Bestimmung von Eigenspannungen auf mikromechanischer Basis in metallischen Werkstoffen mit Hilfe elektromagnetischer Mikroskopie

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Kurzfassung. Eigenspannungen in metallischen Werkstoffen werden konventionell röntgenografisch und im Fall von Makroeigenspannungen (Eigenspannungen I. Art) auch über sog. Bohrlochverfahren ermittelt. Diese Verfahren sind in ihrer Durchführung vielfach mit großem Aufwand verbunden und zeigen auch oft nicht die geforderte Auflösung, die für ein Verständnis von Rissfortschrittsphänomenen erforderlich ist. In einem von der DFG geförderten Gemeinschaftsvorhaben zwischen den beiden o.g. Lehrstühlen ist die Bestimmung der Eigenspannungen in zwei Stählen an plastisch vorverformten, wie auch angerissenen ungekerbten Proben untersucht worden. Für die Untersuchungen wurde ein Barkhausen Noise and Eddy Current Microscope(BEMI) eingesetzt, mit dem an einem hochfesten, feinkörnigen Rohrleitungsstahl sowie an einem Fe-Si-Stahl die Beziehung zwischen aufgebrachter Spannung, plastischer Dehnung und resultierendem mikromechanisch gemessenem Barkhausenrauschen ermittelt wurde. Dabei hat der Werkstoff inert, d.h. herstellungsbedingt, Mikroeigenspannungen, die sich bei aufgebrachter Spannung, insbesondere auch im Bereich der makroskopisch plastischen Dehnungen, umlagern. Dieses Verhalten kann über eine Beziehung zwischen Barkhausenrausch-Signal und der aufgebrachten mechanischen Spannung beschrieben und über die entsprechenden Spannungs- bzw. Eigenspannungszustände ableitbar gemacht werden.

Die Interpretation der mit dem BEMI erhaltenen Ergebnisse wird auf einem auf der Kristallstruktur des Werkstoffs basierenden Modell aufgebaut, über das die elektromagnetischen Phänomene erklärt werden, bevor dann über eine sog. ‚Peak-Shift-Methode' die Eigenspannungen auf mikroskopischer Ebene bestimmbar sind. Auf dieser Basis werden dann Eigenspannungsprofile ermittelt, mit denen am Beispiel der Analyse von Eigenspannungen an Rissspitzen typische Rissschließeffekte bei fortschreitenden Ermüdungsrissen interpretiert werden können.

1 Introduction

In the design process of engineering components, several factors need to be considered. Structural failure and the parameters characterizing this are of major importance and need specific attention. Residual stress is one of those parameters, which may lead to failure in those components specifically when being superimposed by applied stresses due to operational loads resulting in a difference of the component's lifetime that becomes detrimental when the lifetime is shortened. In practice, many components are not free for residual stresses after production process. Therefore analysis of the change of residual stresses becomes vital to determine and/or estimate their effect combined with specific failure mechanisms. In general, residual stresses of type I arise from misfits between different regions (e.g. after shot peening) or different parts (as stresses in two riveted plates) or different phases of material (e.g. composite or multiphase steels like TWIP). A very common classification categorizes residual stresses into three types based on their characteristic length, which is defined as the length over which residual stresses equilibrate [Hauk. 1997, With. 2001]. Type I or macro-residual stresses, which equilibrate over a whole sample (e.g. compressive stresses in shot peening surface), type II or micro-residual stresses which equilibrate over some number of grains (e.g. local stresses between two different phases), and type III or micro-residual-stresses, which equilibrate over a grain (e.g. stresses around dislocation).

