

Non-destructive hardness / microstructure testing of heat-treated parts by mass production, with multiple frequency magnetic induction method

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Abstract

Increasing quality demands, new product liability regulations, as well as international market networks force manufacturers to take special measures encompassing the field of material testing. Nowadays, specified tolerances are extremely small. Therefore, processes have to include the conducting of 100% material, structure and hardening tests on a fast, reliable and simple basis. The technology applied must be the latest state of art, it must comply with maximum safety requirements and be economical.

Introduction

Today, every company carries out spot checks during manufacturing, in order to guarantee the quality of products. Within the framework of control one of the most important problems is to ensure repeatability of quality. Quality control faces major problems within this area; these might start with supply of the material or products.

Parts properties, i.e. structure, hardness, or case depth, which are determined by the heat treatment process, are subject to variations. To ensure the correct heat treatment results, a fast and efficient test method is needed, it should be non-destructive.

It must be clear that heat treatment is not a standard statistical process, each heat treatment batch is a separate production that is not related to the previous one. In a continuous belt furnace, a quasi-statistical process is given; however, a spot check here can only provide limited information about the entire production. The heat treatment company provides only a process which can be verified by spot check, which does not guarantee all other parts comply the specification.

Computer based multi-frequency eddy current testing stations with 8 standard test frequencies and up to 16 test positions have significantly increased the efficiency of this test method. The field of application ranges from testing the microstructure, hardening and case depth to material mingle. One of the outstanding advantages of modern eddy current testing systems using Preventive Multi Frequency Testing (PMFT) is the ability to detect unexpected faults.

History

Magnetic test methods have been used since the beginning of the 1940s. Springer [1] and Maercks [2] have already made their publications in 1941. Figures 1 and 2 show the

permeability measuring device they used with a magnetic coil sorting device.

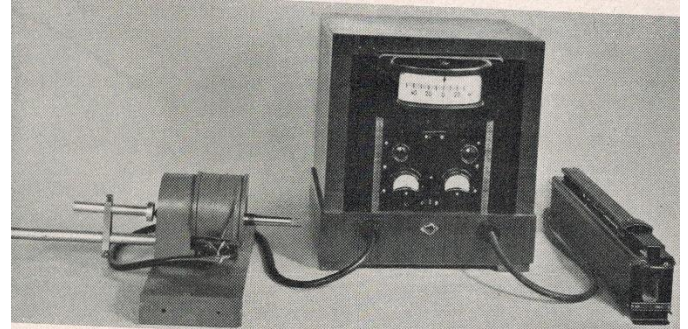


Figure 1 - Magnetic test system from Springer, laboratory setup [1]

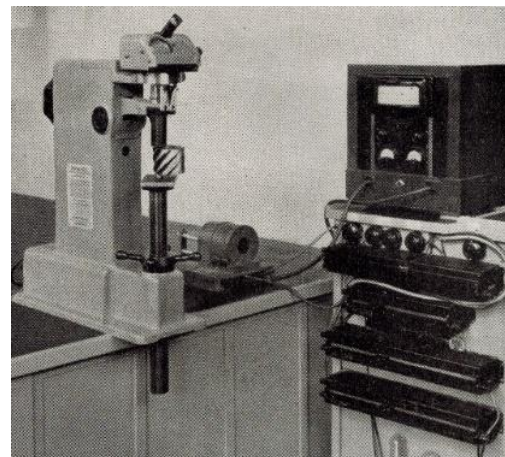


Figure 2 - Magnetic test system from Springer, industrial test system [1]

Both describe successful sorting tests for the sorting of differences in hardness of high-speed steel and hardness depth differences after case hardening on gears.

WHY 100% TEST?

Variation in product usually is in accord with statistical analysis and can be predicted or estimated. For this reason, it is sufficient to make a certain number of spot checks in order to conclude the general nature of the quality from the test data. Table 1 shows typical tested parts [3].

Table 1

<i>Application Examples of Material Testing by Means of Eddy Current PMFT</i>	
Component f. e.	Parameters to be tested
Bearing parts	case depth, structure and hardness pattern
Axle components	case depth, structure and hardness pattern
Pinion pins and axles	case depth, structure and hardness pattern
Linear guide components	case depth, structure and hardness pattern
Steering racks and the like	case depth, structure and hardness pattern
Gears	case depth, structure and hardness pattern
Cam Shafts	case depth, structure and hardness pattern
Bolts, Screws, Nuts	Structure, hardness, decarburization
and much more	

Problems develop if during manufacturing some occurrences arise which are not subject to standard statistical distribution. First, one needs to know what may happen unexpectedly. Table 2 lists possible hardening faults [3]. We also have to keep in mind that materials are not perfect and can have flaws nobody expected.

