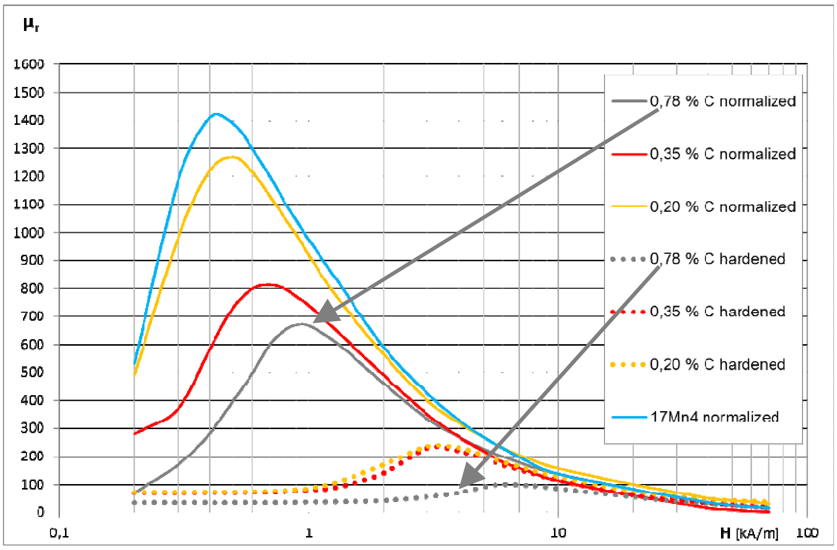
Both induction heating and eddy current testing work with coils, generators, ac-current and ac-voltage, frequencies, field strength and induction law. Contrary to heating of the test parts, the eddy current test does not want to heat the parts at all but wants to examine them for their metallurgical micro-structure, 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

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

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, caused by a damaged inductor, a jammed quench nozzle or an unknown reason are immediately detected, providing an enormous savings in time and costs!

Different from the induction heating, 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 some Hz to some hundreds of kHz 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 are absolutely necessary. Digitization of input voltages immediately at the front end of the electronic evaluation is of huge advantage.

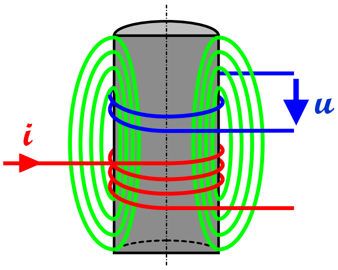


Relative permeability [μ_r] is strongly affected by heat treatment. The amount of carbon and other alloy elements significantly influence the size and course of the permeability curve. Generally, hardened (stressed) structures have lower permeability than soft structures (refer to graph of 0.78% C).

Electrical conductivity [σ] is influenced only a little by structure changes and alloy differences. Whereas, the conductivity of carbon steel is <10 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 (± 5°C).

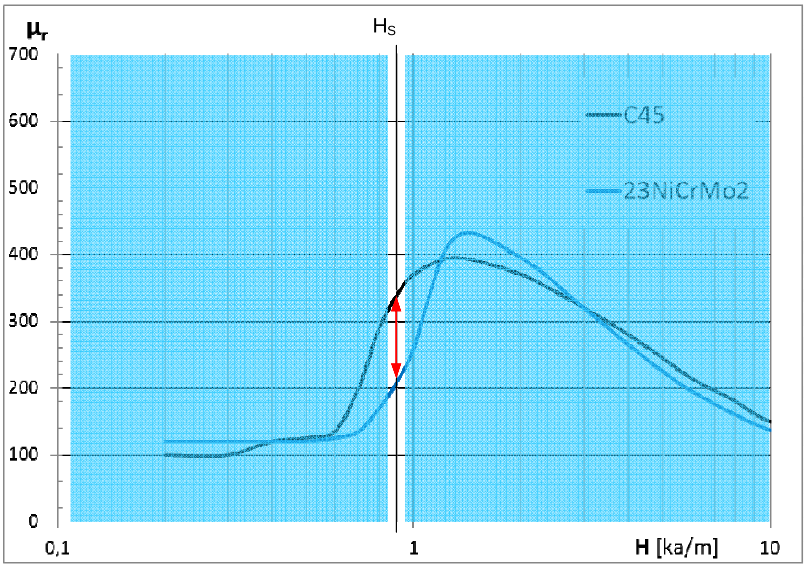
How can magnetic and electrical changes that correlate with the mechanical properties be quickly and reliably tested non-destructively?