By means of modern analytical and simulation techniques, which can nowadays estimate stresses of components during service, the question arises, why stress measurement methods are essentially in need? To answer this question it should be mentioned that computational methods are not sufficient to predict failure in components especially in complicated situations where residual stresses cause failure in combination with applied stresses. On the other hand, a simulation can always only be as good as its inputs are. Thus experimental stress measurement techniques are an essential instrument of validation. In overall, there are three types of destructive, semi-destructive and nondestructive stress measurements methods [Hauk. 1997], where each one has its advantages and disadvantages. Among many stress measurement techniques and methods, just a few are widely used. X-ray diffraction (XRD) and hole drilling are the two most popular stress measurement techniques. The hole drilling method has an easy principle however it is a destructive method and has huge sources of error. On the other hand, although XRD technique is nondestructive, it is essentially complicated and may lead to big errors too. Moreover, it might be necessary to prepare a sample for performing the measurements. When the time consumption factor is added to those disadvantages a new nondestructive stress measurement method being reliable, quick, low cost and also easy to use may be in need. This need is further underlined when a map of stress distributions is required (e.g. stress distribution in front of a crack tip to investigate crack opening procedure), which many conventional stress measurement methods either are not able to do or are very time consuming. The Magnetic Barkhausen noise (MBN) method is a valuable candidate to measure residual stresses nondestructively because of its capability to measure and its sensitivity to residual stresses in general.

2 Objectives

Since German physicist Heinrich Barkhausen discovered the magnetic Barkhausen effect in 1919, further research has been performed to present the sensitivity and capability of MBN with respect to microstructure and residual stress changes. Especially since the 1970's, researchers presented the sensitivity of MBN on stresses. From that time up to now, the effect of stress on MBN or detection of residual stresses using MBN has become an important subject for researchers because of its cleanliness, speed, portability and easy handling of a Magnetic Barkhausen noise (MBN) device. Apart from the capability and sensitivity of MBN on stress, the use of MBN for stress measurement has a substantial drawback, which is the need and complexity of calibration. Although some researchers tried to propose easier calibration methods, this problem still has no appropriate solution. To find a method for measuring micro residual stresses, the behavior of MBN under elastic and plastic deformation in-situ has been investigated.

The objective of this work, based on the short history mentioned above, is to propose a nondestructive approach called the "local micro-residual stress measurement method based on magnetic Barkhausen noise" (RESTMAB) which requires minimal calibration effort. This method is also proposed for a Barkhausen noise and eddy current microscope (BEMI), which has been used as an equipment to develop and validate RESTMAB on the basis of high resolution measurement of local micro residual stresses around a crack tip.

3 State-of-the-art

Kneller reported that Kersten began to investigate the relationship between magnetic properties and micro residual stresses in ferromagnetic materials in the 1930ies [Knel. 1962]. The theory of micromagnetic suggests that the magnetic hysteresis is produced by the microscopic DW motion and its interaction with the microstructure and stress fields.

Cullity was one of the pioneer researchers who proposed a simple model on the interaction between DWs and stresses inside materials [Cull. 2009]. When trying to determine a unit onto which the effect of stress on a DW behavior can be reduced best such that the resulting electromagnetic principle can be generalized the smallest common "denominator" turns out to be a material's single crystal. Figure 1a shows symbolically a single crystal comprising four domains in an unstressed state. A small tensile stress will lead the DWs to move in such a way that the sign of the domains magnetized perpendicular to the stress directions will be reduced because these domains have high magnetoelastic energy (Figure 1b). These domains will even vanish when the applied tensile stress has reached a certain level and remaining magnetoelastic energy turns to a minimum (Figure 1c). Only a small additional applied electromagnetic field is now required to fully saturate the specimen because the transition can be achieved by a simple 180° wall motion (Figure 1d). When a compressive stress is applied to the crystal (Figure 2a), then the domains in the direction of the stress will gradually vanish (Figure 2b and c) and a much higher electromagnetic field has to be applied in case a fully saturated crystal is intended to be achieved (Figure 2d).

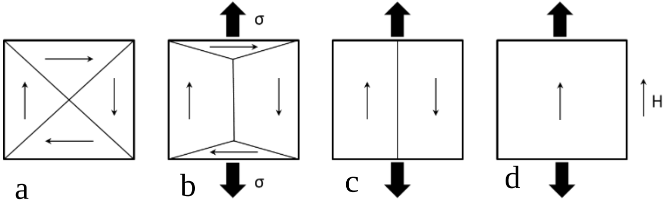


Figure 1: Schematic magnetization of a material with positive magnetostriction under tensile stress.

