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THE SELECTED MEASUREMENT PROBLEMS IN THE ASPECT OF THE NON-DESTRUCTIVE TESTING OF THE GEAR WHEELS AND THE OTHER PARTS

ABSTRACT

This paper presents an overview of the results of studies which, in addition to the detection of differences in the structure of the product and the thickness of the surface layers, aimed to diversify the signal from the stress changes caused by cracks, assess local defects in the microstructure deformed by heat treatment and detect hydrogen „in statu nascendi". Measurements were performed using Wirotest 1000. Specialized probes were used to allow measurements on surfaces difficult to reach. Measurements were taken at different depths of penetration. Assessment of the correlation of eddy current measurements and microhardness was also performed.

Key words: *eddy current method, gear wheels, microhardness, cracks detection, structural changes*

INTRODUCTION

In the non-destructive testing, the detection of changes in electrical conductivity and magnetic permeability is not the only important thing, but also the ability to distinguish signals from various factors causing a significant change in the comparison with the reference material, or a fragment of the part which is considered to be proper. It is important for the elements in which there are many changes and non-compliances, e.g. the welded joints [1, 2], the gear wheels after heat treatment [3] or the heat exchanger tubes.

In accordance with the applicable standards the selected parts are tested by destructive methods. This kind of control does not guarantee, that we will find all of the defective parts. In order to check all of the components, it is necessary to use non-destructive methods. For example, marking the hardness of the material not only on the cut samples, but also on the finished parts. Surface microhardness value may correspond to different structures, and is not adequate to the core structure.

In the manufacturing conditions, especially with regard to the elements responsible, 100% quality control of the batch size is expected. The test should detect not only cracks, but also changes in the structure. As it is known, the defects in the charge material are the cause of some of the defects revealed after heat treatment. The introduction of interop control of these elements could eliminate the faulty parts before further processes. Detection of the surface and subsurface cracks is performed e.g. by magnetic particle test or fluorescent method. These methods, however, do not reveal changes in the structure.

Non-destructive eddy current inspection of control samples and finished products, can complement the metallographic methods. The advantages of this technique are: very short measurement time, the absence of a coupling agent between the probe and testing material, ease of automation [4]. Eddy current testing is a comparative method. The element that is limiting its use is the need to prepare standards or reference samples appropriate for the testing material and process.

MEASUREMENT METHOD

Changes in the material (geometrical defects, changes of the structure, stress) make changes in its electrical conductivity and magnetic permeability, which in turn causes changes in the intensity of the induced eddy currents and magnetic fields.

Signal value of the Wirotest and the probe depends on:

- the electromagnetic properties of the material,
- the geometric changes of tested element,
- the presence of defects,
- the thickness and structure of the surface layer,
- current frequency,
- parameters of the measuring device.

Before testing, there should be selected a frequency providing the penetration of eddy current on the depth required by the inspection. For example, in the case of testing of the thin layers the depth should be about 0,1 mm.

The eddy current depth penetration is dependent on the electromagnetic properties of the tested material, the fill factor (for the encircling probes), the probe frequency.

In the study there were used:

- WIROTESTS production of IMP, portable and stationary, designed for research in laboratories, on production lines and to work in field conditions (e.g. Wirotest 1000 – Fig. 1).
- PROBES production of IMP - each adapted to the expected range of use, also for testing small components and hard to reach surfaces (Fig. 2).
- Standards and reference materials appropriate for the type of research.

Fig. 1. Measurement device: Wirotest 1000

In eddy current measurements the output signal is originating from a relatively large area, which depends on the field of view of the probe (as opposed to point determinations microhardness). The size of the field of view of the probes depends on their build and ranges from about 4 mm to several mm. In the present work the field of view of the probes had a diameter of approximately 4 mm. The diameter and height of the encircling probe were adapted to the dimensions of the tested products.

