Multi-Method Probe Design for the Electromagnetic Characterization of Advanced High Strength Steel

Klaus SZIELASKO[1], Sargon YOUSSEF, Frank NIESE, Miriam WEIKERT, Alexander SOURKOV, Iris ALTPETER, Hans-Georg HERRMANN, Gerd DOBMANN and Christian BOLLER

Fraunhofer Institute for Nondestructive Testing (IZFP), Campus E3.1, 66123 Saarbrücken, Germany

Abstract. Electromagnetic non-destructive testing (NDT) systems have been used in steel strip production lines for a long time. Indirect electromagnetic determination of approximate yield and ultimate strength values can be considered state of the art. However, the excellent mechanical properties of advanced high strength steel (AHSS) are particularly sensitive to process variations. Characteristics and homogeneity of texture, grain size and secondary phase content are crucial during forming and welding of steel strips. Ultrasonic methods can be applied in order to indirectly characterize these properties. Deviations which have not been detected in the rolling mill are known to cause flaws or expensive and time-consuming downtimes of the press. The crash performance of the automotive structure is affected by these properties as well. Current in-line NDT systems determine only a subset of the required parameters and do not assess their homogeneity across the strip width. This raises the demand for NDT solutions which assess a larger set of material characteristics in multiple locations at high strip speeds. This paper describes a probe design which allows ultrasonic time-of-flight measurements as well as Micromagnetic Multi-Parameter Microstructure and Stress Analysis (3MA) using a common, minimal set of components. The implementation of a simplified yet advantageous incremental permeability and eddy current impedance analysis based on this probe type is discussed, and first results are presented.

Keywords. Steel strip, on-line, micromagnetic, electromagnetic, 3MA, ultrasonic, guided waves, Lamb wave, guided SH wave, EMAT, time-of-flight

Introduction

Advanced High Strength Steel (AHSS) enables the automotive industry to simplify manufacturing processes, to increase the stability and crash safety of cars and to reduce weight or CO_2 emissions at the same time. The World Steel Association estimates that the exclusive use of AHSS body parts in all cars worldwide would allow for a total of 150 million tons of annual CO_2 savings [1]. Moreover, according to this article, the use

[1] Corresponding Author: Dr.-Ing. Klaus Szielasko, klaus.szielasko@izfp.fraunhofer.de phone: +49(0)681 9302 3888, fax: +49(0)681 9302 113888

of modern steel grades for wind turbine towers has already led to a weight reduction of more than 50% over the past 10 years.

However, the advantageous properties of AHSS require narrow process windows and therefore represent a significant challenge in terms of process control and quality assurance. The same applies to other advanced steel grades of complex microstructure which require precisely maintained heat treatment and machining parameters. Examples are thermo-mechanically rolled heavy plates, but also micro-alloyed case-hardened steel for transmission components.

The NDT world faces specific challenges for these applications. Besides yield/ultimate strength and hardness, additional important parameters are to be seen in texture, secondary phase content and grain size. Particularly in case of the steel strip production, deviations may lead to significant downtimes if they are not detected in an early processing stage. Suitable NDT methods have to be capable of being integrated into the process at high strip speed. The measuring rate has to be sufficiently high in order to reach high strip coverage and identify local variations. Sensor lift-off is required in order to protect strip and probe from being scratched. Moreover, all of the above requirements have to be fulfilled in a cost-effective way, particularly if multiple probes are used in order to assess the quality distribution across the strip width or in multiple stages of the process.

1. Electromagnetic NDT methods applied

1.1. Micromagnetic Multi-Parameter Microstructure and Stress Analysis (3MA)

In the field of electromagnetic materials characterization, Fraunhofer IZFP pursues the 3MA approach (Micromagnetic Multi-Parameter Microstructure and Stress Analysis) [2-6]. It is based on the observation that under the influence of stress, microstructure and surface-near material gradients, reliable results can only be obtained by a combination of several NDT methods. To date, 3MA involves analysis of the harmonics of the magnetic tangential field strength, Barkhausen noise, incremental permeability and eddy current impedance. Besides 3MA, other micromagnetic methods known to be actually applied in the strip steel production are EMG IMPOC [7] and HACOM [8]. All micromagnetic methods are based on a correlation between the micromagnetic quantities measured and the mechanical-technological properties of the material. This correlation occurs due to similar mechanisms by means of which the microstructure interacts with Bloch walls and dislocations [9].