Table 2

Possible hardening errors during Heat Treatment		
Which parameter was incorrect?	In which way was it incorrect?	What are the effects of this?
Austenitizing temperature	too high	Overhardening, incorrect structure martensite + residual austenite
	too low	Underhardening, incorrect structure martensite + bainite + ferrite
Austenitizing time	too long	Overhardening, case too high, incorrect structure martensite + residual austenite
	too short	Underhardening, shallow case, incorrect structure martensite + bainite + ferrite
Quenching	too fast	Incorrect structure, cracks martensite + residual austenite
	too slow	Incorrect structure martensite + bainite + ferrite
	formation of vapor bubbles	soft spots not defined

Tempering temperature	too low	Hardness too high
	too high	hardness too low
Tempering time	too short	hardness too high
	too long	hardness too low
Rate of feed by induction hardening	too slow	shallow case, misplaced case, austenitizing time too short
	too fast	case too high, misplaced case, austenitizing time too long
Damaged inductor	undefined	undefined
Mal-positioning by induction hardening	undefined	unsymmetrical hardening pattern, overheating, melting

HOW DOES EDDY CURRENT TESTING WORKS [4]

Eddy current testing work with coils, generators, ac-current and ac-voltage, frequencies, field strength and induction law. Eddy current test examine them for their metallurgical microstructure, thus for their mechanical features like hardness, case depth or alloy. The eddy current test does not provide absolute values (e.g. "56 HRC" or "2.6 mm case depth"). The eddy current test does detect fine differences in micro-structure with high sensitivity. In the production line, within a fraction of a second, a non-destructive 100% test for microstructure including:

- case depth
- hardness run out,
- hardness pattern
- tensile strength
- carbon content
- soft spots
- surface decarburization

is completed, and thus quick corrective reactions to any variance from the specified structure can be realized. With a suitable mechanical part handling arrangement, the transport from the hardening station to the test station takes only a few seconds. Faulty parts are immediately detected and separated, which provides enormous savings in time and costs!

The energy for eddy current testing is very small, in the milliwatt range. Field strength is low and permeability is in the range of the initial permeability. Test frequencies ranging from Hz to hundreds of kHz levels provide information on undesired structures via the frequency dependent penetration depth of the eddy current and on the formation of permeability. Very small electrical signals require a very precise evaluation in order to assure their differentiation from ambient interferences. A small drift from variation in temperature and high long-term stability is absolutely necessary. Digitization of input voltages

immediately at the front end of the electronic evaluation is of huge advantage. Relative permeability (μ_r) is strongly affected by heat treatment. The amount of carbon and other alloy elements significantly influence the size and course of the permeability curve. Generally, hardened (stressed) structures have lower permeability than soft structures (refer to graph of 0.78% C), see Figure 3.