Eddy current testing has proven to be well qualified for it. It 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 dependant on the electrical conductivity [σ] and on the magnetic "conductivity" (permeability [μ_r]) of the test part in the coil.

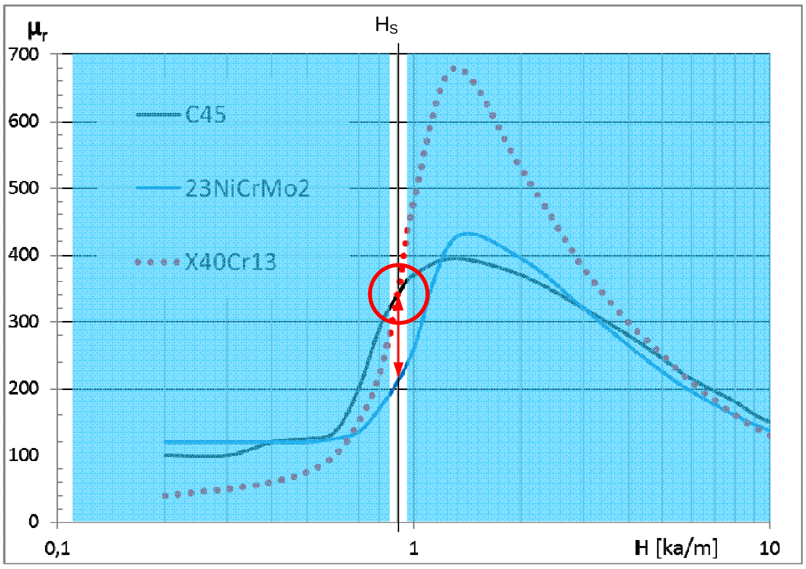
The test part by its σ and μ_r strongly influences the coupling between sender coil (red) and receiver coil (blue). Thus voltages induced in the receiver coil imply the structure, i.e. to verify correct hardness, case depth, core hardness as well as alloy. This complex signal is displayed two-dimensionally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

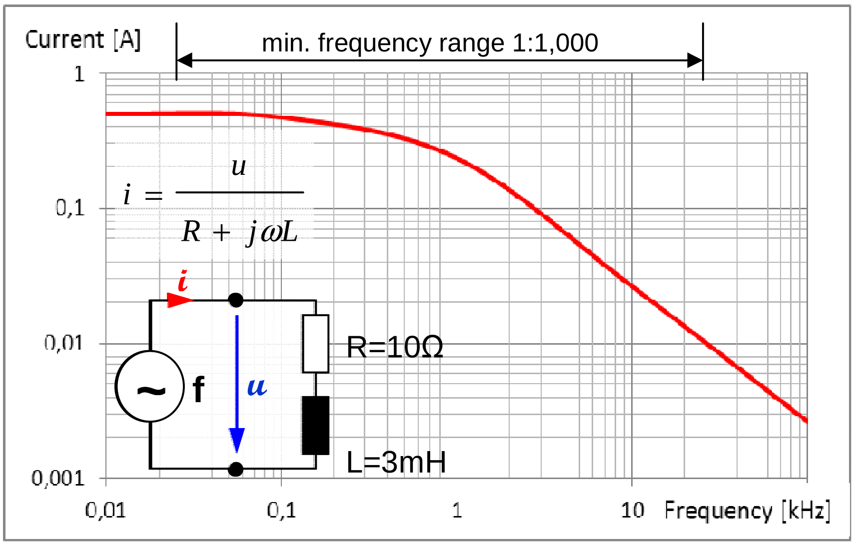


But beware: If permeability is tested with a single magnetic field strength H_S, test results may be unreliable as soon as other types of mixed parts become involved. Let us take a typical mixed part test of two kinds of steel: C45 and 23NiCrMo2. The largest difference in permeability is at H_S. This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

But does this test “see” neighbouring permeability areas related to other unexpected mixed up part types?