Multivariate regression analysis and/or pattern recognition are used in order to associate the measured parameters with target quantities (such as hardness or tensile strength) during a calibration procedure on samples having well-known properties. The statistical concepts of 3MA are basically applicable to any set of (ideally uncorrelated) parameters, so on the one hand, a goal of future development should be to obtain as much information on the material as possible by combining different methods, whereas on the other hand, the transfer characteristics of the required sensors and devices should be reproducible and controllable with low effort as a consequence of cost and feasibility.

1.2. Ultrasonic time-of-flight measurements with EMATs

Previous research has shown that ultrasonic methods, particularly time-of-flight measurements, allow for the determination of quantities which are correlated to deep-drawability characteristics such as perpendicular anisotropy r_m and planar anisotropy Δr [10, 11, 12]. These results were mainly obtained using horizontally polarized guided shear waves (SH waves) excited and received by means of Electromagnetic Acoustic Transducers (EMATs) which require no couplant. Some synergies between the sensor principles of EMAT and 3MA were already pointed out in these works, e.g. using an electromagnetic acoustic transducer (EMAT) as an inductive sensor for Barkhausen noise [12]. It was shown that the extension of the multi-parameter approach by ultrasound quantities significantly increased the accuracy of target quantity prediction. In the context of steel strip testing, the use of EMATs offers the possibility to maintain a small air gap (typically < 1 mm) between sensor and strip.

2. Experimental conditions and results

2.1. Minimalistic approach

Driven by the past findings, current work aims at the development of device and sensor technology required to practically implement a process-ready 3MA/EMAT combination. This is accompanied by an improvement of the analysis procedures and an effective fusion of methods. A minimalistic concept for compact 3MA devices and sensors has been described in [13], where a reduced component number was achieved by means of adapted analysis methods and sharing the same sensor elements across different methods. The general idea behind this is that state-of-the art signal acquisition and digital processing electronics often allow for the use of less sophisticated analog preprocessing and for sensor systems to be implemented “closer to the textbook”, i.e. with less signal-enhancing complexity. This is expected to improve result interpretation and simulation, and to increase the reproducibility of sensor characteristics.

The present paper deals with a novel minimalistic sensor design combining the measurement of multi-frequency eddy current impedance, incremental permeability and ultrasonic time-of-flight with a very low number of shared components.

2.2. Data acquisition and sensor system

A high-speed multi-channel data acquisition platform called *MODIMAG* (Modular Digital Magnetics) was created in order to offer a suitable basis for simultaneous recording and real-time processing of the individual sensor signals. For 3MA, the signals to be recorded and processed are magnetic tangential field strength H, magnetic Barkhausen noise M, and the voltage/current signals of the eddy current mode. Combining 3MA and EMAT, the system additionally has to support one receiver channel per EMAT. Most of these signals contain frequencies between 0 Hz (DC) and 10 MHz. On the output side, MODIMAG has to generate the eddy current drive voltage, the control voltage for the magnetizer and several digital signals, including the EMAT transmitter pulses. The system is based on an FPGA System-on-Chip (SoC) controlled by a PC via Gigabit Ethernet, and a central 50 MSamples/s, 14-bit, 8-channel analog-digital converter (ADC).

The electrical components of EMATs and 3MA sensors are highly similar, since both are based on electromagnetic interactions with the material. The main components are an electromagnet which creates a static or quasi-static magnetic bias field tangential to the material surface, and a high-frequency (HF) coil system.

For these experiments, the HF coil system was implemented as a Printed Circuit Board (PCB) in order to ensure cost-efficient and reproducible manufacturing for commercial use later on. Each PCB contained an EMAT HF coil to be used as transmitter or receiver and a separate coil for eddy current, incremental permeability and magnetic Barkhausen noise analysis. With each transmitted burst, the transducer excites guided SH and Lamb waves propagating perpendicular to each other in the steel sheet. Depending on the transmitter/receiver arrangement, both wave modes may be used.

In order to avoid wear of the sensor and protect the steel sheet from scratches, the baseplate was equipped with air vents which, when supplied with pressurized air, allow the sensor to hover on an air cushion of approximately 0.3 mm in height. Figure 1 illustrates the sensor design and wave mode propagation, Figure 2 shows photos.