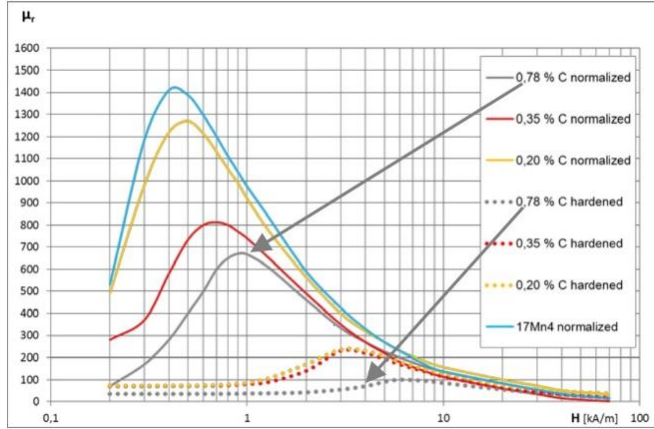


Figure 3 - Relative permeability of different materials

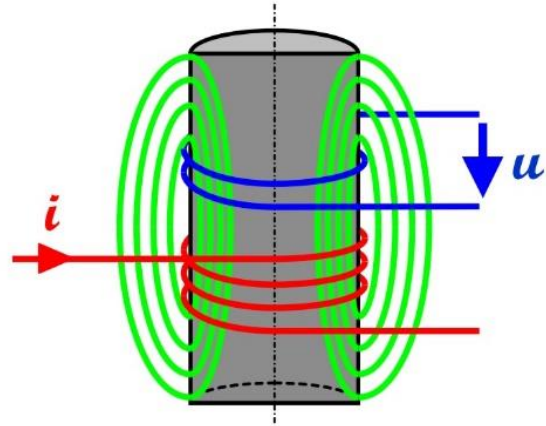
Electrical conductivity (σ) is influenced only a little by structure changes and alloy differences, whereas the conductivity of carbon steel is $< 10 \text{ MS/m}$ high-alloyed chrome-nickel is about 1.3 MS/m . However, the temperature coefficient is about 4 to 5 % per 10°C . Thus, the temperature of the test part has influence on the test result and should be allowed to vary only negligibly ($\pm 5^\circ\text{C}$).

How can magnetic and electrical changes that correlate with the mechanical properties be quickly and reliably tested non-destructively?

Eddy current testing has proven to be well qualified for it, which is a “comparative test”. Values of OK parts (reference parts) which were presented to and stored in the instrument beforehand are compared with the values of currently produced parts.

How can one get values? The alternating current i which flows through the red coil created a magnetic flux $[B]$ through the test part (grey in the sketch). The size of the magnetic flux and thus the size of the voltage u induced in the blue coil is directly dependent on the electrical conductivity (σ) and the magnetic “conductivity” (permeability $[\mu_r]$) of the test part in the coil, Figure 4.

Figure 4 - Test part in coil



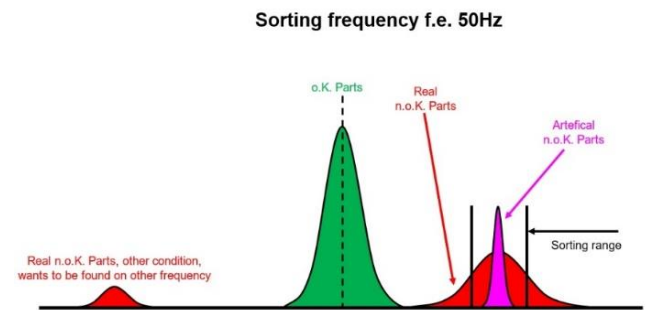
The test part by its σ and μ_r strongly influences the coupling between sender coil (red) and receiver coil (blue). Thus, voltages induced in the receiver coil imply the structure, e.g. to verify correct hardness, case depth, core hardness as well as alloy. This complex signal is displayed two dimensionally as vector (complex number).

Check against known faults

First of all, we have to determine how faults occur in the heat treatment process. In principle, they do not arise as expected faults, but they always arise as unexpected faults. If an eddy current test system is set to an expected fault, these setting master must be manufactured under controlled conditions. This means that the unexpected real faults never look like artificially created faults, furthermore only this one specially calibrated fault can be found. Another fault will not be found and go into production and will be installed e.g. in an engine.

An expected error will not be sorted out, the processes must be adjusted so that this error cannot occur. Figure 5 shows the possible distributions of OK parts, artificial NOK parts, real NOK parts and unexpected fault parts, clearly showed the not all faults will be sorted out by the method with expected artificial faults. The real NOK parts lift a larger spread than the artificially manufactured parts, that means not all NOK parts will be sorted out. The unexpected fault will not be found.

Figure 5 – Error distribution real and artificial NOK parts



If permeability is tested with a single magnetic field strength HS, test results may be unreliable as soon as other types of mixed parts become involved. Let us take a typical mixed part test of two kinds of steel: C45 and 23NiCrMo2. The largest difference in permeability is at HS. This test can be done with

a single frequency test instrument set up with that field strength, because this setting provides the largest difference between both, Figure 6a.

What occurs if another material, e.g. X40Cr13 is mixed up unexpectedly and tested? The example in Figure 6 b shows that the permeability curve of C45 crosses the curve of X40Cr13 at HS (red circle). A differentiation with one field strength (frequency) is not possible. Both remain mixed up in spite of the eddy current test [4]. That means there is no separation.