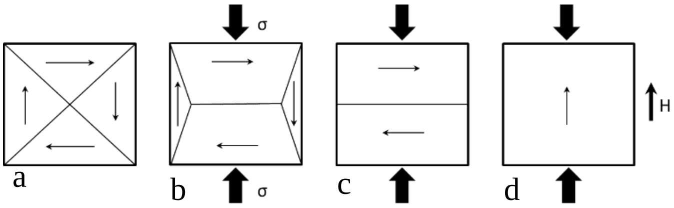


Figure 2: Schematic magnetization of a material with positive magnetostriction under compressive stress.

The type of crystal and its orientation can therefore become the building block on how to understand a structural material's as well as component's stress behavior based on MBN measurements or to interpret MBN measurement results when stresses in a material and/or structure are known.

Concerning the effect of stress on the DW motion, Cullity proposed that the effect of micro stresses on the motion of DWs depends on the type of DW and is related to magnetostriction [Cull. 2009]. When a 90° DW moves, the magnetization direction changes, and a distortion in volume due to the magnetostriction arises. This distortion interacts with stress distribution. On the other hand, when a 180° DW moves, the magnetization direction will not change, therefore no magnetostriction occurs. Just local stresses change the DW energy by adding a stress anisotropy term ($K\sigma=3/2\lambda\sigma$) to the crystal anisotropy.

4 Experimental setups

In the first step, non- and pre-deformed samples were in-situ investigated under applied stress. The effect of elastic applied stress was investigated on non- and pre-plastically deformed samples. It should be noted that the effect of tensile stress was investigated under gradually increasing applied stress until half of yield stress and tests were performed at each at each 50 MPa steps. Note that the magnetizing frequency and amplitude were 100 Hz and 15 A/cm for MBN measurement, respectively.

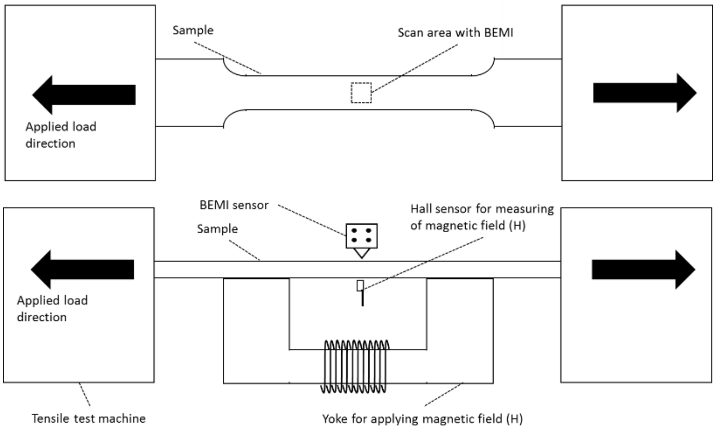


Figure 3: Schematic setup of in-situ MBN measurement under applied stress.

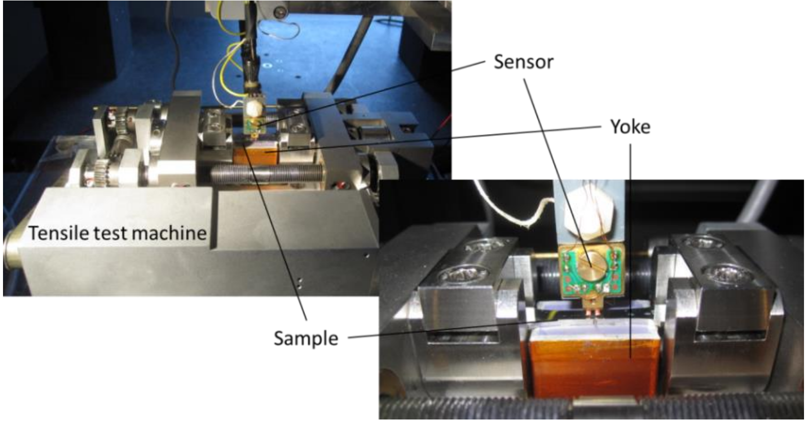


Figure 4: Actual setup of in-situ MBN measurement under applied stress.

The measurement setup for in-situ measuring of micromagnetic parameters under applied stress is illustrated in Figure 3 and Figure 4. The results include very considerable information which is the foundation of the proposed stress measurement method based on MBN.

