Possibilities of the Application of the Metal Magnetic Memory Method to the Analysis of Gear Durability

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Abstract This paper presents the results of the analysis of the gear transmission conducted by the metal magnetic memory method. A following thesis was formulated: the values of a magnetic self-field in a gear wheel are related to the number of load cycles, load level and distribution along the gear teeth. The paper presents also a diagnostic criterion, which allows to determine whether the occurrence of creep damage in a gear is possible.

1. Introduction

Gear transmission need to comply high standards as for their reliability and durability. Even a small defect in a gear transmission makes its operation impossible. Usually the damage in a gear transmission occurs when a part of one or more teeth breaks. A traditional investigation of the reasons, which caused the damage, involve: the analysis of the gear design, the analysis of the quality of its manufacture and the determination of the operation history with a special respect to the abnormal operation states, which might affect the gear durability.

Standard operation repairs include various diagnostic investigations. They aim to find the already advanced defects. This is insufficient to guarantee a safe and reliable operation. Such investigations provide no information neither about load states in the components nor about new and advancing defects.

The gear teeth are designed with respect to the unrestricted creep durability. However they occasionally break. These accidents require the analysis determining whether the teeth deplete their durability and if so, then why? The obvious mistakes in design or manufacture are of course omitted. The author of this paper believes that the reason of the accidents is the load state and particularly its distribution along the teeth, which differs from the assumed values.

The metal magnetic memory method was applied to the investigations of the accidents. with the believe that the results would allow to find the load distribution, the locations with stress concentration and perhaps the reasons for damages. This paper describes the results and its further application.

2. Metal magnetic memory method

This passive method of non-destructive tests records the magnetic self-field of the investigated component. The self-field is formed around dislocations. Physical fundamentals of the method are well described in [2 ÷ 8, 10, 16]. Not going further into details it may be stated that the method bases on: the magnetic-elastic effect, the diffusion effect at the external magnetic field due to material discontinuity or heterogeneity and the mutual influence between magnetic field and dislocations involving also the accumulation of the dislocations.

The metal magnetic memory method records the distribution of the magnetic field component H on the surface of the investigated part. This distribution reflects to some extents the distribution of strains (stresses) in the investigated part [4].

The basic diagnostic parameter applied in magnetic memory procedures is the boundary line between the areas where the normal component of the magnetic field has positive or negative sign. This is the sign-alteration line $H_n = 0$.

The magnetic texture of a metal is formed during the manufacture process, when the metal cools down below the temperature of the Curie point in the magnetic field of the Earth. Due to the heterogeneous structure of the metal each concentration of the defects in the crystal network forms the nodes of the magnetic domain walls. These concentrations reflect at the surface as the boundary lines between the areas where the normal component of the magnetic field is positive or negative. Laboratory tests proved that this sign-alteration lines mark the area of maximal heterogeneity of the metal structure, which refers to the concentration of the structure defects and in turn to the concentration of internal stresses [4,5, 7].

The formation of the sign change boundary line during the operation of machines has not been yet entirely explained. There are only some hypotheses. The load in a component causes a specified stress distribution. The magnetic-elastic effect describes the influence of the stresses on the metal magnetic properties. A ferromagnetic material subjected to a magnetic field changes its magnetization intensity. The change of the magnetization intensity has two components. The first component vanishes when the load does but the second one remains. The relation between the stresses and the magnetization intensity is very complex. It depends on the material, magnetic field density, the progress of the magnetization, the progress of the load and temperature. Local load changes reflect in local changes of magnetization intensity [2 ÷ 7].

According to [5] the micro-elasticity and permanent displacement of dislocations occur when the stresses cause by external load exceed the level of internal stresses (for a carbon steel this level is not higher than $\sim 0.3\ R_e$). According to [1] the permanent displacement of dislocations occurs when the tangential stresses in the dislocations plane exceed the critical stress value for dislocation slip (which is between $\sim 0.3\ R_e$ and $\sim 0.5\ R_e$). The magnetic self-field and domain boundaries appear in the areas of constant crystal zones and slip planes due to overlapping magnetic and dislocation planes. These domain boundaries formed in planes of dislocation slip under a dynamic load remains permanently also after the load vanishes [2 ÷ 7].

If these boundaries coincide with the area of a high gradient of magnetic field variation then they indicate a location where defects advance very quickly while durability rapidly decreases [2, 3].

