5B), which is referred to as a *tribological node*.
3) Two fluids are separated by a solid: In addition to hydrodynamic load, the fluids can be affected by thermal, electrical, or magnetic loads. The applied loads cause the relative motion of the fluids and / or relative fluid-solid motion, Fig. 5C.

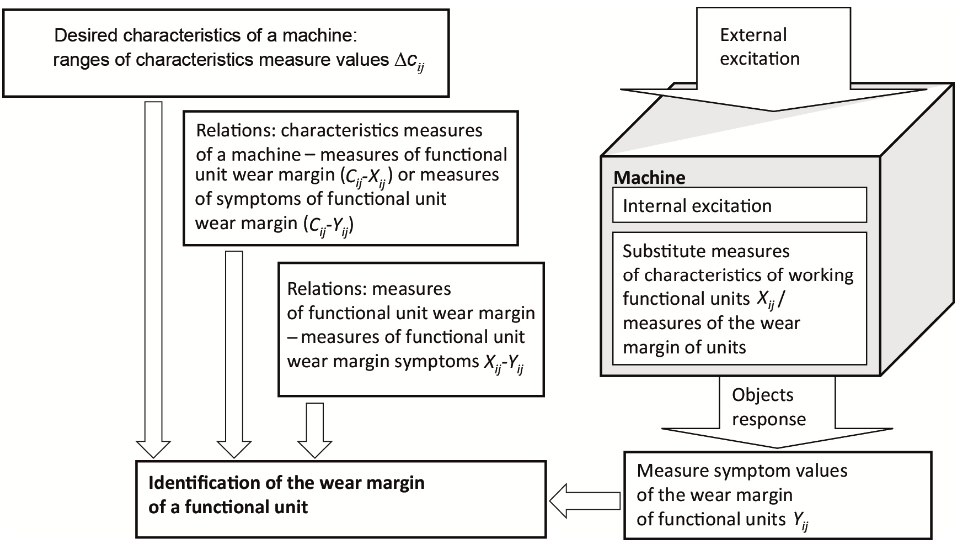

Fig. 4. The algorithm for the identification of the wear margin of a functional unit of a working object [4].

In publications, one can find specific models of the above basic models, which are models that take into account the shape of solids and physical-chemical properties of fluids. Physical-mathematical descriptions of specific models use multi-dimensional and/or non-dimensional factors of proportionality (similarity numbers / criteria of similarity). As factors of proportionality are generally quotients of the values of selected measurements of built-in element characteristics, working fluids, load, and relative motion, we can regard them as substitute measurements of the wear margin of a given functional node (for instance, two functional nodes with the same similarity number have the same value of a given measure of wear margin characteristic).

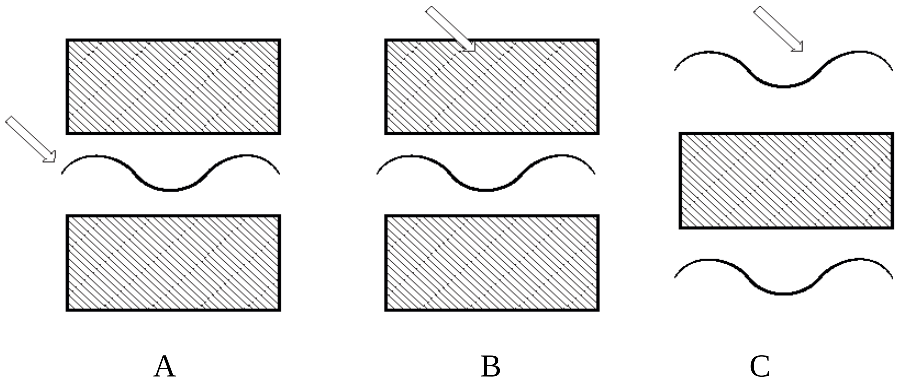

Fig. 5. Node models of functional units: A, B, C – type of model, solid, fluid, direction of conveyed load

If model A represents a pipeline, longitudinal pressure drop depends on the Reynolds number, roughness quotient, pipe diameter, and fluid flow rate and density [7], or in general terms, on the characteristics of built-in elements, load characteristics, and working fluid characteristics. Since pressure drop is measurable, it can be used as a diagnostic symptom of the pipeline wear margin. Pressure drop translates into the energy efficiency of the pipeline, consequently affecting the efficiency of the production system.

Model B is a case of a sliding bearing, where the thickness of the oil film depends on the Sommerfeld number. This number in turn depends on relative backlash (a measurement of a built-in element characteristic), relative rotary speed (movement characteristic), viscosity (working fluid characteristic), and average pressure (load characteristic) [8]. The thickness of the oil film is not directly measurable, but it affects the measurable position of the journal centre in the backlash circle of the bearing. The position of the journal centre may be determined by the measurement of the relative radial vibrations of the shaft. The position of the journal centre determines the mechanical efficiency of the bearing, which affects the reliability and efficiency of the production system.

In Model C, illustrating a heat exchanger, heat transfer from one fluid to another depends on the heat transfer surface area, fluid temperature difference, and a factor of proportionality – overall heat-transfer coefficient k. The value of this coefficient depends on built-in element characteristics (thickness and type of wall material, the conductivity coefficient of wall material, channel geometry), working fluid characteristics (viscosity, density, specific heat of the fluids), movement characteristic (fluid rate), and load (fluid temperature difference) [9]. Fluid temperature differences at the inlet and outlet of the exchanger depend on the coefficient k. Therefore, the coefficient k can be a substitute measure of the heat exchanger wear margin. We can calculate the heat exchanger efficiency from the measurable differences of the inlet and outlet temperatures of the two fluids (diagnostic symptoms of the heat exchanger wear margin).

