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Industrial Applications of 3MA – Micromagnetic Multiparameter Microstructure and Stress Analysis

Gerd Dobmann, Iris Altpeter, Bernd Wolter, Rolf Kern
Fraunhofer IZFP, University Campus 3 1, 66123 Saarbruecken
Phone: +49 681 9302 3855, Fax: +49 681 9302 5933; e-mail: gerd.dobmann@izfp.fraunhofer.de

Abstract
Micromagnetic NDT techniques like the measurement of the magnetic Barkhausen noise, the incremental permeability and the harmonic analysis of the tangential magnetic field allow deriving inspection procedures to online monitoring and control machinery parts and components in production processes in order to characterize mechanical properties like hardness, hardening depth, yield and tensile strength. These types of inspection procedures continuously were further developed in the last two decades so that today the second generation of system hard and software is in industrial use. The application is in steel industry where steel sheets in hot-dip-galvanizing lines were annealed after cold rolling but also in heavy plate rolling mills where after thermo-mechanical rolling special textures and texture gradients can occur. An increasing number of applications are also to find in the machinery building industry and here especially in case of machinery parts of the car supplying industry. Besides mechanical hardness determination the measurement of residual stresses and the detection of in-homogeneities in the surface of machined parts is an inspection task. In different case studies the advantage to implement a micromagnetic NDE technique into the industrial processes is discussed.
Keywords: Micromagnetic NDE, hardness, hardening depth, residual stresses, yield strength, steel industry, steel sheets, heavy plates, machinery building, automotive

1. Introduction[1]

The reason for the 3MA development starting in the late seventies in the German nuclear safety program was to find microstructure sensitive NDT techniques to characterize the quality of heat treatments, for instance stress relieve of a weld. George Matzkanin *[1]* just has published a NTIC report in USA to the magnetic Barkhausen noise. The technique was sensitive for microstructure changes as well as for load-induced and residual stresses. Therefore a second direction of research started in programs of the European steel industry and the objective was to determine residual stresses in big forgings. Beside the magnetic Barkhausen effect also a magneto-acoustic-one became popular *[2]*. The technique has based on acoustic emission measurements during a hysteresis cycle and was – because of the high amplification – also sensitive for electric interference noise. Therefore the acoustic Barkhausen noise technique has never found a real industrial application. Later further micromagnetic techniques were developed: the incremental permeability measurement, the harmonic analysis of the magnetic tangential field and the measurement of the so-called dynamic or incremental magnetostriction by use of an EMAT *[3, 4]*.

The methodology of the micromagnetic multiparameter microstructure and stress analysis (3MA) in detail is described in *[4]*. It only can be applied at ferromagnetic materials. Here the techniques are especially sensitive for mechanical property determination as the relevant microstructure is governing the material behavior under mechanical loads (strength and toughness) in a similar way as the magnetic behavior

[1] The paper was presented in a larger version at the ENDE 2007 Conference held in Cardiff, 19-21 June. The proceedings are planned to publish with ISO Press.

under magnetic loads, i.e. during the magnetization in a hysteresis loop. Because of the complexity of microstructures and the superimposed stress sensitivity there was a need to develop the multiple parameter approach.

Whereas the first generation of 3MA equipments was basing on the magnetic Barkhausen noise and magnetic tangential field analysis only, 3MA equipment exist now in the forth generation also integrating incremental permeability and eddy current impedance measurements (see Figure 1.). More than 100 installations are in use in different industrial areas. This mainly covers the steel and machinery building industries.