Figure 6a - single frequency test with limited test range to a defined known error

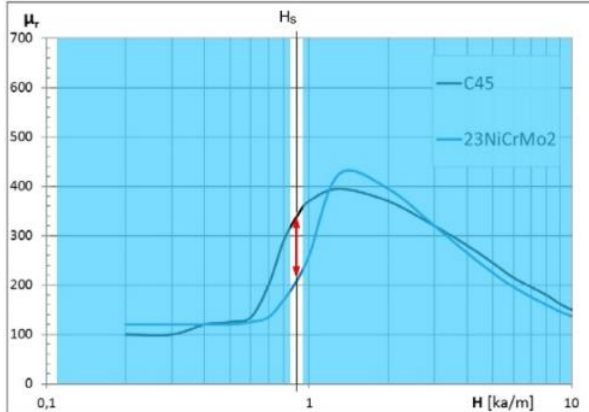
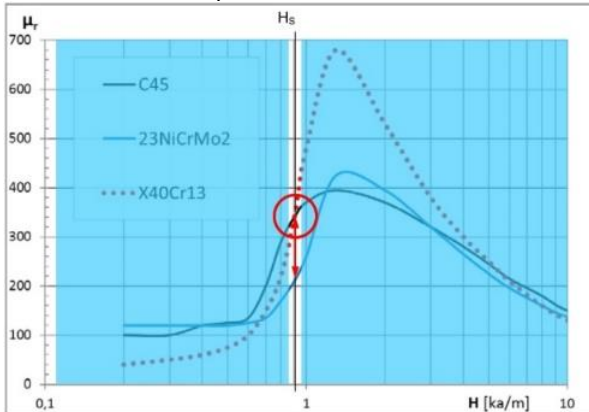


Figure 6b - single-frequency test with limited test range to a defined known error and an unexpected error that is not found



Check against unknown faults

If we want to sort against an unexpected fault, we need a completely different approach to the testing task. We need a technique, which

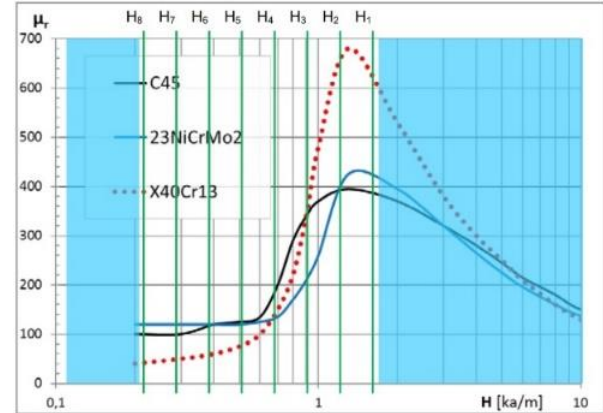
- has the ability, to calibrate only with OK parts
- a broad spectrum of tests and many test frequencies
- fast enough
- provides maximum warranty to find unexpected errors

Eddy current testing, especially PMFT offer this and is applicable for a large range of uses. It has been successfully introduced worldwide to test all kinds of material, including the determining of microstructure and hardening characteristics. There are numerous applications for such a system.

How it works?

The use of several test frequencies to induce different field strengths (H1-8) in the coil means that all these differences are detectable or viewable. Different structures from different heat treat methods (and by heat treat process faults) create different permeability curves which are detected. Thus, the eddy current testing becomes reliable, expected and unexpected wrong structures are detected. Different to Figure 6a+b, Figure 7 shows the “curtains” be moved aside in order to widen the view. The test take place at different field strength, so to say “preventively” over a larger area.

Figure 7 - closed curtains be moved aside in order to widen the view, unexpected errors will be detected



If several frequencies of alternating current are used, a voltage vector is obtained for each frequency in the impedance, and there is a locus curve. Of course, other factors also influence the induced voltage. The position of the test part in the coil, geometric variances in the test part and other factors alter the received voltages. These factors must therefore be controlled. Nevertheless, received voltage values of several OK parts will always vary slightly. They are subject to scattering. The vector tips of the voltages form a cloud (refer to the green dots at 4 kHz). If the vector tips are now enclosed with an elliptical tolerance zone, the test can be reduced to a comparison of the vectors to inside (OK) or outside (NOK) of the tolerance zone. Testing current production with such a frequency band (eight frequencies), Figure 8 a, and the comparison with the previously created tolerance zones made with good parts has become well known in professional circles as PMFT. A quite wide frequency band (at least 1:1000) is used in order to detect all abnormal structures detectable by eddy current as faulty and to sort them out. Ten to twenty OK parts only are needed to setup the instrument and to form the tolerance zones (calibration). A challenge test with NOK parts (e.g. not-hardened, incorrectly quenched, austenitizing temperature not reached, too short or too long tempering, annealing temperature too high or too low, etc.) can be done, but is not needed. The test system will reliably detect faulty parts with both known and unknown defects. The multi frequency test method works reliably for all kinds of defects which may happen during heat treatment of steel. It works like a fingerprint comparison, only when all parameters are 100% fit, a part will be recognized as OK, Figure 8 b [5].