The quantitative measure of stresses concentration may be evaluated through a gradient K_{in} (the variations intensity) of the normal component of the magnetic field H_n while crossing the sign-alteration line ($H_n = 0$) - the line of stress concentration.

$$K_{in} = \frac{|\Delta H_n|}{2\lambda_k} \tag{1}$$

where:

$|\Delta H_n|$ - absolute value of the difference H_n between two control points located in equal distance λ_k from the sign-alteration line $H_n = 0$. The line segments λ_k are perpendicular to the sign-alteration line.

The absolute values $K_{in.max}$ refer to the state of the metal before the defect advances. These values in manufacture conditions depend on the geometry of the investigated component, corrosion and creep processes, residual welding stresses, the depth of the defect and various other causes. This leads to a conclusion that applying the $K_{in,max}$ values in the analysis requires considering all possible causes of the defect. That is the reason why a database containing such values is so essential for the diagnostic procedure.

Further details as for the diagnostic parameters associated with the metal magnetic memory method may be found in [2 ÷ 8, 10, 16].

3. Methodology of the analysis for gear wheels [11]

Each teeth contact in a gear transmission causes a cyclic change of mechanical stresses. This in turn results in the change of residual magnetism in a ferromagnetic components. It means that the magnetic self-field of a component changes due to the magnetic-elastic effect. In addition there are local areas of plastic strain on the loaded surfaces of the teeth.

It is assumed that the magnetic self-field of a component results from both factors mentioned above. With this assumption a thesis may be formulated that the analysis of the distribution and gradient of the magnetic self-field allows to:

- Allocate the stresses concentration in the gear teeth and identify teeth or whole wheels, which are likely to damage,
- Determine the stress distribution along the teeth.

The investigated components were the gear wheels with skew teeth from various machines. Their magnetic field was scanned at each of the teeth near its tip. Each teeth has its own distribution of the magnetic field along its width. The tips were chosen according to their geometry and location - meaning whether they were reachable.

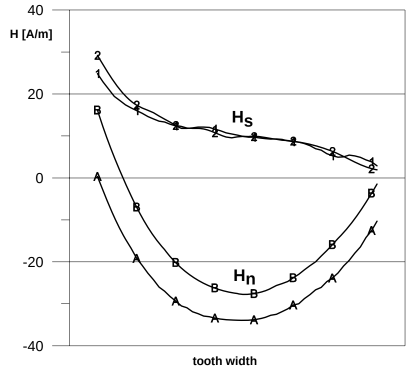
4. The analysis of the variations in the magnetic self-field in gear wheels during an operation

4.1 The aim and scope of the investigations

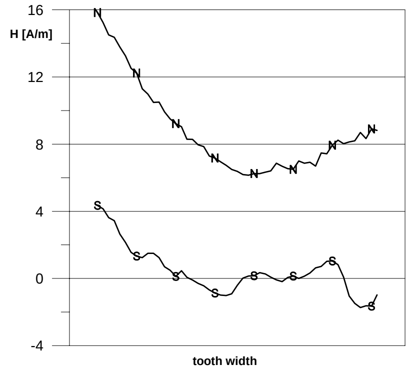
The aim of the investigation was to determine and define in quantitative measures the variations of the magnetic field in gear wheels subject to operation loads. More than ten wheels were analyzed in two series. The first sequence of measurements were to establish a reference level for the already operating wheels. The second measurements were conducted one year of operation later. The results were averaged for the whole wheel to identify the trends of magnetic field variations. The analyzed parameters were the normal H_n and tangential H_S components of the magnetic field as well as their gradients along the teeth. Several examples of the results are shown in the figures 1 and 2 (line 1 corresponds to the first sequence of the measurements while line 2 to the second).

4.2 The analysis of the results

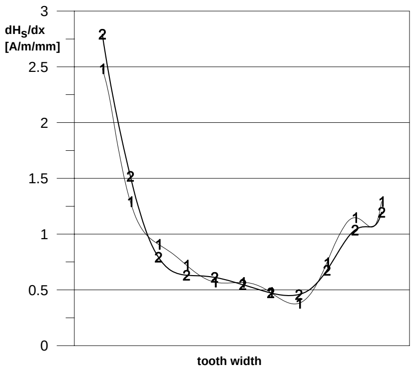
1. The normal component of the magnetic field increased in all of the wheels while its distribution remained unchanged.