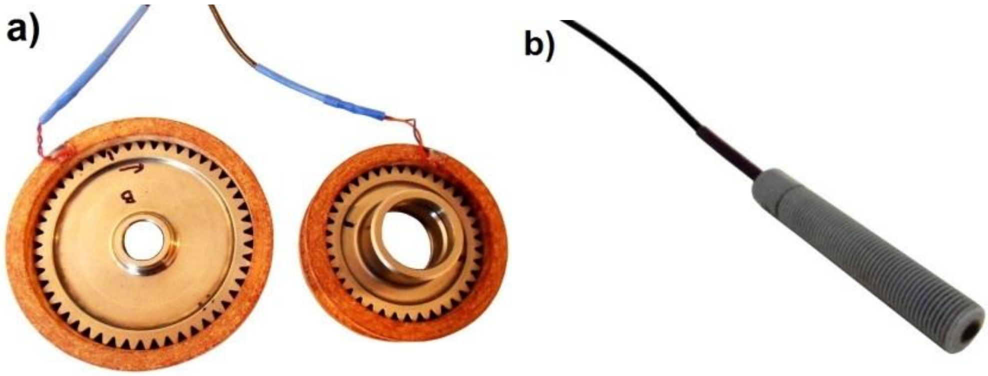

Fig. 2. The encircling probes (a) and pencil probe (b)

Measurements of the microhardness on the tested samples were performed with hardness tester Struers DuraScan 70.

THE QUALITY TESTS OF GEAR WHEELS

In the case of gear wheels tests we are dealing with the occurrence of cracks, non-uniformity of structure and stress gradient. The compression stress is formed in the induction hardening process in toothed-wheel rim. The value of the stress varies with depth of the layer. Structural stresses are caused by the change in volume (martensite - the largest volume, austenite - the smallest). The resulting compressive stresses, through their slow decline, counteract the tensile stresses. The decrease in hardness is caused directly by increase of the tensile stresses.

The stresses in the surface layer are characterized by a large gradient. The tensile stresses can lead to cracks and hard-detectable microcracks of surface layer.

In quality control it is important to differentiate the signal from the stresses and the signal from the cracks.

In the works [3, 5, 6] there were presented the results of measurements of the characteristics of eddy current caused by cracks, changes in stresses and structure. In the remainder of this work the example graphs were featured.

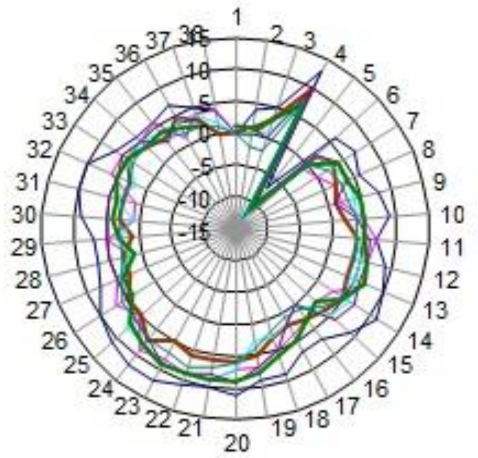

Fig. 3. Graph of Wirotest's signals on the circumference of the gear wheel (at the base of the tooth) after the process of hardening, tempering and sweep

Figure 3 shows a radar graph of the gear wheel after the process of hardening, tempering and sweep. There is a crack visible on the tooth No. 4 and structural defect on the tooth No. 5.

To test the influence of the natural cracks (causing stress relaxation) and notches, on the measurement signal value, studies were carried out on the experimental gear wheel (side B, 38 teeth). On the tested gear wheel, in which a deep crack was detected microscopically on the tooth No. 4, there were made notches of different depths by using a diamond circular saw with a diameter of 12 mm and a thickness of 0,1 mm (Table 1).

Table 1. *The depth of the notches on the teeth of the experimental gear wheel*

The tooth number	15	22	26	29	32	36
The depth of the notch [mm]	1,5	0,1	0,3	0,5	0,75	1,0

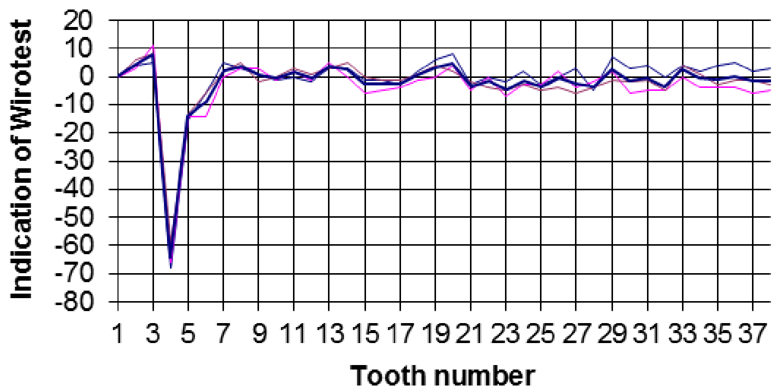

Fig. 4. Graph of the decomposition of Wirotest's signals around the perimeter of the experimental gear wheel before performing the notches