In the next step, an application of calibrated BEMI with RESTMAB method was investigated, that BEMI can deliver residual stress mapping of sample. In this section, BEMI was used to monitor the stress distribution and the size of plastic zone in front of the crack.

To this end, a non-deformed sample with a notch was fatigued in a stress-controlled situation with σ_{max} was 250 MPa and the creation and propagation of crack was monitored using replica method on each 1000 cycle. When the crack size was around 100µm, the test was stopped for further tests. SEM images were taken and BEMI scan was performed to measure stress distribution. Then sample was overloaded to 575 MPa to generate a plastic zone in front of the crack. Then it was fatigued again up to stress amplitude of 250 MPa, and crack propagation was monitored with replica method and after each 100 µm of crack propagation the fatigue test was interrupted to measure the size of plastic zone and stress distribution at crack tip. BEMI was used to measure stress distribution at crack tip and the size of plastic zone at the crack tip. Finally using BEMI results, the trend of crack opening rate (da/dN) vs stress intensity factor was described.

5 Results and discussion

Figure 5 presents the effect of elastic applied stress on micro-magnetic properties on non- and pre-deformed samples. Since the behavior of all MBN parameters have similar information, here we will concentrate on M_{MAX} behavior first. M_{MAX} is the maximum amplitude of MBN.

Altpeter and Rabung [Altp. 2009, Rabu. 2014] have shown that the position of maximum of $M_{MAX}(\sigma)$ curve is proportional to the micro-residual stresses of samples. It was also reported that the difference between the positions of two peaks presents the micro residual stress difference between samples [Altp. 2009, Rabu. 2014]. In other word, the peak shift of $M_{MAX}(\sigma)$ of an known sample related to the reference sample is equal to the micro residual stress of the unknown sample. Therefore two things are very important to have reliable results:

- Since a sample must be compared with a reference sample, a reference non-deformed sample in a stress-free state is needed.
- Determination of position of maximum of $M_{MAX}(\sigma)$ curve is precisely required.

Figure 5 shows the position of the maximum of $M_{MAX}(\sigma)$ curve for non- and pre-deformed samples calculated with software. Since for the non-deformed sample it was assumed that it has 0 MPa residual stress, the difference between maximum of non-deformed and pre-deformed samples indicate the micro-residual stress of pre-deformed sample. The sign of micro-residual stresses were defined with the position of maximum of $M_{MAX}(\sigma)$ curve of pre-deformed sample related to the $M_{MAX}(\sigma)$ curve of non-deformed sample. If the maximum of $M_{MAX}(\sigma)$ curve of pre-deformed sample locates at left side of the maximum of $M_{MAX}(\sigma)$ curve of non-deformed sample, pre-deformed sample has tensile micro-residual stress (σ+). It has compressive micro-residual stress (σ-) when the maximum locates at right side related to the no-deformed sample [Altp. 2009, Rabu. 2014].

Table 1 shows the micro-residual stresses of non- and pre-deformed samples calculated with peak shift method as well as measured residual stresses with XRD method. Since tensile plastic deformation generates compressive micro-residual stresses after unloading, the sign of calculated and measured residual stress are describable. Besides, the difference between calculated and measured residual stresses values are in acceptable range for 0 and 1%, in contrast there is a big difference between calculated and measured value of residual stress for 3% pre-deformed sample. The 1% pre-deformed sample shows -11 MPa residual stress which is caused by the martensitic microstructure [Bhad. 2001]. Martensite induces small compressive residual stress because of its nature of martensitic transformation [Bhad. 2001].

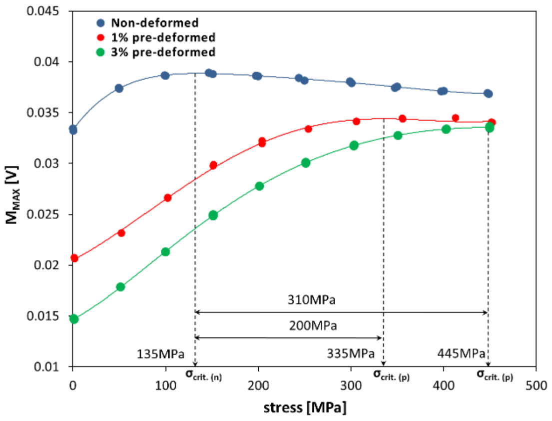


Figure 5: Difference between maximum of $M_{MAX}(\sigma)$ curve of non-deformed (reference) sample as well as pre-deformed samples of a) pipeline, and b) Fe-Si steels.

