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Working point determination of 3MA micromagnetic NDT-technique for production integrated detection of white layer during turning of AISI4140

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Abstract

High strength steels are important in terms of lightweight, safety and economical aspects for mobility concepts of the future. In fact, machined surfaces and its characteristics are essential for the entire product-lifecycle. In the presented work, the capability of micromagnetic nondestructive-testing (NDT) techniques combined in 3MA, and optimal working point determination to detect critical surface states such as white layer (WL) associated to hardness increase and its characteristics is discussed. An outlook is given how in terms of Industry4.0 production-integrated determination of material characteristics can enable in-line monitoring and closed-loop control for an optimization of production processes.

Keywords: Hardness; Heat treatment; High strenth steel; Micro structure; Quality assurance; Surface analysis; Turning; White Layer;

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1. Introduction

High strength steels are important when lightweight, safety and economical aspects for mobility concepts of the future have to be considered. In fact, for safety-critical parts or components which are exposed to high thermal- or mechanical stresses the machined surface is essential for the whole product-lifecycle. Machining-induced changes in material properties such as microstructure, dislocation density, local strength, hardness and residual stress [1] lead to critical surface states such as the formation of white layer (WL) [2, 3]. The overall objective is to achieve homogeneous surface states by developing a real-time and closed-loop system to control and predict the formation of WL during turning of AISI4140. It is well known that an identification of mechanical material properties can be realized via destructive testing (DT) and nondestructive testing (NDT) methods. A suitable NDT-technique for the detection of WL is the so called "Micromagnetic, Multiparametric Microstructure and Stress Analysis" (3MA). This paper deals with fundamental research to develop an adapted 3MA-system, which is suitable for in-process detection of WL-formation. Therefore, a favored solution is to measure WL-formation contactless with a lift-off to avoid disturbances of contact-based friction between the 3MA probe head and the rotating part. Thus, the electromagnetic interaction depth is depending on the lift-off, the probe head design, the magnitude and frequency of the applied magnetic field as well as on the electromagnetic properties (magnetic hysteresis and electric conductivity) of the inspected ferromagnetic material [4, 5]. This paper focusses on the working point of 3MA for WL detection determining a basic set up of high sensitivity and less disturbances for the 3MA-system by varying the air gap (LiftOff) magnitude and frequency of the applied magnetic field. The setup and outcome of these experimental laboratory investigations is discussed.

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2. State of the art

Torrance [6] discussed hardened surface structures in AISI52100 and other materials due to the grinding process. He could show that surface irregularities in near surface-near zones appear white after etching combined with martensite formation and hardness increase due to rehardening burns.

Stampfer et al. [1] discuss the occurrence of WL during turning of AISI4140 for different heat treatment stages and its white appearance via optical microscopy due to light dispersion at nanocrystalline structures. Mechanical induced WL and thermally induced WL were observed. Microhardness measurements at the cross-section could be correlated to the thickness of WL formation. For defining a process model and surface integrity model a non-destructive hardness detection will be the next step.

Wolter et al. [4] have described research activities related to micromagnetic methods for nondestructive characterization of microstructures and mechanical properties of ferrous material. Here the so called 3MA technique was used, which is a combination of the four micromagnetic NDT methods Barkhausen Noise (BN), Incremental Permeability (IP), multi-frequency Eddy Current (EC) and Harmonic Analysis of the tangential magnetic field strength (HA).

For a specific excitation system, which is in this case the combination of yoke and magnetization coil in the 3MA probe head, it is clearly described that the electromagnetic interaction depth is solely dependent on the magnetic field strength and the excitation frequency and can reach depths of up to 10 mm.

Based on FEM simulations Gabi [5] has developed models for the simulating 3MA signals and signal parameters in different gradient materials such as in case hardened and machined components. Based on these simulations, it was possible to correlate measuring parameters of IP, EC and HA with depth-dependent material properties like case depth, hardness and residual stress profile. Furthermore, maximum analyzation depth and lift-off influence (distance between sensor and sample) could be described analytically based on these simulations. 3MA opens up the perspective for new application areas due to the fact, that it can be sensitive to raw material changes and batch fluctuations in terms of microstructure, hardness and more as also described in [4].

Brown et al. [3] discuss machining-induced WL and several NDT methods for its detection. The authors conclude that BN has been a capable method for WL detection but further development has to be done to separate hardness changes from residual stress influences. Stupakov et al [7] also conclude BN as a capable method for WL detection of milling induced surface damage.

In general, the 3MA micromagnetic measuring technique is suitable for AISI4140 and similar groups of materials. Regarding the machining of AISI4140, several types of white layer can be investigated for different production processes. Therefore, it is necessary to understand the micromagnetic behavior for the explicitly used raw material AISI4140. It is essential to distinguish between base material prior to the turning process and hardness increase along with WL formation after turning process and to correlate it to the micromagnetic parameters measured by the 3MA-system.