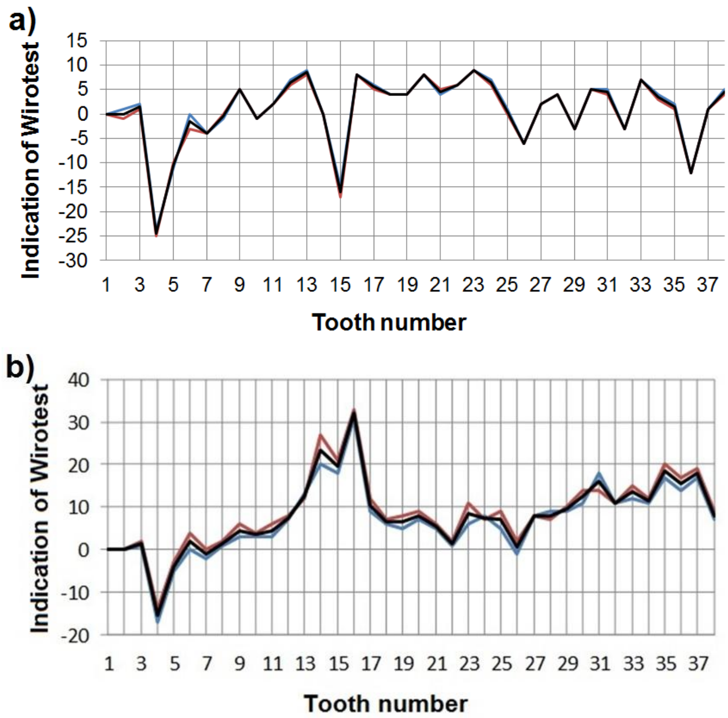

Fig. 5. Graph of the decomposition of Wirotest's signals around the perimeter of the experimental gear wheel by using the pencil probe (after performing the notches): a) standard probe 250 kHz, b) probe AHF 4 MHz

Figure 4 shows a graph of Wirotest's indications for the gear wheel before performing the notches. The graph shows a decrease of the signal value at place of the natural crack occurrence (tooth No. 4). As a result of notching, a local work hardening of the material occurred, causing a local stress increase (Fig. 5). Positive peaks are visible on the teeth No. 14 and No. 16 (caused by the local damage), whereas on the tooth No.15 there is a visible difference which is a result of the deep loss in the material. The teeth No. 32 and No. 36 have notches with a slight damage to adjacent teeth. Attention should be paid to the signal peak on the tooth No. 26, where microscopic observations revealed mechanical surface damage.

As can be seen from the comparison of the graphs, the Wirotest's signal value from the cracks is negative (comparison Fig. 4 and Fig. 5a), whereas the compressive stresses cause an increase in the signal (comparison Fig. 4 and Fig. 5b).

The possibility of differentiation between the signals from the stress relaxation caused by the natural cracks and signals from notches was confirmed. The high-frequency probe differently detects natural cracks - tooth No. 4 (relaxation of the compressive stresses) than notches with the deep plastic deformation: the teeth No. 14 and No. 16.