Figure 8 a – Test range with 8 test frequencies and tolerance fields

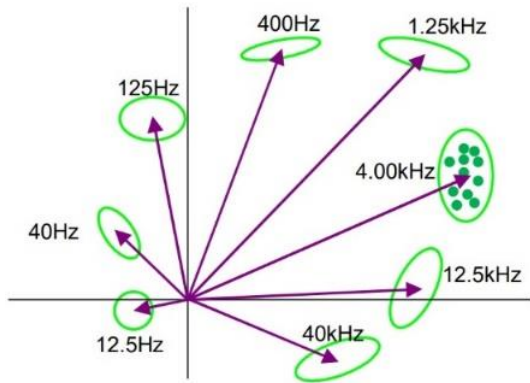
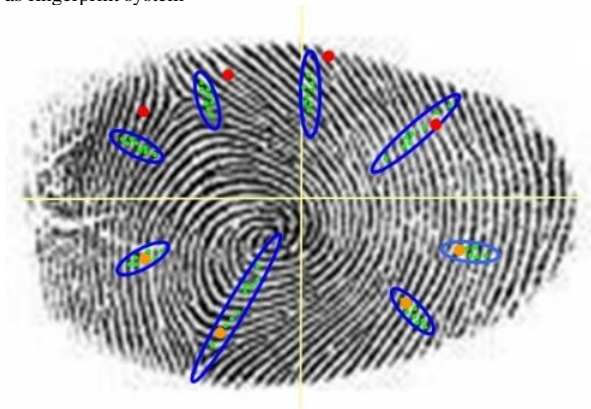


Figure 8 b - Test range with 8 test frequencies and tolerance fields, shown as fingerprint system



Only if all tolerance fields are matched part will be OK, if only one tolerance field is not matched, the part is sorted as NOK. [5]

Careful choice of OK parts is a precondition to reliable testing. One or several NOK parts (red dot), Figure 9, included during calibration blows up the automatically formed tolerance zones, and the instrument's sensitivity is deteriorated. Vectors of bad parts must be deleted before the actual test is started.

Figure 9 – Tolerance field included a NOK part



PRACTICLE EXAMPLES

USED TEST SYSTEM

Modern test equipment, which are fulfilling all the described requirements are few. Only one test equipment meets the requirements of PMFT perfectly, Figure 10 a + b shows this equipment.

Figure 10 a – eddyvisor® Eddy Current test system
Company pictures, *ibg Prüfcomputer GmbH*



Figure 10 b – Test coils
Company pictures, *ibg Prüfcomputer GmbH*

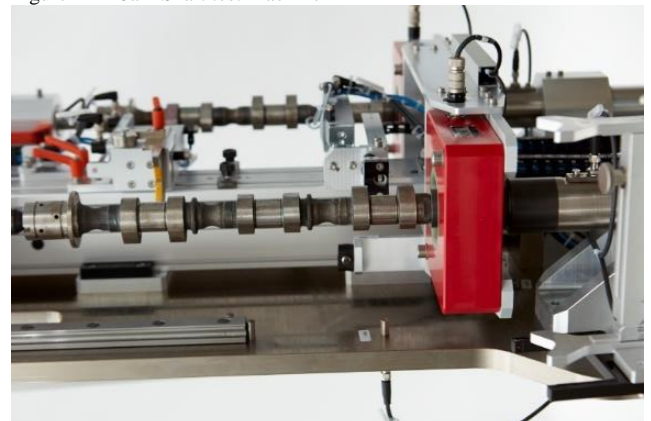


INSPECTION OF INDUCTION HARDEND CAM SHAFTS

Forged camshafts are inductively hardened in the series. In this example, the camshafts are automatically tested in a test machine in the production line Figure 11. Checked for:

- case depth
- structure
- hardness pattern
- material mix

Figure 11 – Cam Shaft test Machine



INSPECTION OF SCREWS

Screws and other fasteners are extremely important high-security components throughout different industries and construction industries. The failure of a screw can lead to production stoppages or serious accidents. In the fastener industry is the permissible error quantity less than 1 ppm.