What occurs if another material, e.g. X40Cr13 is mixed up unexpectedly and tested? The example on the right hand side shows that the permeability curve of C45 crosses the curve of X40Cr13 at H_S (red circle). A differentiation with one field strength (frequency) is not possible. Both remain mixed up in spite of the eddy current test. Could the "curtains" be moved aside in order to widen the view? Could the test take place at different field strengths, so to say “preventively” over a larger area?

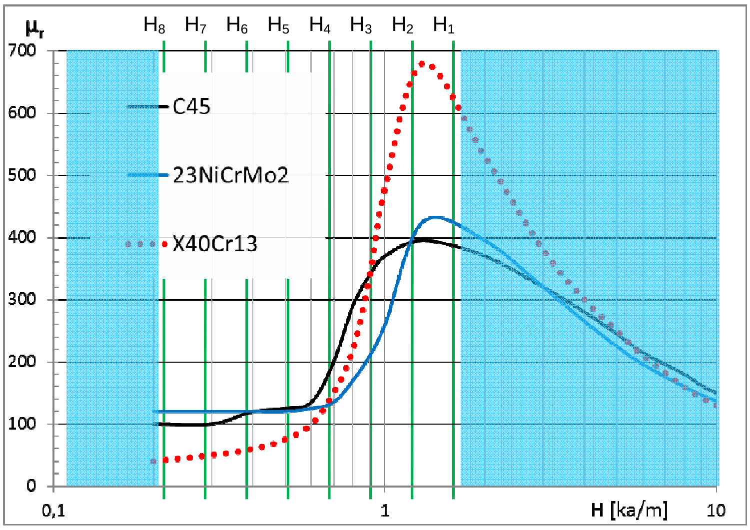




That is the "Preventive Multi Frequency Technology" (PMFT) invented by ibg which uses eight test frequencies that cover a wide area of the coil current and thus field strength. The frequency range from the lowest to the highest frequency should be at least 1:1,000 in order to vary, via the inductivity of the sender winding, the exciting current and thus the field strength in the coil.

The use of several test frequencies to induce different field strengths (H_{1-8}) in the coil means that all these differences are detectable or viewable.

Different structures from different heat treat methods (and by heat treat process errors) create different permeability curves which are detected by means of PMFT. Thus the eddy current testing becomes reliable. Expected and unexpected wrong structures are detected.

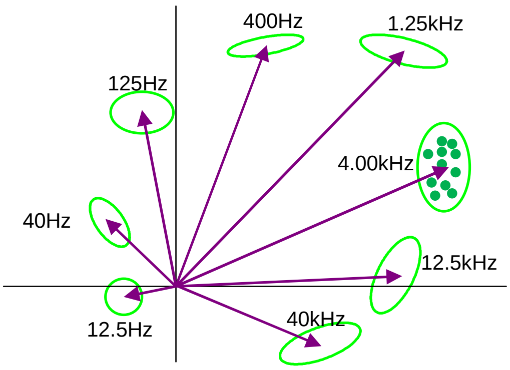


If several frequencies of alternating current are used, a voltage vector is obtained for each frequency in the impedance, and there is a locus curve.

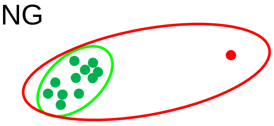
Of course, other factors also influence the induced voltage. The position of the test part in the coil, geometric variances in the test part and other factors alter the received voltages. These factors must therefore be controlled.

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 elliptic tolerance zone, the test can be reduced to a comparison of the vectors to inside (OK) or outside (NG) of the tolerance zone.

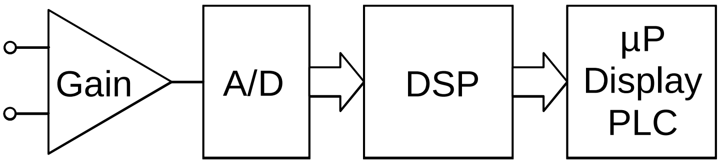
Testing current production with such a frequency band (eight frequencies, at least 1:1,000) and the comparison with the previously created tolerance zones made with good parts has become well known in professional circles as PMFT (ibg's Preventive Multi Frequency Test). A quite wide frequency band is 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 NG parts (e.g. not-hardened, incorrectly quenched, austenizing 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 PMFT method works reliably for all kinds of defects which may happen during heat treatment of steel.