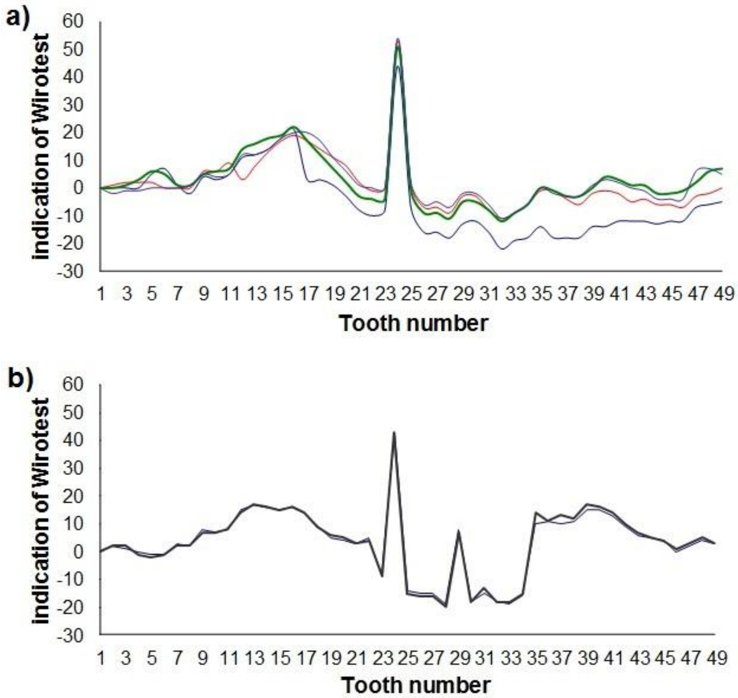

Fig. 6. The eddy current characteristics of the gear wheel on day 24.06.2010 (a) and 05.12.2011 (b)

One of the studies was to examine the effect of storage time on the eddy current characteristics of the gear wheel (Fig. 6). The shape of the characteristic curve has changed after 15 months of gear wheel storage. Characteristic peak on the tooth No. 24 from the crack has remained, however on the tooth No. 29 additional peak occurred. Based on the photomicrograph, it was confirmed that the cause is the occurrence of microcracks in the area tested. There is also an increase in the tensile stresses in the area between the teeth No. 35 and No. 41. Based on the measurements carried out with probes of different work frequency, the possibility of distinguishing the signals from the stresses and cracks was confirmed. The ability to analyze the state of the gear wheel after a period of storage was demonstrated.

ASSESSMENT OF STRESS STATE CAUSED BY THE PENETRATION OF HYDROGEN WITH USING THE EDDY CURRENT METHOD

The penetration of hydrogen causes stresses in the material. At the Institute of Precision Mechanics there has been developed a method and equipment for examination of the stresses with the eddy current method [7]. This method can be also used to evaluate changes in stress state caused by the penetration of hydrogen [8].

In the hydrogen charged steels, damages such as cracks and blisters can occur, both in the surface layer and in the depth of the material. These defects are caused by not only the hydrogen trapping, but also the formation of significant internal stresses caused by local magnification of the network parameter due to hydrogen charging. Using Wirotest it is possible to determine the rate of desorption of hydrogen from the Armco iron after electrolysis process, as well as the stresses resulting from presence of trapped hydrogen [8].

THE SUITABILITY OF ENCIRCLING PROBES FOR GEAR WHEELS TESTS

In gear tests, the change of eddy current signal can be caused by various factors. For rapid control of the whole set, e.g. from a batch, encircling probes were developed and tested. Encircling probe averages eddy current signal from the whole surface of the test and signals which details are different from the pattern or from the rest of the set. The eddy current results were validated with indications of microhardness. Microhardness is used as the basic method of quality control. It is known, however, that not only the microhardness, but also the layer structure affects the reliability of parts. It is also known that in some cases the specified value of microhardness may correspond to different structures. The microhardness of the surface is not adequate to the core structure. In previous studies it was observed that the eddy current measurements can detect this type of discrepancies [6].

Examples include the results of cams series testing and the gears and shafts measurements described later in this work.

The gear wheels tests

Gears with outer diameter Ø41 mm, made of steel grade 36NiCrMo16 were the object of the measurements. After the heat treatment, gears were quenched to 40 HRC hardness, and then nitrided in the low temperature plasma [9]. Eddy current measurements were performed using Wirotest 1000 and encircling probes with nominal frequency: 2,5 kHz, 5 kHz and 10 kHz. Microhardness indication of test samples was performed using Struers DuraScan 70. The gears test was performed as part of the subject.