For this reason, more and more testing machines will be equipped with PMFT. Figures 12 a + b shows such a high-speed testing system for screws, the test speed is appr. 10-15 parts/sec. In this system, with a turntable, with newly developing U-coils, screws can be checked very sensitively for unexpected various faults, as:

- strength
- structural analysis
- carburizing
- decarburizing
- material mix
- aso.

Such testing technology can be adapted at any time to existing testing machines.

Figure 12 a – Bolt test machine, rotating table

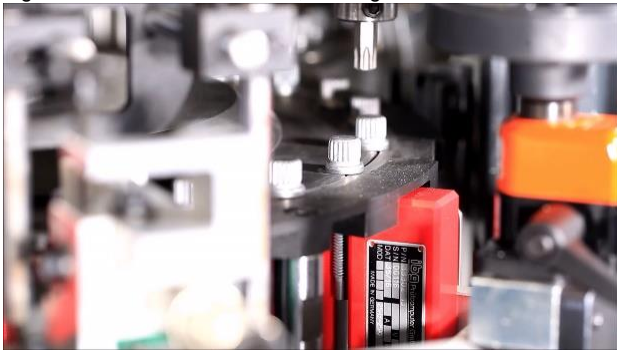
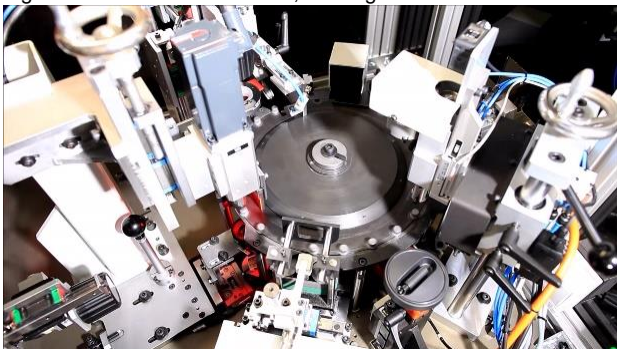


Figure 12 a - Bolt test machine, rotating table



INSPECTION OF BALLS

Balls, as shown in Figure 13 a, are used everywhere in the industry, not just in ball bearings. Here balls of 0.6 - 4.5mm are tested in a flexible system. The goal is not to deliver wrong balls. The challenge was:

- 28 different materials
- different heat treatments in one material
- test speed 17 parts/sec.

must be sorted against each other, there is no mingling allowed. Figure 13 b -+ c, shows the realized machine, with 4 test channels, each test channel works with 8 test frequencies.

Figure 13 a - Balls



Figure 13 b – Ball testing machine



Figure 13 c – Ball testing machine, detail from Fig. 13b



INSPECTION OF DISTANCE PINS

The typical fault of this part is a wrong hardness pattern, Figure 14, against this fault the parts are tested. The material is a Carbon steel with 0.35 % C content, tolerance SHD 0,5⁺mm, ≥50HRC.

During the series test parts were found which failed during the eddy current test. A macroscopic test with etching did not reveal any errors. A microscopic test together with a hardness depth measurement gave the hardness profiles shown in Fig. 15 and 17. Part 1, Figure 16, had a decarburization and Part 2, Figure 18, a ferrite space within the hardness zone. This bug was certainly found with PMFT.

The fault by Part 1 is a classical decarburization and the fault by Part 2 is first also a classical decarburization, followed by a subsequent faulty carburization to reverse the decarburization.