Table 1: Micro residual stress values of pipeline steels measured with and peak shift method and XRD.

	Residual stress	
Samples	Peak shift method [MPa]	XRD [MPa]
non-deformed	0	-11.5
1% pre-deformed	-200.18	-208.4
3% pre-deformed	-310.87	-185.3

Another case which needs to be explained is why sample with 1% and 3% pre-deformation show relatively the same compressive residual stress in XRD results while peak shift method shows a significant difference! To answer of this question should look into the nature of two methods. XRD method for measuring macro residual stress is based on change of position of peak at lattice parameter-intensity curve while for measuring micro residual stresses is based on change of width of peak at half maximum at lattice parameter-intensity curve [Hauk. 1997]. In this work, the first mentioned method was used since no change in width of peak at half maximum of lattice parameter-intensity curve was observed. Therefore, the XRD values indicate the macro residual stresses of samples while slope method shows the macro plus micro residual stresses. In other word plastic deformation more than 1% just increases the local micro residual stresses by increasing the number of dislocation tangles. [Kleb. 2004]. Since the micro residual stresses caused by dislocations are type III of residual stresses, it is difficult for XRD to detect it. In contrast slope method is capable to measure residual stresses of IInd and IIIrd types. Therefore slope method based on MBN is more sensitive when measuring residual stresses of IInd and IIIrd types. Also, the penetration depth of XRD technique is much less than MBN. This is also an error source in XRD measurements.

After calibration of BEMI an application of BEMI and RESTMAB method which is micro residual stress distributions in front of crack tip is presented. To this end a series of experiments were carried out to detect the size of plastic zone and residual stresses distribution around the crack as well as crack tip after fatigue test. As can be seen in Figure 6, the crack opening rate is increasing linear before over load position (position 1). After over load, the crack opening rate (da/dN) decreases although the stress intensity factor (ΔK) increases. Generating of micro compressive residual stresses in front of crack tip is the reason of decreasing da/dN. In other words, the micro residual stresses in front of crack compress the crack and prevent it for growing. This trend continues up to position 4, then da/dN increases again parallel to the linear trend before over load (position 1).

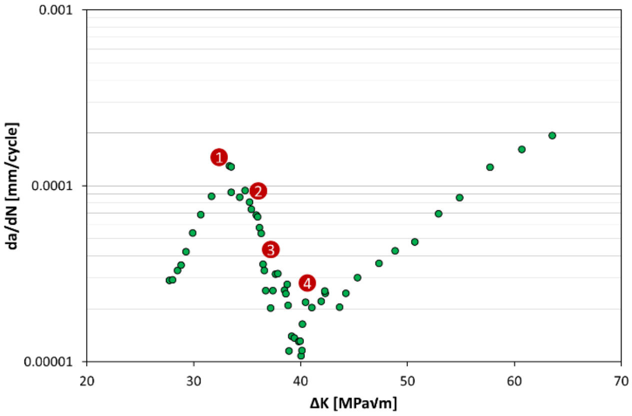
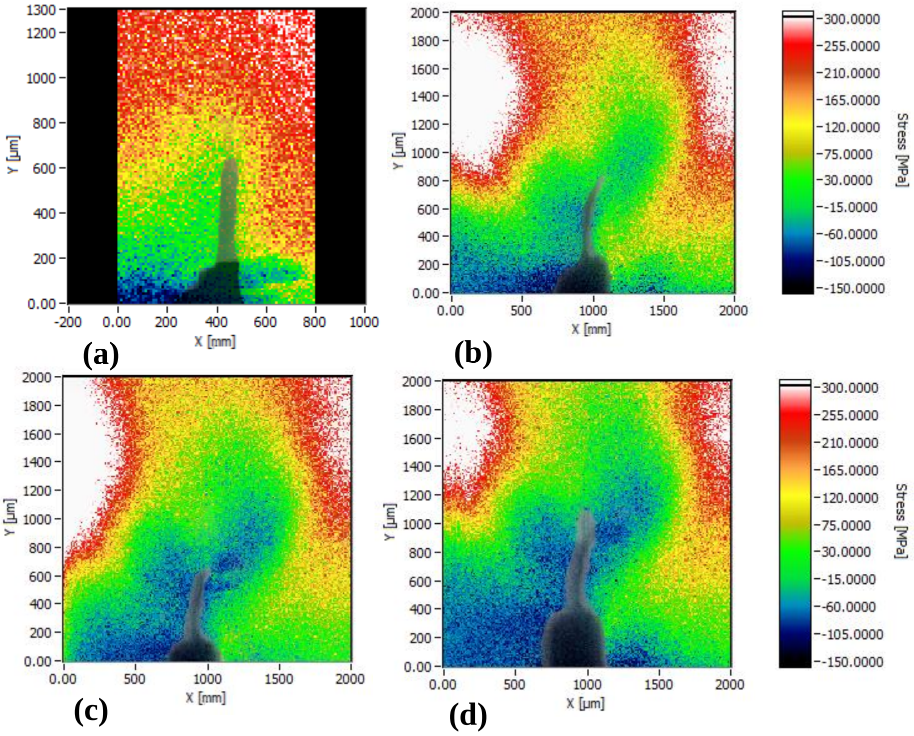