Careful choice of OK parts is a precondition to reliable testing. One or several NG parts (red dot) 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.

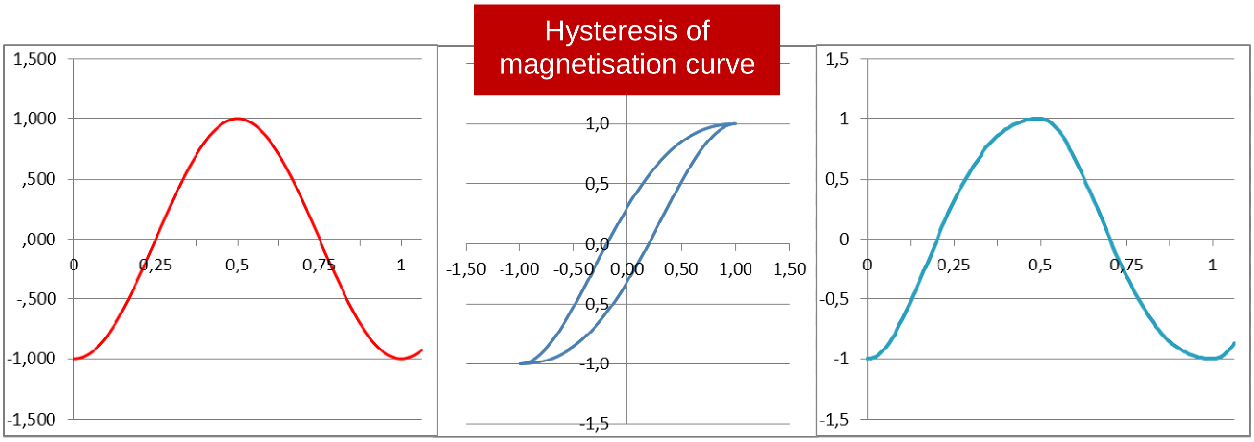


Very small voltage differences in the µV range are processed and visualised for this non-destructive test. Highly sensitive and stable measuring devices are necessary to measure such small voltages reliably and free of interferences. The solution is to digitalize measuring values immediately at their input to the measuring device. The gained samples (20.000.000/sec.) with 18 bit resolution are put into a digital signal processor (DSP) and converted within shortest time (2 ms) to a 2*32 bit data word. This is compared with the stored tolerance zones and a test result is given.



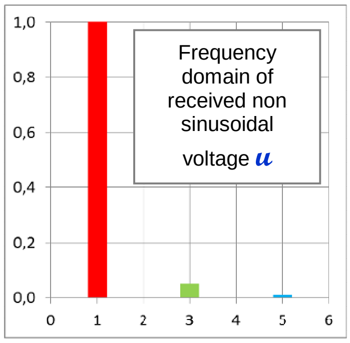
Newly developed is calculation of the vectors of harmonics up to the 7th without additional time requirement. So now there is also preventive harmonic analysis (e.g. iSHA = ibg's Simultaneous Harmonic Analysis).

The harmonics arise by a hysteresis of the magnetisation curve of the test part in the coil arrangement. The sinusoidal current ***i*** in the exciting coil causes a sinusoidal field strength H which triggers a magnetic flux B in the test part. The chronological sequence, however, is (depending on permeability) not sinusoidal anymore. Thus the chronological sequence of the magnetic flux B induces a voltage differing from the pure sine in the receiver coil.