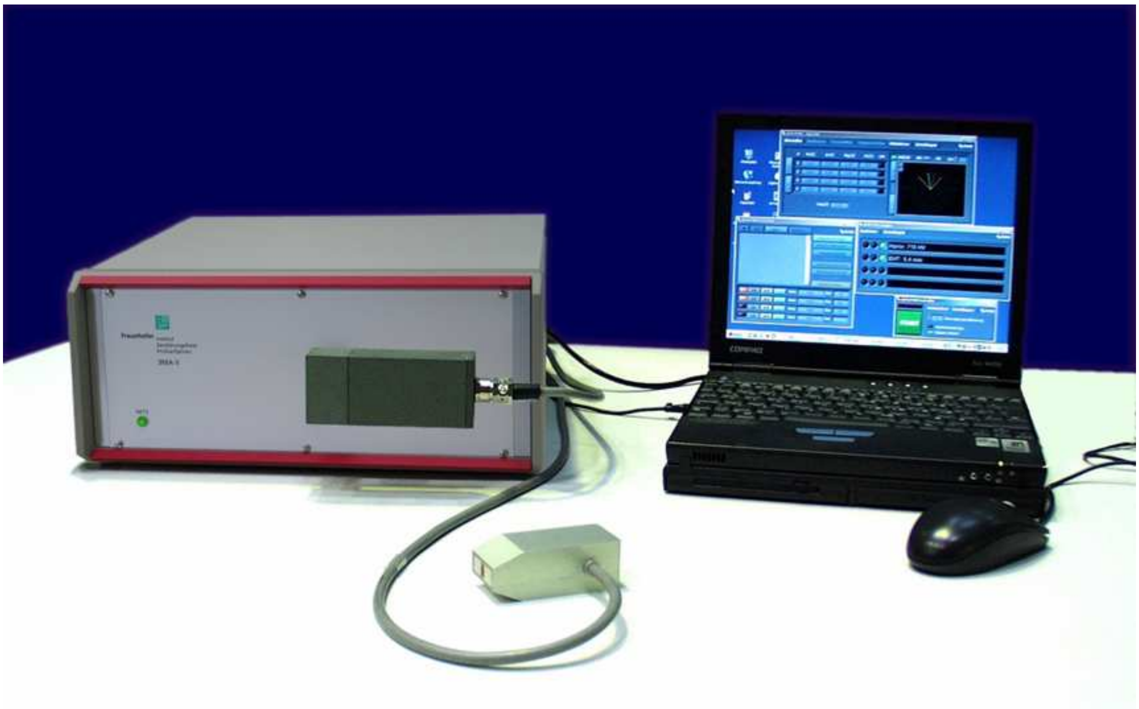


Figure 1. TCP-IP-based 3MA equipment and software in combination with a laptop

2. Applications in the steel industry

2.1 Steel Strip Inspection

A lot of experiences with 3MA in the last 2 decades were to the continuous mechanical property determination at steel strips for car body production *[5]* running with a speed of 300m/minute for instance in a continuous galvanizing and annealing line. Yield strength, tensile strength, planar and vertical anisotropy parameters are in the focus of quality assurance measures, all of them are defined by destructive test and cannot be measured continuously. Therefore 3MA correlations were calibrated.

Figure 2 shows a yield strength profile along a coil of 2.5 km length. At the beginning and the end an unacceptable strength increasing is detected higher than the upper acceptance level (blue line). The strength values are calculated by the 3MA approach from measured micromagnetic data. The red dots indicate the selection of specimens taken for destructive verification tests after performing NDT. The residual standard errors found by validation are in the range 4-7 % concerning the yield strength. Figure 3 shows the 3MA installation in the line of a strip producer by a robot for transducer handling.

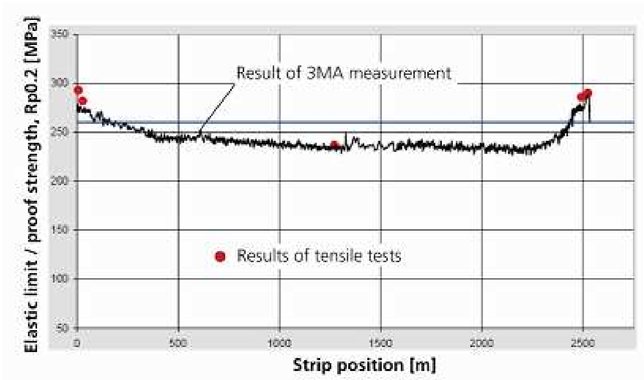
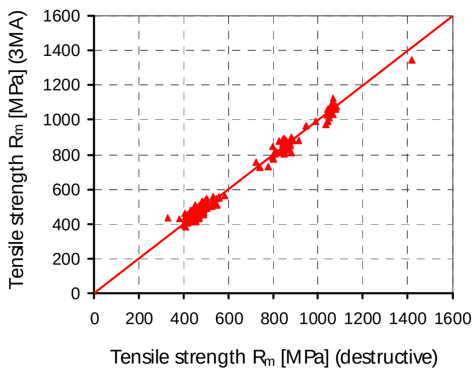


Figure 2. 3MA predicted Yield strength

Figure 3. 3MA with robot at a strip line

2.2 Heavy plate Inspection

Ongoing research is to heavy plate inspection. The customer asks for geometrical and mechanical properties, which are uniform across product length and width, especially for high-value grades used in off-shore application. Tensile and toughness tests are performed according to codes and delivery from highly qualified and certified personnel. The tests cannot be integrated into online closed loop control with direct feedback. For mechanical hardness tests the surface must be carefully prepared by removing scale and decarburized surface layers and relieving residual stresses. The coupon extraction and testing is very time and cost extensive. Costs in the range of several thousands Euro per year arise in a middle-sized heavy plate plant only from coupon scrap.