Figure 6: Change of crack opening rate (da/dN) related to the changes of stress intensity factor. Fatigue process was interrupted at marked points for further investigations.

Since it was reported [Lee. 2011] that the local residual stresses are the reason of behavior in Figure 6, stress distribution in sample especially in front of the crack was measured using the BEMI to find a reason for trend observed in Figure 6. Therefore an area in front of crack was scanned in 10µm lateral resolution using BEMI which was calibrated with RESTMAB method. Figure 7 shows BEMI results which illustrate stress distribution as well as plastic zone in front of the crack. As can be seen in Figure 7a, before over loading of sample, there is not a visible plastic zone around the crack but Figure 7b shows a drastic changes of stresses distribution which are localized in front of the crack. Using BEMI scans, the size of plastic zone and stress distribution around of crack was measured.

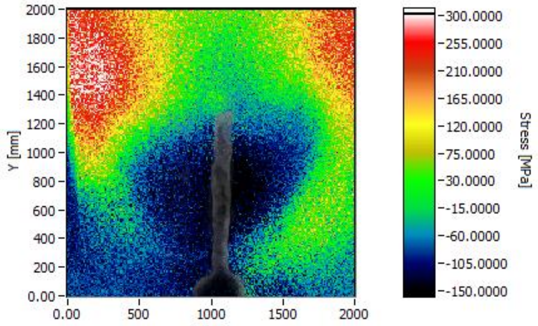


(a)

(b)

(c)

(d)



(e)

Figure 7: BEMI scans at different positions of crack opening curve (Figure 6). a) position 1 (before over load), b) position 2 (after over load), c) position 3, d) position 4, e) position 5 (when crack passes from compressive residual stresses area). Dark gray sketch shows notch and crack.

The size of plastic zone was measured with the BEMI, DIC (Digital Image Correlation), light microscopy with Normarski contrast method and analytical calculation based on Irwin method. Table 2 shows the results which illustrates that BEMI result is in good agreement with other ones. Just there is difference between sizes of the plastic zone measured with DIC.

Table 2: The size of plastic zone in front of crack after over load which measured with different methods.

Method	DIC	N-DIC	Irwin	BEMI
Pl. Zone [µm]	675	838	828	840

Furthermore, BEMI scans show that a big compressive residual stress zone has been built in front of the crack after over load. This is the reason why crack opening rate decreases after over load. The maximum measured compressive residual stress is -150MPa in plastic zone.

In short conclusion, it can be noted that BEMI calibrated with RESTMAB successfully detects stress distributions in front of a crack tip with high lateral resolution. The BEMI scan which is quick with high resolution is useful to investigate the crack opening process during fatigue.

Aknowledgment

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