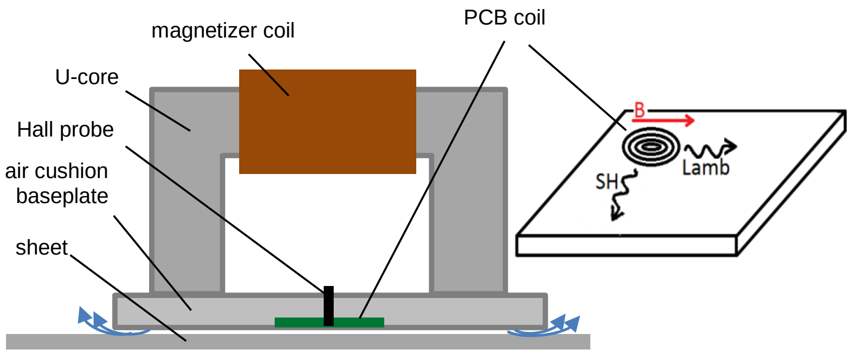

Figure 1. Sensor concept, propagation of SH and Lamb waves from the PCB coil in the bias field *B*

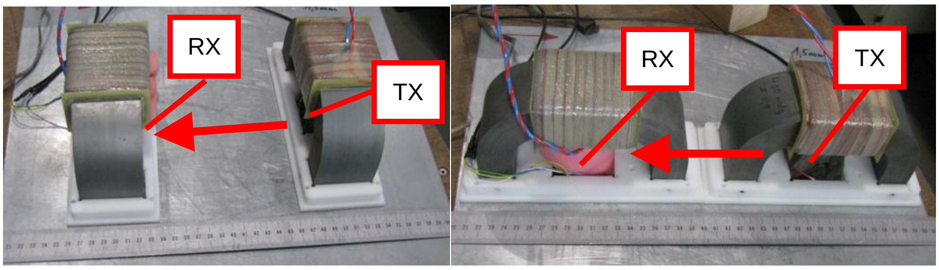

Figure 2. Orientation of transmitter (TX) and receiver (RX) for analysis of guided SH wave modes (to the left) and Lamb wave modes (to the right). The arrows indicate the direction of wave propagation.

2.3. EMAT performance

The operating frequencies needed for transmitting the desired wave modes were calculated using a-priori knowledge of the sheet thickness (see table 1). Different wave modes may be obtained, depending on the frequency and sheet thickness.

Table 1. Frequencies computed for different plate wave modes (assuming a track wavelength of 4 mm)

sheet thickness	guided SH wave		Lamb wave	
	SS0	**AS1**	**A0**	**S0**
1.0 mm	800 kHz	1790 kHz	460 kHz	1320 kHz
1.5 mm	800 kHz	1330 kHz	560 kHz	1260 kHz

The performance of different PCB coils has been compared to the one of their hand-wound counterpart of same size and number of turns. For reference purposes, the same hand-wound receiver was used in each experiment. So far, the highest efficiency was observed for a nearly square-shaped coil. The received signal amplitude was observed to be lower than the one obtained with the corresponding hand-wound transmitter (Figure 3). Impedance measurements explained this observation with an increased coil resistance which limits the quality of the receiver's resonant circuit. Next steps will focus on increasing the copper layer thickness and track width in order to reduce the electrical resistance an increase the resonance quality.

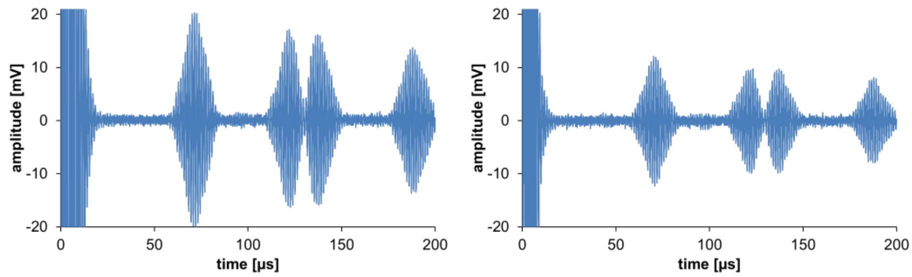

Figure 3. Ultrasound transmission signal of SS0 mode at 800 kHz, transmitted by hand-wound coil (to the left) and PCB coil of same specification (to the right)

2.4. Absolute eddy current impedance and incremental permeability analysis

Using the same sensor design as shown in Figure 2, it was possible to implement all four methods currently considered part of the 3MA approach. The following two remained unchanged with respect to the state of the art.