For specific design solutions of functional units, we can create models that combine specific models. The wear margin of a functional unit can be described by several similarity numbers / factors of proportionality related to symptoms having various energy forms and varied signal waveforms (for a periodically variable load, these signals may have a form of periodical signals). The same signal may be a carrier of many wear margin symptoms.

Due to errors in manufacturing and the assembly of functional unit elements, the wear margin of the unit may reach a limit value immediately after the machine start-up. This may initiate a process of intensive wear that leads to machine failure. Such events are referred to as early failures. Approximately 50% of rolling bearing failures are early failures. The measured values of the characteristics of load, movement, or working fluid other than those given in machine specifications may also lead to a drop of functional unit wear margin to a limit value and initiate intensive wear followed by machine breakdown. Causes of a temporary decrease in wear margin are called disturbances, while conditions causing the permanent wear margin to drop to the limit value are described as 'not intended use of a machine / functional unit'.

Seeking wear margin symptoms when the wear margin measurement–symptom relations are not known, we should analyse the process and effects of wear to properly categorize diagnostic symptoms. Under the impact of loads acting in the functional unit nodes, the response (signal) is generated and node elements are subject to wear, simultaneously. The load conveyed by the node has a certain form and energy value. Similarly, the response of an element node is a signal / signals with a certain energy and distribution in time. Depending on the possible or selected signal energy form, the responses can be divided into the following three cases:

1) The forms of the response of the other body or fluid to the active load is the same as that of excitation. The measured response value is dependent on the wear margin of the node – diagnostic symptom is a symptom of the margin wear of the node.
2) Energy is converted in the unit node, and the form of response energy is different from that of the load energy. Energy conversion is dependent on the wear margin of the functional unit node – the diagnostic symptom is a symptom of the margin wear of the node.
3) The wear of solid materials and fluids in the elements of the unit node is a consequence of the acting load and involves energy conversion. The wear process takes place in three stages: the accumulation of energy (conditions are formed for the progress of wear), wear with the possible formation of defects and particulate matter, and the dissipation of the energy released in the process of wear. The response energy value is dependent on the value of the accumulated energy or on the intensity of the wear process – the diagnostic symptom is a symptom indicating that conditions have emerged for intensive wear or a symptom of wear process intensity (rate).

Detailed relations of between measurements of the wear margin of a functional unit and measurements of functional unit symptoms are specific for a given design solution of a functional unit and must be considered separately.

Summary

One problem when creating systems for the effective and efficient management of production systems is the lack of measurements and limit values of the wear margins of machines. It can be solved by decomposing the desired characteristics of the company into desired characteristics of the machine and by introducing the concept of the wear margin of an operating functional unit.

Measurements of the wear margin of an operating functional unit are substitute measurements, which include measurements of relevant characteristics: material of the elements, free elements, built-in elements, working fluids, load, and the movement of unit elements. The measured values of the wear margin of a working functional unit can be determined only indirectly by using output signals, which are the responses of machine elements to loads. Symptoms extracted from the signals may be wear margin symptoms, symptoms of the emergence of conditions for intensive wear, or symptoms of wear process intensity. Seeking symptoms of wear margin and establishing relations between a wear margin measurement and a symptom measurement, we may decompose a functional unit into nodes and make use of existing node models. In such models, similarity numbers and/or multidimensional factors of

proportionality are substitute measurements of the functional unit wear margin, while measurable physical quantities depending on these measurements may be wear margin symptoms.

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Miary i wartości graniczne potencjału eksploatacyjnego maszyn systemów produkcyjnych

Słowa kluczowe

Potencjał eksploatacyjny maszyn, miary potencjału eksploatacyjnego zespołów funkcjonalnych, identyfikacja potencjału eksploatacyjnego.

Streszczenie

W artykule wskazano na potrzebę opisu zależności między jakością przedsiębiorstwa i jakością maszyny jako obiektu systemu produkcyjnego przedsiębiorstwa, natomiast za niedostatecznie rozwiązany problem opisu uznano miary i wartości graniczne potencjału eksploatacyjnego maszyn systemu produkcyjnego. Wykazano, że w oparciu o pojęcie „jakość” możliwa jest dekompozycja pożądanych cech jakości przedsiębiorstwa na pożądane wartości cech maszyny i zespołu funkcjonalnego maszyny oraz możliwe jest zdefiniowanie pojęcia „potencjał eksploatacyjny maszyny” i „potencjał eksploatacyjny zespołu funkcjonalnego maszyny”. Wymieniono miary cech zespołu funkcjonalnego składające się na wytworzony (rzeczywisty) potencjał eksploatacyjny i wskazano na potrzebę znajdywania miar zastępczych rzeczywistego potencjału eksploatacyjnego. Podano algorytm identyfikacji potencjału eksploatacyjnego oraz typy relacji wymuszenie – odpowiedź węzła zespołu funkcjonalnego. Zaprezentowano podstawowe modele węzłów i uzasadniono celowość ich rozwoju oraz stosowania w identyfikacji potencjału eksploatacyjnego maszyn.