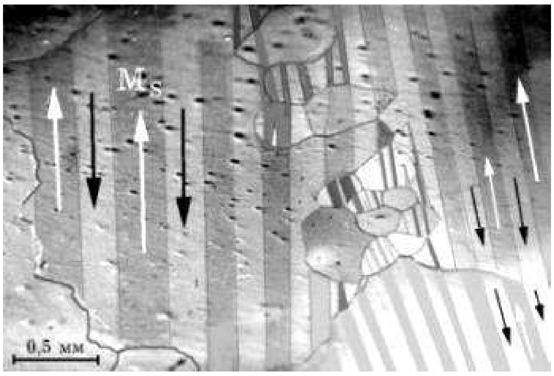
sinusoidal exciting current — Flux B — received non sinusoidal voltage

Fourier analysis of that voltage ***u***, reveals higher frequency components of the **fundamental wave**, namely harmonics of the **3**- and **5**-times frequency. Analysis of these harmonics provides a much more precise view of the magnetic features of the test part and thus detailed information on its structure. The signals of the harmonics, however, are very small. A significant electronic effort is required to extract such small signals from the noise and to display them.

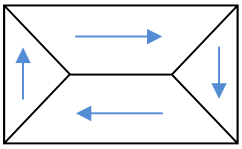


iSHA performs this in a precise and highly repeatable manner.

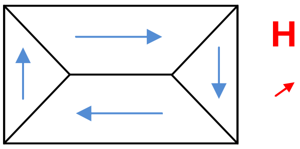
Why does a hysteresis curve arise?
This has to do with the ferromagnetism of the materials and their structure. A short introduction about how magnetism arises is helpful to understanding eddy current testing. Based on the smallest magnetic area, e.g. the electrons with their spin and the nucleus with its magnetic moment, there are magnetic domains in the material under a minimum free energy conditions. Size and direction (north-south) of the domains are random such that (at first) no overall magnetic field



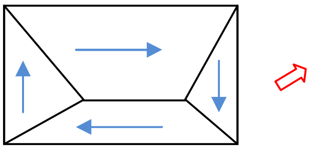
Domain structure of Fe-3%Si polycrystals with crystallites exists. These domains are separated by Bloch walls. The current in the eddy current coil introduces an external magnetic field H which works on the domains. Let's have a look at a simplified picture about the influence of the external magnetic field on the domains and their boarders, the Bloch walls:



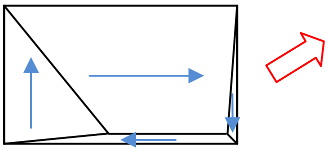
First there is formation of the domains and Bloch walls without external field H. The magnetic circle is closed within the material.



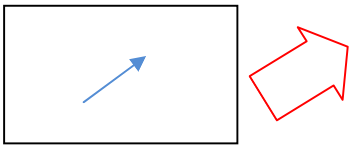
A very external small field H (red arrow) does not yet change the Bloch walls irreversibly. The magnetic conductivity changes slightly.



Growth of the external field moves the Bloch walls. The domains in similar direction to the external field become bigger, the opposite ones become smaller. The magnetic conductivity becomes bigger.

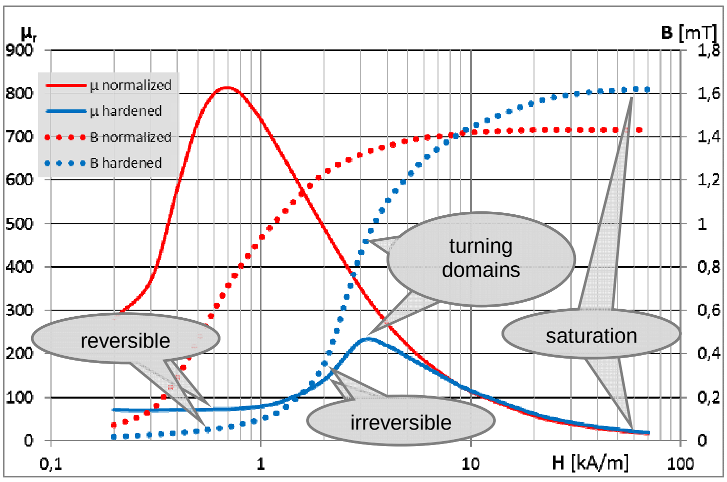


Still stronger field strength H means practically only one domain in preferred direction.



The preferred direction of the domain at very high field strength is turned to the direction of the strong external field. The material approaches its magnetic saturation.