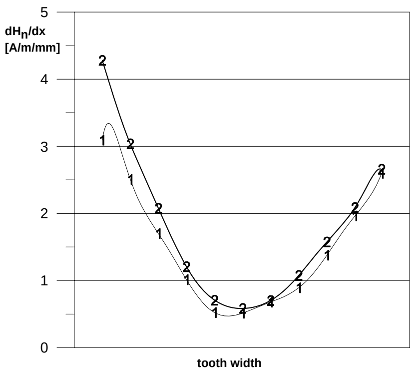
a) average components values in the magnetic field



b) average changes of the components in the magnetic field

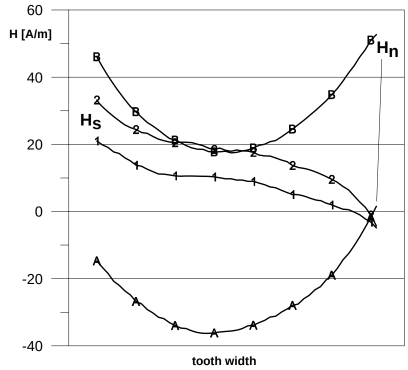


c) average values of the gradient of the tangential component

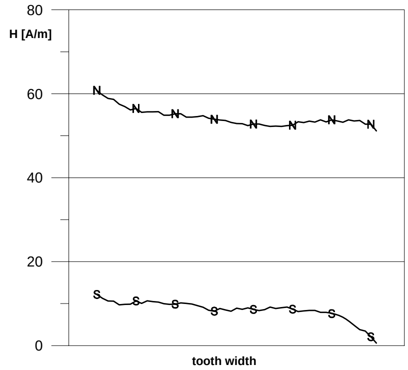


d) average values of the gradient of the normal component

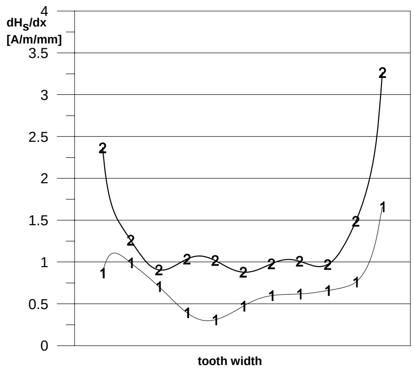
Fig. 1. Gear wheel 1



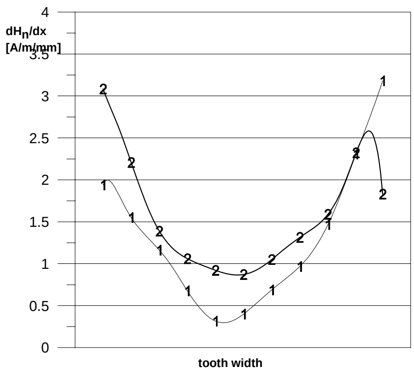
a) average components values in the magnetic field



b) average changes of the components in the magnetic field



c) average values of the gradient of the tangential component



d) average values of the gradient of the normal component

Fig. 2. Gear wheel 2

2. Tangential component did not follow any specified trend. Measurements identified its increase, decrease or no change at all. However the maximal value of this component increased in all teeth.
3. The variations of the magnetic field components were not uniform along the teeth width.
4. The gradients of the normal and tangential component had increased maximal and average value.

The above statements allow to form a thesis that the values of the magnetic field depend on the number of load cycles, load level and distribution along the teeth. However further laboratory tests are necessary to form a specific relationships.

5. Prediction of the creep damage in gear meshing [12]

5.1. Example 1

The gear wheel with a broken tooth is shown in figure 3. Figure 4 shows the distribution of the normal and tangential component of the magnetic field, which were measured along the width of the broken tooth.