- Harmonics analysis of the magnetic tangential field strength was performed the same way as described in [13, 16], analyzing the field strength signal picked up by the Hall probe.
- Magnetic Barkhausen noise was picked up by the outer circular coil on the PCB and amplified on the electronics board.

In the state-of-the-art 3MA sensors, the differential transfer impedance of two pancake-shaped transmitter-receiver coil pairs is the basis of eddy current (EC) impedance and eddy current based incremental permeability (ECIP) analysis, a practical alternative to the DIN standard [14]. One of the coil pairs is close to the material under test, another coil pair is in the air, some centimeters away from the material. Back in the time of development (around 2002), this approach was required in order to obtain a sufficient signal-to-noise (S/N) ratio for the analog demodulation.

In the new, simplified approach discussed here, it was shown that using most up-to-date signal processing components, performing both methods (EC+ECIP) in a combined manner has become possible using a single coil on the same PCB described in the EMAT section before.

The measurement was performed by means of a simple circuit (Figure 4) that drives a voltage signal V_{EC} of higher frequency f_{EC} (typically between 10 kHz and 10 MHz), generated by the MODIMAG board, through a precision resistor and the combined EC testing / Barkhausen noise pick-up coil on the PCB. The voltages across resistor (V_R) and coil (V_L) were then amplified and finally digitized. Digital coherent demodulation was performed in order to compute the phase vectors of voltage and current [15]. The quotient of these phase vectors represents the absolute coil impedance Z (in correct Ohm units). ECIP curves were obtained plotting the variations of the imaginary part of Z ($Im\ \Delta Z$) as a function of the magnetic field strength H.

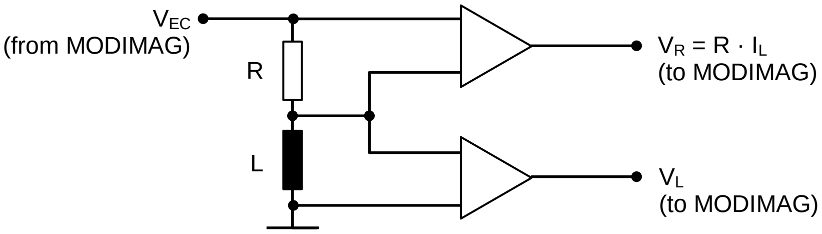

Figure 4. Absolute impedance measurement circuit

Knowing the fact that an absolute impedance measurement is strongly affected by the temperature-dependent resistance of the copper coil, the system was programmed as to periodically measure the DC coil resistance R_L by supplying a constant voltage to the output instead of the EC testing frequency. It was expected and experimentally observed that the temperature effect in the real part of Z is several orders of magnitude higher than the one in the imaginary part. A temperature-compensated impedance Z' was defined according to (1) by correcting the real part of the impedance with the measured resistance R_L and a constant nominal resistance $R_{L,0}$:

$$Z' = Re\ Z - \left(R_L - R_{L,0}\right) + i\ Im\ Z \tag{1}$$

Figure 5 shows the effect of increasing coil temperature on the measured impedance Z in air (to the left) and the temperature-stabilized impedance *Z'* (to the right).

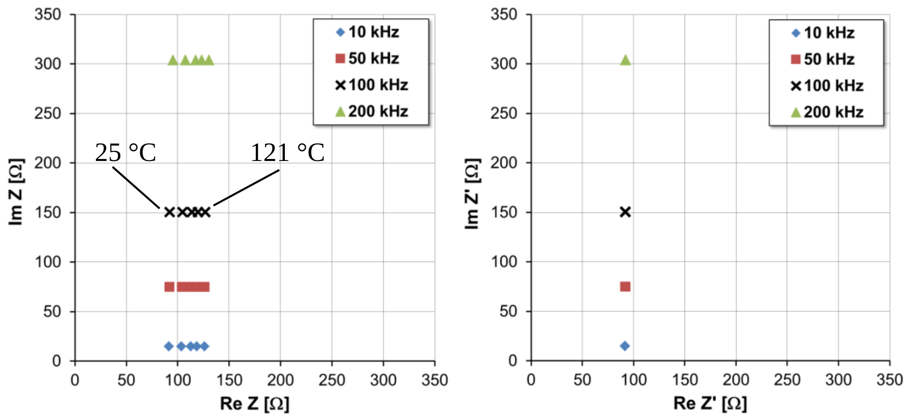

Figure 5. Uncompensated impedance *Z* and compensated impedance *Z'* at different frequencies, measured with the coil in air (data points appear as one, but in fact there are three repetitions close to each other; error bars would be too small to be recognizable)