Moving Bloch walls is not a continuous process. The Bloch walls hang more or less fixed on pinning defects in the crystal lattice. More magnetic energy loosens them and they jump to the next pinning defect. (Jumping causes Barkhausen noise.) When the outer magnetic field is switched off, the Bloch walls partly remain at their new pins. And the part which was originally outwardly in magnetic balance keeps an outer residual magnetism (remanence), which can be zeroed after a negative field strength (coercive field strength) is applied. The magnetic hysteresis is born.



Permeability μ_r on the left axis (line)

Magnetic Flux B on the right axis (dotted)

The flatter the ascent of the μ_r curve (blue line) the more distinct the linear (reversible) area of the magnetisation curve (blue dotted line). No harmonics are expected of the linear area. The hardened C35 structure (blue lines) will show harmonics at higher field strengths. The soft structure (normalised, red lines), however, shows a clear ascent of the permeability at 10 times smaller field strength, thus comes early the irreversible area of the magnetization curve. A distortion of the induced voltage is observed at small field strengths and harmonics are generated at small field strengths.

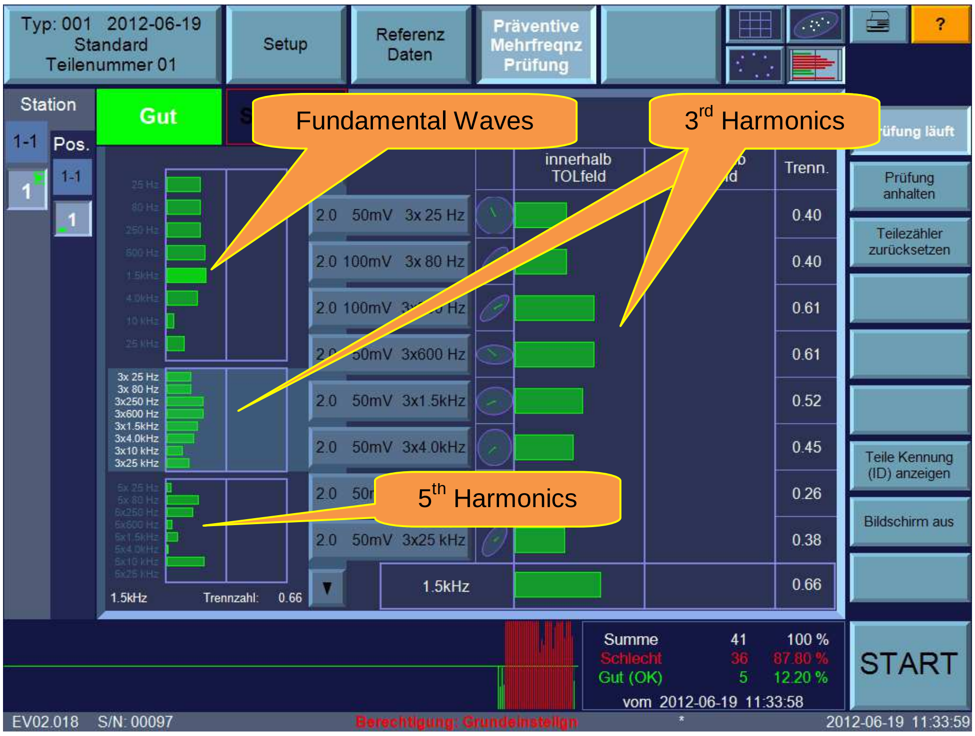
This phenomena is exploited in eddy current testing for detection of not-hardened parts or for recognition of soft areas on the surface. Too shallow case depth versus specification and too soft surface hardness versus specification also provide very good signals for harmonic evaluation.

iSHA, e.g. testing simultaneously with harmonic evaluation and “Preventive Multi Frequency Technology”, enables eddy current testing to get maximum metallurgical information from the parts non-destructively.