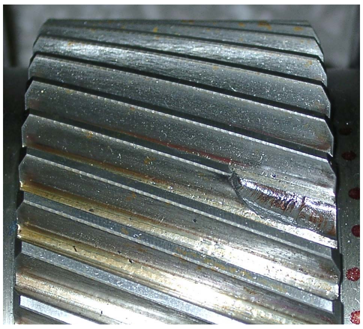


Fig. 3. Gear wheel with a broken tooth

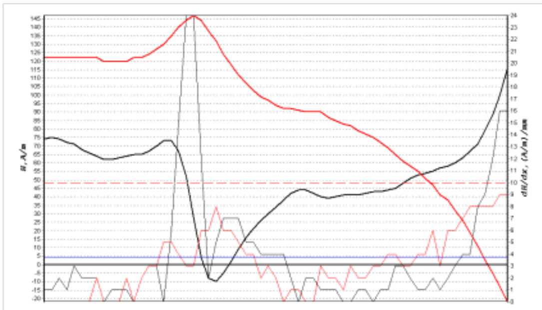


Fig. 4. Distribution of the tangential (black line) and normal (red line) components as well as their gradients

5.2. Example 2

Analyzed gear wheel is shown in fig. 5. Investigation was conducted during a repair of the machine. The chosen results are shown in table 1, where black line marks the tangential component H_S of the magnetic field and its gradient dH_S/dx, while red line - normal component H_n and its gradient dH_n/dx. The analysis stated that about 30% of the teeth had a specific distribution of the magnetic field. However additional non-destructive tests did not detect any possibility of cracks appearance.

Despite the suggestions of the author of this paper the wheel operated further. After several months some of the teeth broke (fig. 6) and the machine was severely damaged.

5.3. formulation of the diagnostic criterion

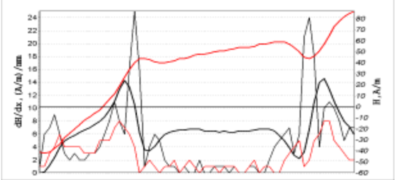
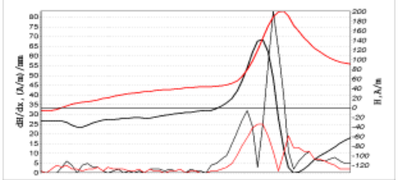
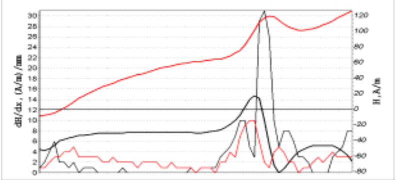
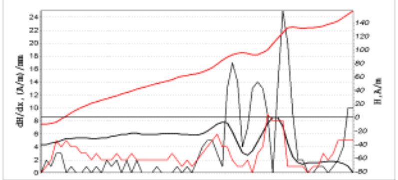
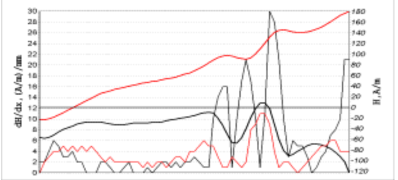
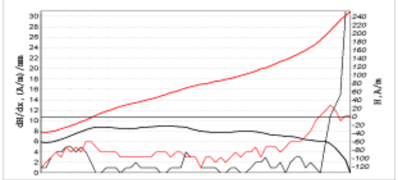
The results of two analysis are presented above. Both identified a specific distribution of normal and tangential component of the magnetic self-field in gear teeth. This distribution included location with extremely high gradient of the tangential component, which often changed from positive to negative values (or vice versa). This location had also a relative extremum of the normal component. In the example 1 such specific distribution was identified after a damage occurred while in the example 2 before the accident. Several other gear wheels were analyzed, which did not have such distribution and still are in operation.

The above allows to form a diagnostic criterion, which determines the possibility of creep damage occurrence in gear wheels. This criterion corresponds to measurements conducted at the tip of the gear teeth.

If a distribution of the magnetic field in a tooth has a high local gradient of the tangential component (often with the change of sign) and relative extremum of the normal component then there is a significant possibility of the damage.

Table 1.

Tangential (black line) and normal (red line) components of magnetic field distribution and their gradients

Tooth number	Graph	Tooth number	Graph
3		6	
13u		15u	
16u		35u	

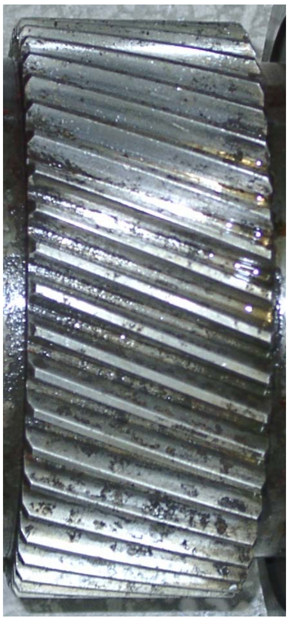


Fig. 5. Investigated gear wheel

Fig. 6. Gear wheel after a damage

6. Analysis of the heterogeneous load distribution along the gear tooth

The previous section introduced the diagnostic criterion to determine whether a damage may occur. The problem is now to assess how long a gear wheel may operate when the damage is identified as a potential treat. One way to solve the problem would be ana analysis of the load on the gear transmission. The data for such analysis may be obtained from the actual coefficient of the heterogonous load distribution.