Figure 14 - DISTANCE PINS OK and NOK part

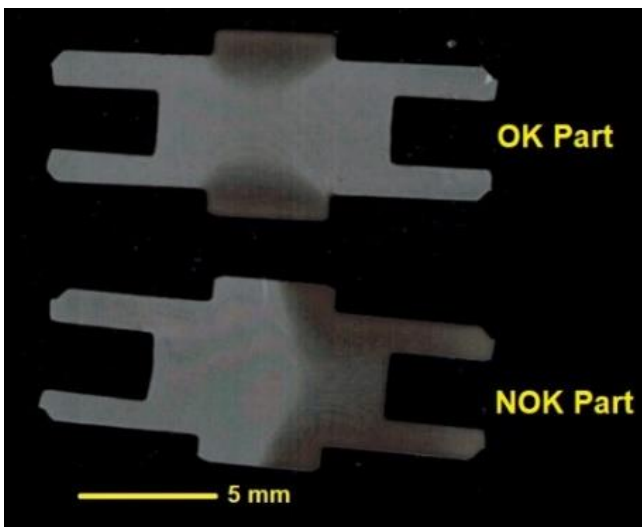


Figure 15 - Hardness trace with decarburizing

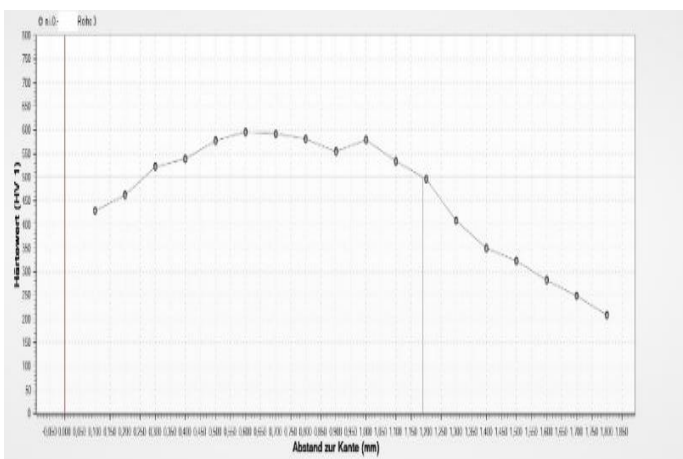


Figure 16 – microstructure below the subsequent carburization, Bainite, Martensite and Ferrite 500:1

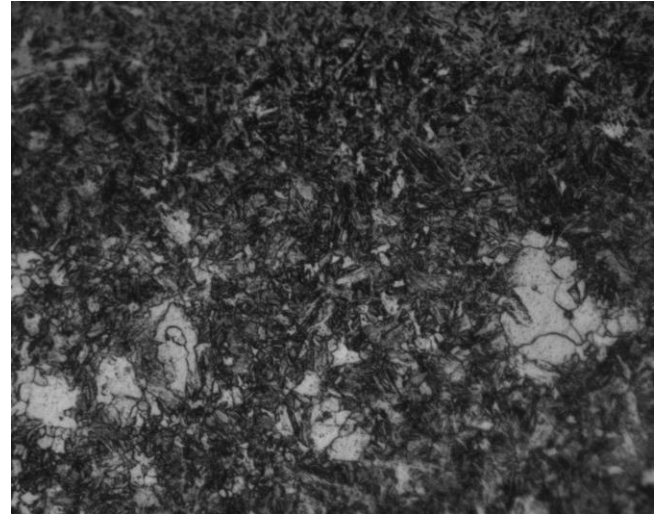


Figure 17 - Hardness trace with Ferrite space under surface

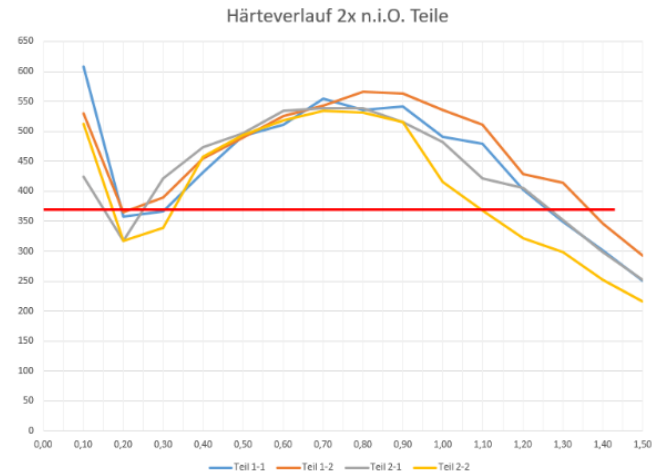
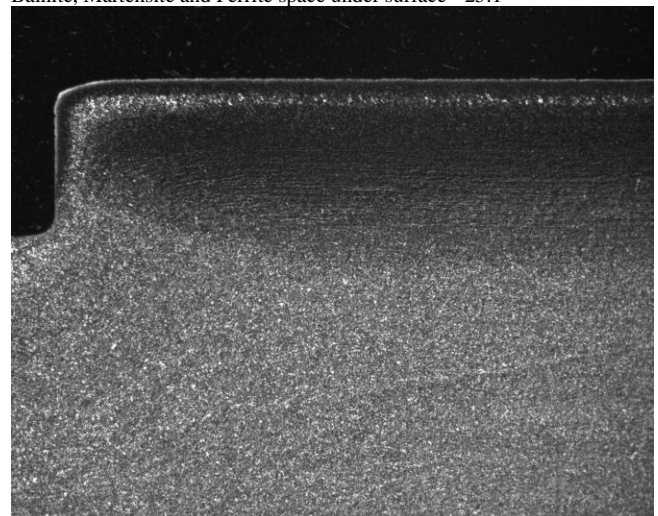