Applications:

Inductively hardened (case depth) ball studs

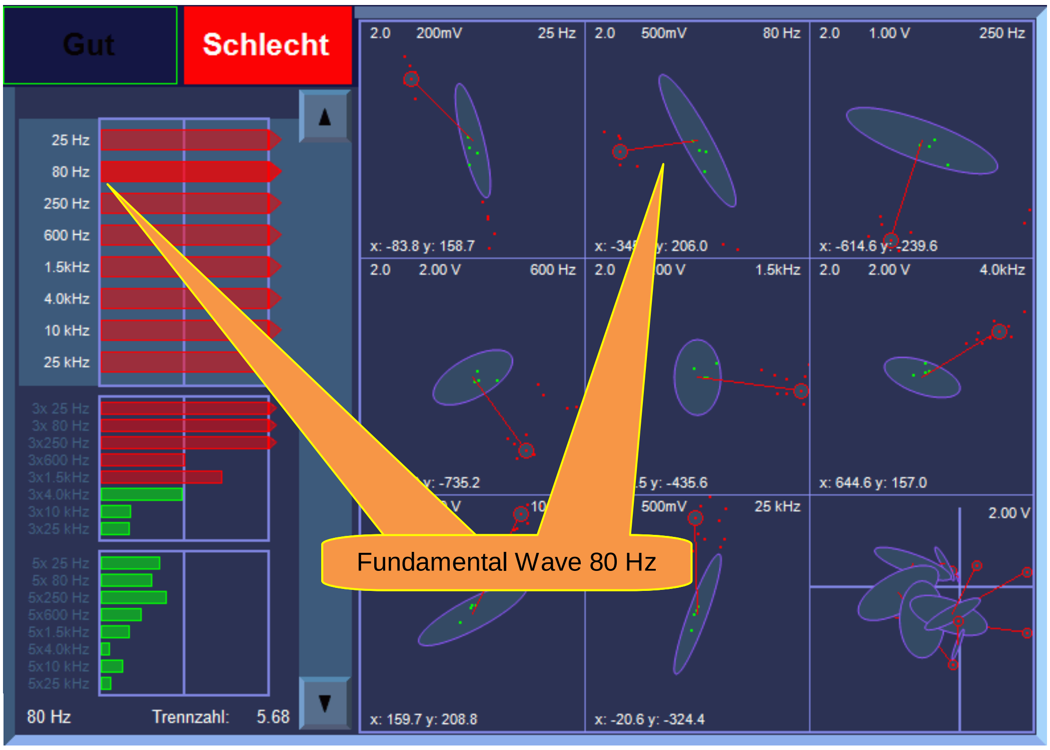
hardness profile of a cut and etched ball stud, OK part



eddyvisor® (digital) screen in sorting mode, OK part displayed

At first, these OK parts are taught as reference parts to the test instrument at all test frequencies. Considering scattering of parts, tolerance zones of fundamental wave and harmonics (PMFT+iSHA) are automatically calculated. The voltage vectors of the test parts are compared with these tolerance zones and a sorting decision is made. The screen shows bar graphs for each fundamental wave frequency and for each frequency of the harmonics (includes green bars). When all induced voltage vectors in the test coil fall within the tolerance zones, the tested part is OK.

hardness profile with too deep case depth



eddyvisor® (digital) in sorting mode, NG part displayed, best separation at 80 Hz fundamental wave

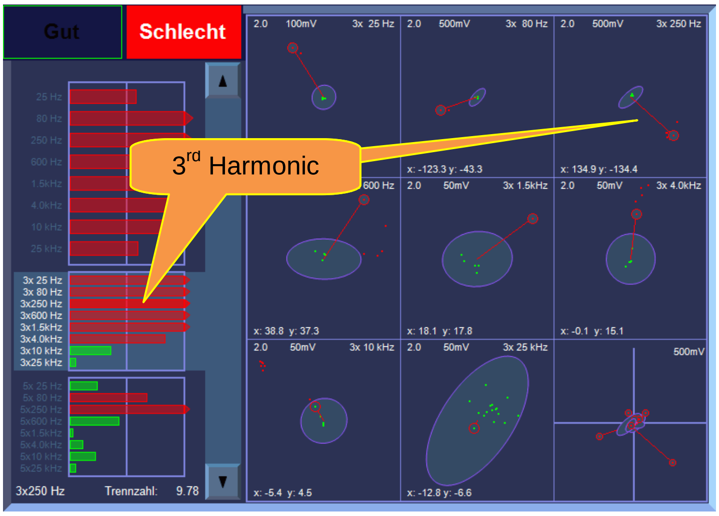
It does not surprise that the best separation figure for too deep hardened parts is achieved at a relatively low frequency of the fundamental wave (80 Hz). Furthermore, the separation figures at the 3rd and 5th harmonic are smaller than at the fundamental wave which fits into the picture. The penetration depth of the eddy current signal at low frequencies and low permeability values is deeper, and the reversible area of the magnetisation curve is extended to higher field strengths.