Compared to the state of the art, several advantages are expected from the simplified to EC/ECIP measurement:

- easier and lower-cost sensor construction due to single-coil approach
- higher reproducibility of sensor characteristics, since only one coil has to be aligned in the sensor head
- easier interpretation and simulation of material behavior due to a measuring procedure close to the textbook
- absolute comparability of obtained results across several studies
- absolute measures for the magnitude of effects, since the actual impedance and its changes are always represented in Ohm units, independent from gain settings

In Figure 6 (left hand side), the temperature-compensated EC impedance at f_{EC} = *100 kHz* is plotted for different materials placed under the coil. In the graph on the right hand side, typical ECIP curves are shown for different drive voltages V_{EC}. It is remarkable that the drive voltage has no influence on the overall features of the curve and merely affects the S/N ratio. This means that the method poses low requirements to the quality and stability of the drive voltage. Increasing the drive voltage, at some point Bloch wall motions might be triggered, finally leading to an altered curve appearance. However, with a drive current in the low mA range (e.g. here 215 mV at roughly 200 Ω), such phenomena may be excluded.

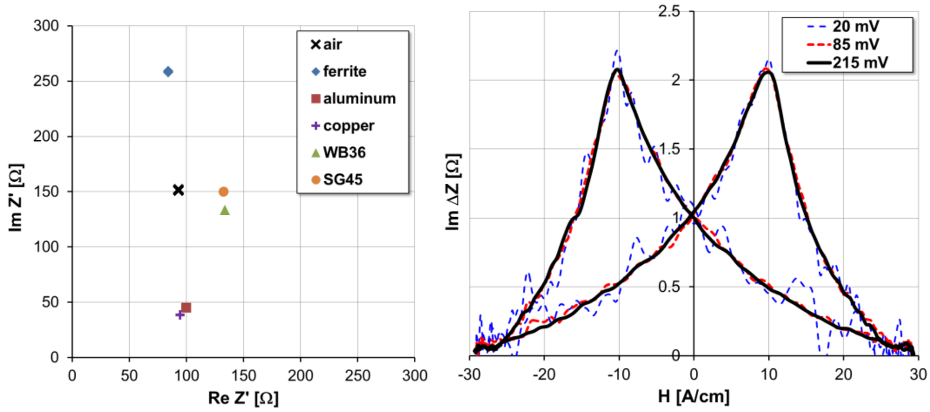

Figure 6. EC impedance on different materials (to the left, f_{EC} = 100 kHz); typical ECIP curves at different amplitudes of the drive voltage V_{EC} (f_{mag} = 100 Hz, f_{EC} = 100 kHz)

3. Conclusion

A combined ultrasonic/micromagnetic probe was developed using a minimal number of shared components and using synergies between the 3MA and EMAT sensor principles. The development focuses on the later application in the strip steel manufacturing process, particularly in the context of advanced high strength steel, AHSS. Printed circuit board (PCB) coils were designed and tested as a simple, low-cost answer to the demand for reproducible sensor characteristics. A combined method using eddy current (EC) impedance and incremental permeability analysis was developed requiring just a single EC coil which was part of the PCB. A new approach of temperature compensation in the EC impedance was demonstrated. Future work will focus on the improvement of the PCB coils regarding their efficiency as EMATs.

Acknowledgements

The underlying research project *Hybrid Micromagnetic and Ultrasonic Testing System for the In-Line Inspection of Advanced High-Strength Steel* (MAGNUS) is supported by the German Federal Ministry of Education and Research in the framework of the Fraunhofer-Carnot cooperation, ref. no. 01SF0804.

References

[1] N. Coleman, C. Breadbent, G. Coates: *Using Steel to Reduce Greenhouse Gas Emissions*. Worldsteel Association, URL: http://www.worldsteel.org/dms/internetDocumentList/bookshop/LCA-poster/document/LCA%20poster.pdf, April 2013.