Figure 18 – Overview microstructure, Bainite, Martensite and Ferrite space under surface - 25:1



INSPECTION OF SPECIAL BOLTS

This component as shown in Figure 19 requires uniform hardening in a very narrow tolerance band. The drawing tolerance is 260-340 HB, but all parts of a hardening batch must be in a tolerance of 20HB.

A high risk is a material-batch mixing that leads to different hardness within the drawing tolerance. In this example, we have two mixed material batches from the same material,

- batch 1, 275-285 HB, microstructure Figure 20
- batch 2, 315-330 HB, microstructure Figure 21

both batches are in the drawing tolerance but the spread in the heat treat batch is too high. With PMFT, established a safe test system which made sure that no batch mixing or other faults are in production.

Figure 19 – Tested special bolts



Figure 20 – Microstructure batch 1, 275-285 HB 500:1

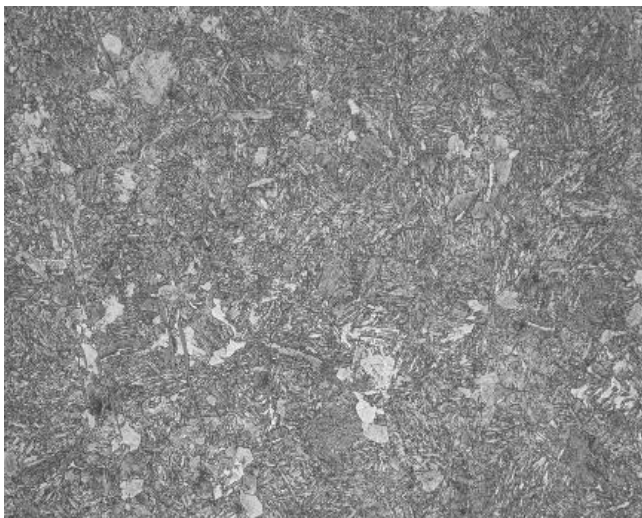
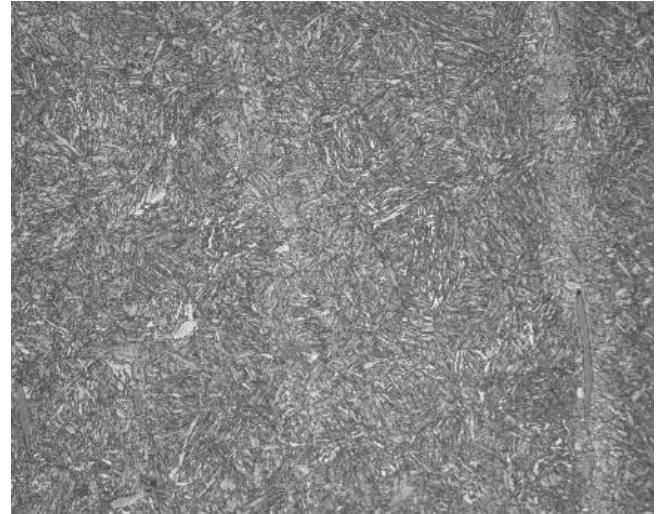


Figure 21 - Microstructure batch 2, 315-330 HB 500:1



SUMMARY

The test against unknown heat treatment defects / material mingling by means of preventive "PMFT" eddy current test gives the heat treatment department a safe test method with the highest possible safety. Due to the integration in production lines, very low test costs are possible, with enormous security.

In addition to high test sensitivity for microstructural changes, hardness faults and case depth changes, PMFT provides a very high level of test safety for unexpected heat treatment defects / material mingling. Thus, the eddy current test is perfectly suited for a 100% test for medium and large quantities in order to ensure production quality.

The older testing technique of a single frequency eddy current test against expected errors with artificially manufactured adjusting parts is not a reliable test to find heat treatment defects / material mingling, at all.

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