Only a few harmonics distinguishable from OK parts are generated.

hardness profile with too shallow case

The too shallow hardened parts show interestingly the best separation figure of 9.78 at the 3rd harmonic. The thin hardened surface with small μ_r allows the magnetic field strength to penetrate remarkably into the soft basic structure with high μ_r and irreversible magnetization curve. The result is very strong harmonics which differ considerably from the structure of the OK parts.

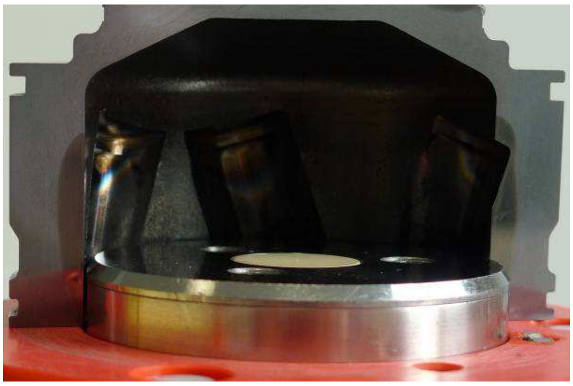
The superiority of iSHA is revealed especially at detection of faulty (incorrect) soft structures.



eddyvisor® (digital), NG part displayed,
best separation at 3 x 250 Hz harmonic wave

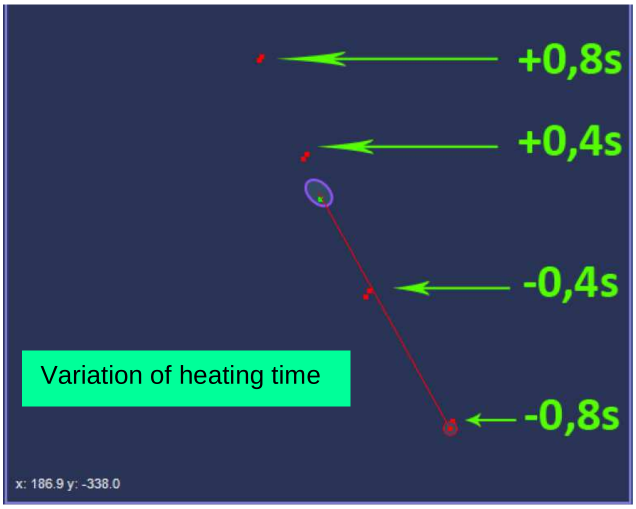
Case depth of races of CV-Joints

Induction hardening of the ball race in the bell, subsequent eddy current testing for correct hardness position (pattern and run out) and for correct case depth and core hardness are big challenges for the induction hardener, as well as for the test equipment manufacturer and for the coil designer.



Exact insertion depth of the test coil and the coil design are decisive for a high sensitivity test against the requested hardness run out.

In addition, the possibility of the simultaneous harmonic analysis offers a highly sensitive test of correct versus incorrect hardening time and the corresponding over or under heating.



This display of the 3rd harmonic of 1.2 kHz gives a significant expansion of the eddy current signals.

Summary:

In addition to high test sensitivity for hardness, hardness runout and case depth, ibg's instruments (eddyvisor S, eddyliner S and eddyguard S) using iSHA+PMFT enable a very high test reliability regarding material mix up.

Thus, this eddy current test method perfectly suits a 100% test for medium and high volume production to assure manufacturing quality.

Other ibg instruments (eddyvisor SC, eddyvisor C, eddyliner C and eddyguard C) are capable of reliably detecting surface defects like cracks, pores and grinding burn by using higher test frequencies and surface test probes.