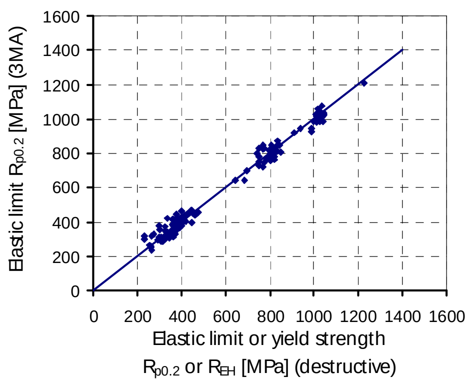


Figure 4. Tensile strength predicted by 3MA

Figure 5. Yield strength predicted by 3MA

For a mother plate of several meters length the boarders are usually subjected to other cooling conditions than the rest. Indeed especially the plate ends are known to cool faster, generating an undesired increase in tensile strength Rm and yield point $Rp_{0.2}$. State-of-the-art is to trim the plate boarders with non-conform properties based on empirical values. The destructive coupon testing follows the trimming, i.e. it can not be assured, if to much or to less material is cut-out. This lack of knowledge results in enormous costs due to reworking, pseudo-scrap and delayed shipment release. The European steel producers put their annual costs at 11 million Euros. Knowing exactly the contour of the zone with unacceptable material would allow an open loop control for the trimming process. For these reasons, heavy plate producers have an itch to replace the mechanical testing of coupons by a NDT technology. Applying 3MA (see Figure 4. and 5.). By manufacture-specific calibration residual standard errors of 10 MPa respectively 20 MPa for Rm respectively $Rp_{0.2}$ determination and 4HB in the Brinell hardness can be obtained. It should mentioned here that 3MA is free to integrate also other measuring quantities so far they provide other divers information, for instance elastic properties. By using ultrasonic waves propagating in thickness direction, i.e. a compressive wave excited by a piezoelectric transducer (index L) and two linearly polarized shear waves (polarized in, index SHR, and transverse, index SHT, to the rolling direction) excited by EMAT, normalized time-of-flight quantities can be derived describing crystallographic texture effects. Taking into account these quantities (t_{SHR}/t_L, t_{SHT}/t_L, $(t_{SHR}-t_{SHT})/t_L$) together with the micromagnetic parameters then a regression result is obtained tremendously again reducing the residual standard error.

3. Application in Automotive and Machinery Building Industry

3.1 Car Engine casting

For the weight reduction of the power supply unit the car combustion engines cylinder crankcases can be made of cast iron with vermicular graphite (GJV), because this material in a Diesel engine allows a higher loading pressure even by reduced wall thickness. However, the service live of machining tools is during processing an engine block made from GJV substantially smaller compared with a block from cast iron with lamellar (flake) graphite (GJL).

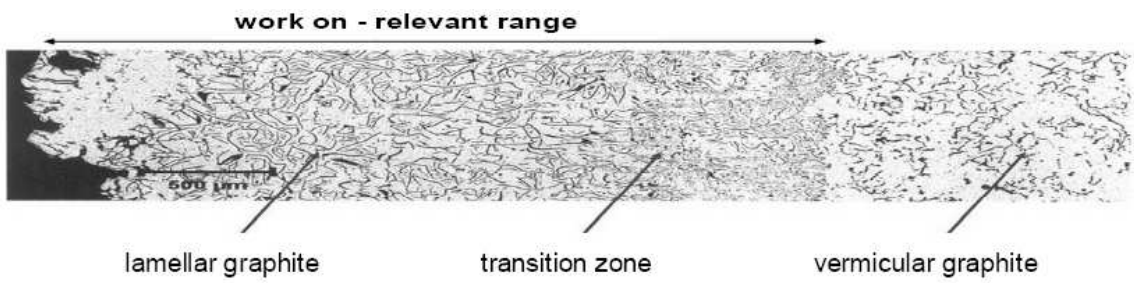
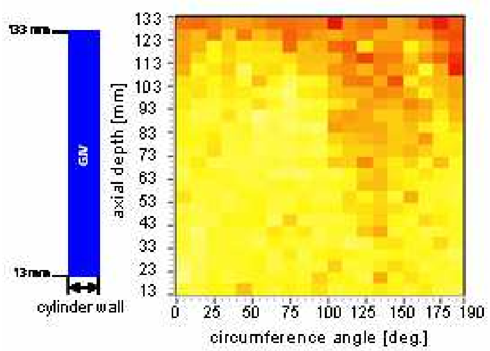


Figure 5. Microstructure gradient obtained in a cylinder region of a cast engine

This disadvantage can be eliminated by an innovative casting technology that produces a continuous microstructure gradient in the cast iron from lamellar graphite at the inner surface of the cylinders to vermicular graphite in radial direction. By implementing some chemical additives into the core of the mould which can diffuse in the cast iron during the solidification process in the mould the gradient with a continuous transition from lamellar graphite and finally vermicular graphite is obtained. However, the technology can only be used by the casters so far the gradient quality can be characterized and monitored by NDT. In figure 6 the micrograph documents such a gradient beginning at the left side with cast iron (inner cylinder surface) and lamellar graphite followed by a transition region and vermicular graphite on the right side.