This coefficient is defined as a ratio of the maximal local load p_{max} applied to a gear tooth per the unit length to the average value p_m calculated for a uniform load [7].

$$K = \frac{p_{max}}{p_m} \tag{2}$$

The results of the investigations presented in section 4 as well as the essentials of the metal magnetic memory method allow to form a thesis that there is a relation between magnetic field distribution and load distribution.

It was further assumed that the average load p_m arising from the transmitted momentum is the same in each teeth and that there is a relation between the ratio of the local load p to the average load p_m in a given tooth and the ratio of the local vector of magnetization intensity H_i to its average value $H_{i,m}$. The latter may be expressed as:

$$\frac{p}{p_m} \sim \frac{\vec{H}_i}{\vec{H}_{i,m}} \tag{3}$$

There are several algorithms, which combine the load distribution in the teeth with the parameters of the magnetic self-field. Examples of the results obtained by application of these algorithms are presented in fig. 7. Although the calculated distributions differ from each other, they are the same as shown in [9]. Only further experiments may decide, which distribution reflects the actual state in the gear wheel.

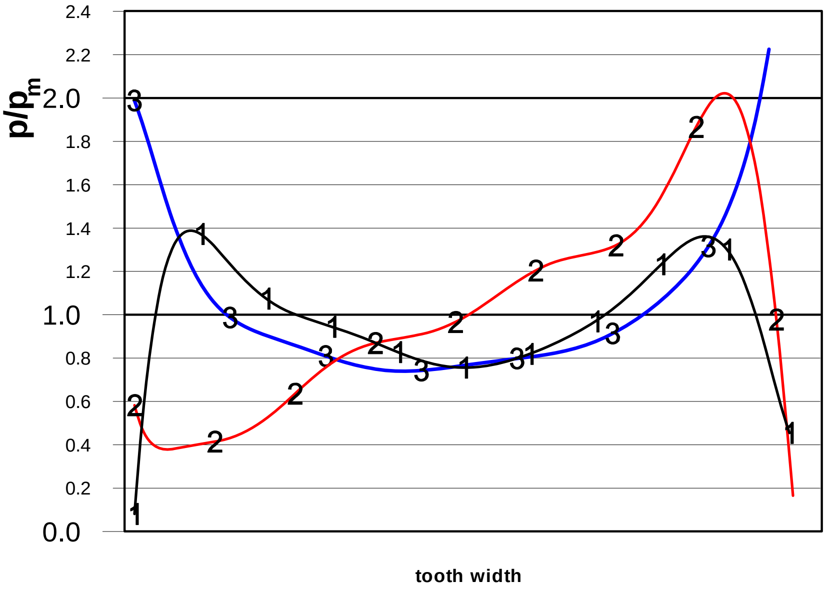


Fig. 7. Average load distribution p/p_m according to the developed algorithms

7. Summary

This paper presents results from the analysis of the gear wheels. The analysis applied the metal magnetic memory method. A thesis was formulated that the values of a magnetic self-field in a gear wheel are related to the number of load cycles, load level and distribution along the gear teeth. A diagnostic criterion was also presented, which allows to determine whether there is a possibility of damage occurrence. The criterion along with the metal magnetic memory method extend the repair diagnostic of the gear transmissions.

The paper suggests also a correlation between the parameters of the magnetic self-field and the load distribution on gear teeth. Results of the calculations conducted according to several developed algorithms are presented.

Further laboratory tests are necessary to verify the presented theses. Such tests should allow to fully measure the reference state of the investigated components as well as control and monitor the load and its distribution along the teeth.

Assuming that the theses are correct it may be stated that investigations of the self-magnetism in gear teeth provide quantitative and qualitive information about the load distribution. Therefore such investigations create a new approach for the determination of the residual durability of the gear transmission.

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