[2] G. Dobmann, I. Altpeter, B. Wolter, R. Kern: Industrial Applications of 3MA – Micromagnetic Multiparameter Microstructure and Stress Analysis. in: Tamburino, A.; Melikhov, Y.; Chen, Z.; Udpa, L. (eds.): Electromagnetic Nondestructive Evaluation (XI): ENDE 2007. Amsterdam, Washington, Tokyo: IOS Press, 2008. 18-25.

[3] B. Wolter, G. Dobmann: Micromagnetic Testing for Rolled Steel. European Federation for Non-Destructive Testing (EFNDT): European Conference on Nondestructive Testing (9). DGZfP-Jahrestagung 2006. Berlin: Deutsche Gesellschaft für zerstörungsfreie Prüfung (DGZfP), 2006.

[4] G. Dobmann, B. Wolter, R. Kern: Mechanical Property Determination of Heavy Steel Plates and Cold Rolled Steel Sheets by Micromagnetic NDT. in: Canadian Inst. for NDE: World Conference on Nondestructive Testing (16): WCNDT 2004. 2004, TS4.12.3.

[5] G. Dobmann, I. Altpeter: Nondestructive Characterization of Textures in Cold-Rolled Steel Products using the Magnetic Technique. In: Green. R.E.; Kozaczek, K.J.; Ruud, C. (eds.): Nondestr. Char. of Materials VI. New York: Plenum Press, 1994, 807-816.

[6] G. Dobmann: Zerstörungsfreie Ermittlung von Werkstoffeigenschaften und Kenngrößen mit mikromagnetischen und elektromagnetischen Verfahren. In: Pohl, M. (ed.); Deutsche Gesellschaft für Materialkunde (DGM): Konstruktion, Werkstoffentwicklung und Schadensanalyse: DGM Tagungsband Werkstoffprüfung 2010. Düsseldorf: Verlag Stahleisen, 2010, 63-78.

[7] EMG Automation GmbH: IMPOC Pro Flyer, URL: www.emg-automation.com; file: ImpocPro_Prospekt_EN_01.pdf, June 2011.

[8] J. Kroos, W. Reimche, B. Heutling, A. Krys, D. Stegemann, M. Stolzenberg, G. Westkämper, R. Angerer: Development of a prototype facility for the nondestructive determination of direction dependent mechanical-technological sheet properties. Proceedings of the ECSC workshop „On-line control of flat product rolling“, 2000, 120-128.

[9] I. Altpeter: *Spannungsmessung und Zementitgehaltsbestimmung in Eisenwerkstoffen mittels dynamischer magnetischer und magnetoelastischer Messgrößen*. Dissertation. Saarland University, Saarbrücken, 1990.

[10] H.J. Bunge: *Texture Analysis in Materials Science*. Butterworth, London, 1983.

[11] M. Borsutzki, G. Dobmann, W.A. Theiner: Online ND-characterization and mechanical property determination of cold rolled steel strips. Advanced Sensors for Metals Processing, Proceedings of the International Symposium, 38th Annual Conference of Metallurgists of CIM, 1999.

[12] I. Altpeter, G. Dobmann, N. Meyendorf, E. Schneider: Erfassung von Eigenspannungen und Textur in Walzprodukten mit zerstörungsfreien Prüfverfahren. VDI Berichte Nr. 1142, 1994.

[13] K. Szielasko, I. Mironenko, I. Altpeter, H.-G. Herrmann, Ch. Boller: Minimalistic devices and sensors for micromagnetic materials characterization, IEEE Trans. Mag. **49** (2013), 101-104.

[14] Deutsches Institut für Normung (Hrsg.): *Elektromagnetisches Feld – Materialgrößen*. DIN 1324 part 2. Berlin: Beuth, 1988.

[15] S. Youssef: *Entwicklung und Erprobung einer Vorrichtung zur Wirbelstrom-Absolutimpedanzmessung für die mikromagnetische Werkstoffcharakterisierung*. Master thesis, HTW des Saarlandes, Saarbrücken, 2012.

[16] G. Dobmann, H. Pitsch: Magnetic tangential field-strength-inspection, a further NDT-Tool for 3MA. in: Dobmann, Green, Hauk, Höller, Ruud (eds.): *Nondestructive Characterization of Materials III*. Berlin; Heidelberg; New York: Springer (1989), 636-643.