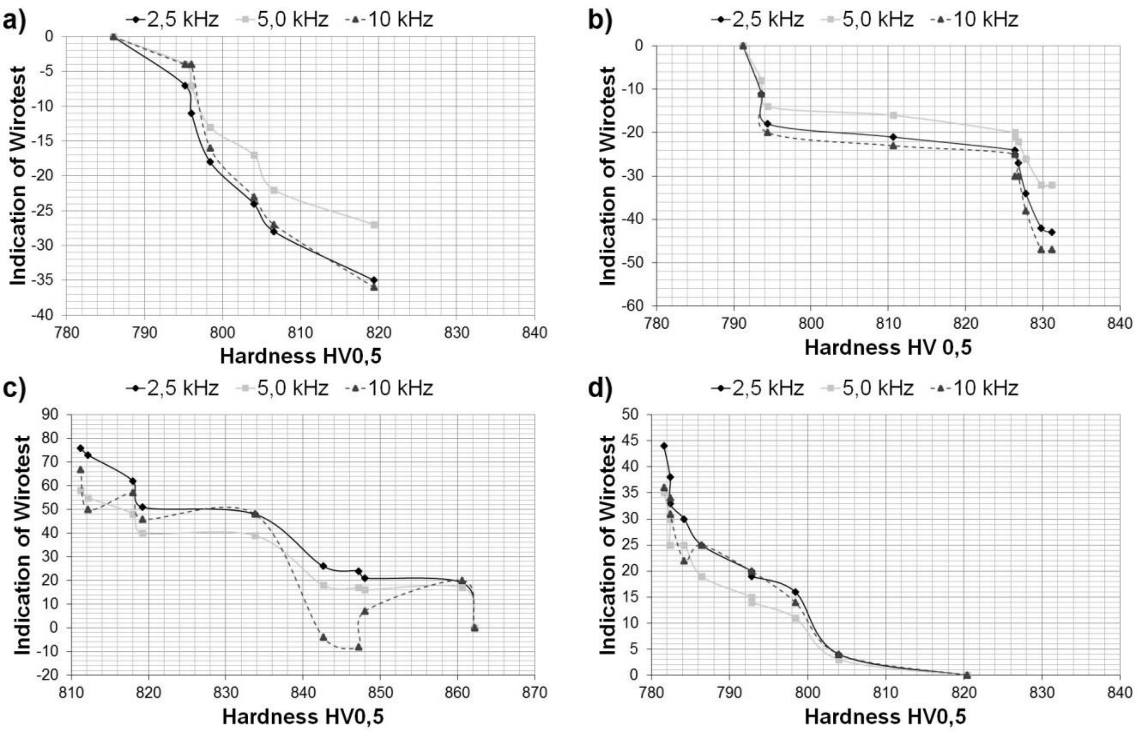

Fig. 7. The dependence of the Wirotest's signal from the gears microhardness HV0,5: a) process 9/2014/PZ, b) process 10/2014/PZ, c) process 11/2014/PZ, d) process 12/2014/PZ

Figure 7 shows the dependence of the Wirotest's signals from microhardness HV0,5 determined for 10 samples of each of the four processes of manufacturing.

In all of the processes, the microhardness above 780 HV0,5 was obtained - according to the customer's requirements, however the dependence of the eddy current signal from microhardness was not rectilinear. Deviations were particularly evident in the process 10 - there are 3 groups of gears clearly visible, with different eddy current characteristics. This applies in particular to gears of microhardness ranged from 827 to 832 HV0,5. After the analysis of the results of work [10] differences in the thickness and structure of the nitride layer can be expected.

Figure 8 shows the distribution of eddy current signals for the whole batch of 90 pcs gears received in the process 12. For the reference level, 820 HV0,5 value was taken – Wirotest's signal = 0. Measurement time of 90 gears using encircling probe was 30 min.

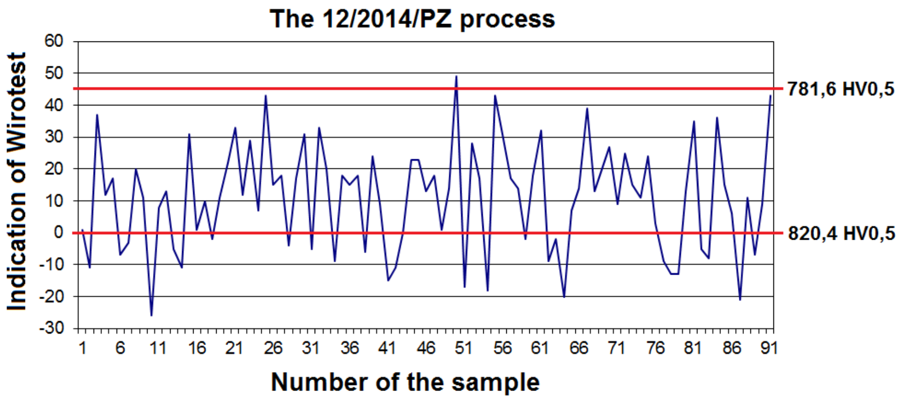

Fig. 8. The eddy current measurement of 90 gears from the process 12/2014/PZ using 2,5 kHz encircling probe

In Figure 8 a level corresponding to the 820 HV0,5 hardness was indicated. Only sample No. 50 is characterized by a hardness below 780 HV0,5 (the highest Wirotest's signal). The hardness of some gears is higher than 820 HV0,5 (Wirotest's signals below zero).