3MA techniques always cover a certain analysing depth depending on the magnetising frequency and geometrical parameters of the magnetisation yoke, etc. So far the gradient has different graphite compositions within the analysing depth, 3MA quantities should be influenced. Based on measurements at an especially designed calibration test specimen set 3MA quantities were selected to image the gradient with optimal contrast. As reference quantity for calibration the local thickness of the GJV-layer was evaluated by using micrographs and optimized pattern recognition algorithms in the microscope. A special designed transducer head was developed to scan the cylinder surface by line scans in hoop direction and rotating the head, then shifting the head in axial direction to perform the next line scan. Figure 7. and Figure 8. show as example the coercivity images derived from the tangential field strength evaluation (H_{C0} in A/cm) and line scans covering an angle range of 190°.



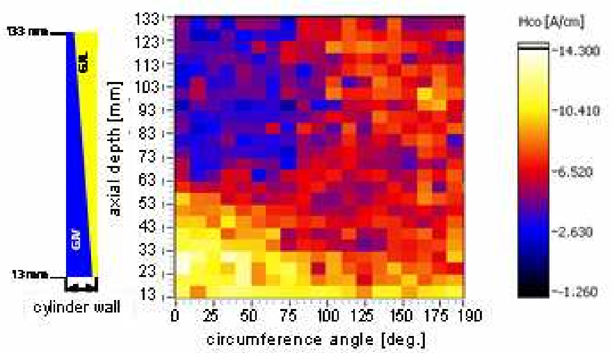


Figure 7. Coercivity image of a reference block made from GJV

Figure 8. Coercivity image of block with GJV/GJL gradient

Combining different 3MA quantities in a multiple regression the thickness of the GJL layer was predicted. A regression coefficient of R^2= 0.93 and a residual standard error of σ = 0.06 mm was obtained *[6]*.

3.2 Wheel Bearing Testing

The fixation of the inner ring of wheel bearings is performed by a wobble riveting process. As a consequence a residual stress is built up in the ring which may not exceed a limit value of about 300 MPa to get a perfect quality.

The usual technique to inspect the residual stress state is x-ray diffraction which is destructive in nature because it requires a preparation of the test location. Furthermore it can only be performed statistically. The 3MA technique allows a fast non-destructive estimation of the residual stress level (Figures 9, 10). After a calibration step by using x-ray reference values a 100% quality inspection of these parts is possible. The calibration procedure requires a coincidence of the 3MA and x-ray calibration positions because residual stress varies along the circumference. That means the 3MA data have to be recorded in a first step before the x-ray test location is prepared by etching. According to Figure 10 the residual standard error in the calibration is in the 20 MPa range. Besides the residual stress additionally the surface hardness can be measured.

Figure 9. 3MA-Probe at test location

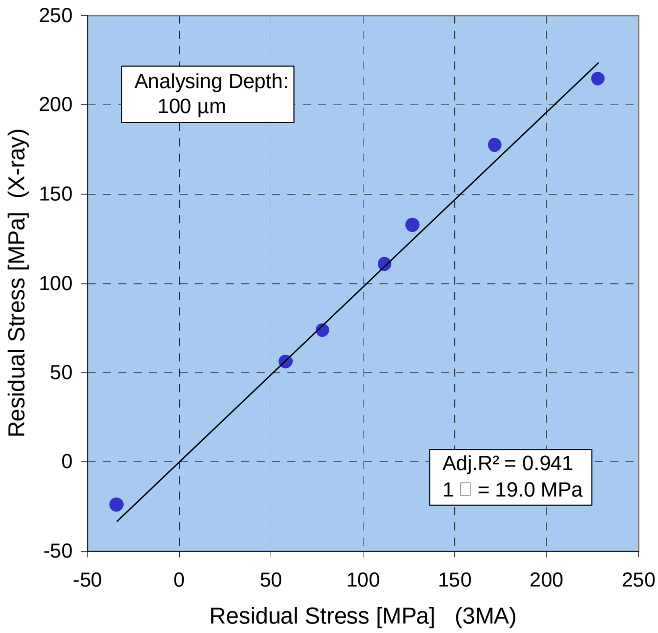


Figure 10. Residual stress calibration

4. Conclusion

3MA is a matured technology and a wide field of applications is given. However, besides the success story we also can find critical remarks from industrial users. These are mainly to the calibration efforts and problems of recalibration if a sensor has to be changed because of damage by wear. Therefore actual emphasis of R&D is to generalize calibration procedures.

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