Shafts tests

Samples with the following dimensions were used as a material for testing: outer diameter Ø44 mm, height 30 mm. These samples were cut from rolls of 40HNMA steel after quenching and tempering. Samples had different tempering temperature and hardness. Eddy current signal was determined using pencil probe - 3 kHz. The markings of the samples after tempering process at different temperatures, for which were obtained different values of hardness and Wirotest's indications, are presented below:

- A - tempering temperature 430°C, 45 HRC, Wirotest's signal = +7
- B - tempering temperature 490°C, 40 HRC, Wirotest's signal = +33
- C - tempering temperature 540°C, 35 HRC, Wirotest's signal = +61

After eddy current measurements notches were made on the samples, using electrospark machining reference - with width 0,25 mm and depth from 0,2 to 2 mm. The notches were made on one side of the sample, at a distance of 15 mm from the edge.

Eddy current measurements were performed using Wirotest 1000 and encircling probes with nominal frequency: 2,5 kHz, 5 kHz and 10 kHz. Microhardness indications of test samples were performed using Struers DuraScan 70. Test results were shown in Table 2.

Table 2. *Results of microhardness and eddy current signals from 40HNMA steel shafts*

Tempering temperature	Notch 0,2 mm		Notch 0,5 mm		Notch 1 mm		Notch 2 mm	
	Hardness	Wirotest's signal	Hardness	Wirotest's signal	Hardness	Wirotest's signal	Hardness	Wirotest's signal
430°C	442HV1	0	444HV1	-4	446HV1	-10	442HV1	-16
490°C	408HV1	66	406HV1	45	415HV1	36	406HV1	30
540°C			372HV1	96	378HV1	86		

The data of Table 2 show that the encircling probes detect changes in hardness and material defects. The possibility of sorting parts according to the hardness (type of heat treatment) was confirmed, as well as the opportunity to identify parts with defects in materials.

Cam tests

Measurements were performed on the cams, which were subjected to the same treatment process as gears (section: The gears wheels tests). Tests were done on series of 10 pieces of cams. The measurement results were shown in the graph of dependence of the Wirotest's signal from the surface hardness of the cams (Fig. 9).

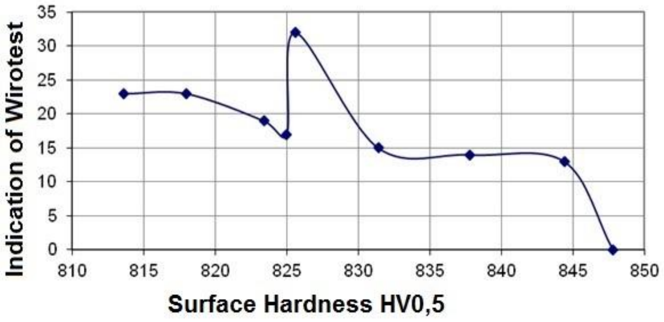

Fig. 9. The dependence of the Wirotest's signal from the surface hardness of the cams

For two cams: No. 5 and No. 8 the surface hardness was the same – about 825 HV0,5. Measurements with a 10-times higher indenter load (HV5) revealed a difference in hardness in the deeper layer. The cam No 8 has a lower hardness than a typical cam No. 5. These results were confirmed by eddy current method. Higher signal corresponds to a lower hardness - similarly as in measurements of the other samples (Table 3).

Table 3. *Results of microhardness and eddy current measurements for cams No. 5 and No. 8*

Cam No.	Surface hardness HV0,5	Hardness HV5	Wirotest's signal
5	825,0	755	17
8	825,6	733	32

CONCLUSIONS

- A review of measurement problems encountered during quality control of gears was made.
- A new type of encircling probes to the pre selection of gears, in particular under production conditions was developed.
- An assessment of the correlation of eddy current measurements and microhardness measurements was presented.
- The possibility of detecting deviations was ascertained, which were not detectable using microhardness measurements.
- The use of encircling probes could allow rapid control of all of the elements and complement destructive tests.

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