3. Experimental setup

The examined workpiece AISI4140 with tempering stage was machined by longitudinal dry turning tests with a preworn tool (TiCN-coated carbide insert, VB 0.1) on a machining centre (Index G200). The heat treatment was conducted according to DIN10083 involved quenching and subsequent tempering with 300°C at a duration of 1 h, as described in [1]. The workpiece is hereafter termed as AISI4140 QT 300 and has an outer diameter of 44mm with a shape depicted in Fig .2. (c). The machining parameters are given in Table 1.

Table 1. Cutting parameters and tool geometry for the turning test of AISI4140 QT 300 (Cutting velocity v_c, Feed rate f, Depth of cut a_p Clearance angle α, Rake angle γ, Cutting edge angle κ, Cutting edge inclination λ, Tool corner radius r_ε).

v_c	f	a_p	α	γ	κ	λ	r_ε
m/min	mm	mm	°	°	°	°	mm
300	0.3	0.3	7	0	95	0	0.4

Applying these parameters leads to a formation of thin and thick WL in near surface zones during the turning process, as depicted in Fig. 1. (a) (b), with approximately 10µm thickness in depth.

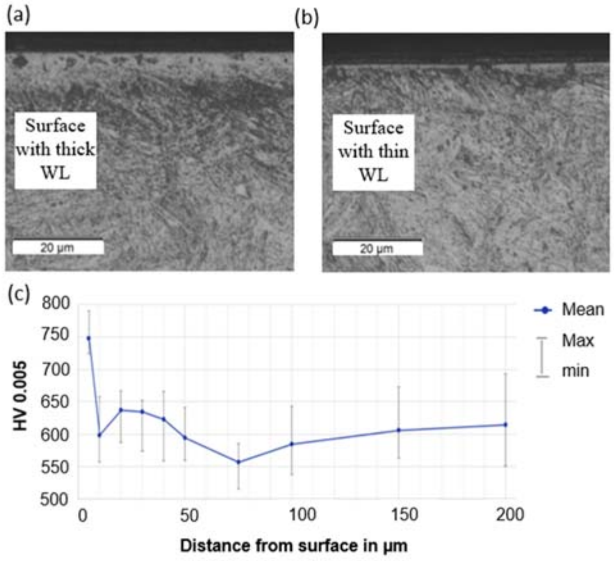

Fig. 1. Microsection of AISI4140 QT 300 cross section with bulk material in bottom and surface area on top with (a) thin WL formation; (b) thick WL formation; (c) hardness curve of specimen with thick WL.

Hardness was measured with instrumented indentation testing IIT, see Fig. 2. (c) and corresponding hardness curve Fig. 1. (c), with approximately 750 HV in 5µm depth from surface and a hardness decreases sharply at a depth of 10 µm. The bulk material already has a high hardness of approximately 600 HV in a depth of 200µm due to its tempering stage.

The further examination was performed using a 3MA-II system and a probe head containing a fixed and therefore non-moveable hall sensor, transmitter and receiver coils to be able to position the probe head with LiftOff to the workpiece. The magnetic pole shoe with pyramid shape, see Fig. 2. (a), has an inner diameter of 7mm and an outer diameter of 11mm

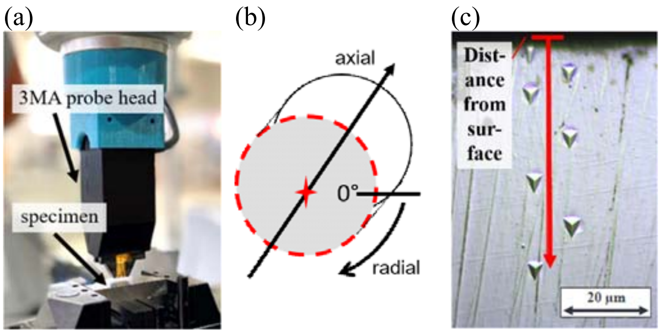

Fig. 2. Experimental setup of (a) 3MA probe head in bulk material position; (b) scheme of the initial specimen for 3MA radial measurements; (c) depth indentation testing on cross section of specimen with thick WL formation.

The measuring parameters are listed in Table 2 such as applied magnetic field with its variation in amplitude (MagAmp), frequency (MagFreq) and LiftOff.

Table 2. Measuring parameters of the 3MA-II system for applied magnetic field with variation in Amplitude (MagAmp), Frequency (MagFreq) and variation of air gap (LiftOff).

MagAmp	MagFreq	LiftOff
A/cm	Hz	mm
15, 20, 25 ,30 ,35 ,40 ,45 ,50 ,55 ,60 ,65 ,70 ,75, 80	352	0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1

4. Results

Experimental laboratory 3MA investigations on AISI4140 QT300 were conducted first in bulk material area which is equal to initial state before the turning process and secondly on surface regions with WL formation. The used experimental setup is described in the previous chapter.

Fig 3. shows the Coercive magnetic field Hcm derived from BN of bulk material as a function of MagAmp in steps of 5A/cm from 5A/cm to 80A/cm for different LiftOff in steps of 0.1mm from 0.0mm to 1.0mm, see Table 2.

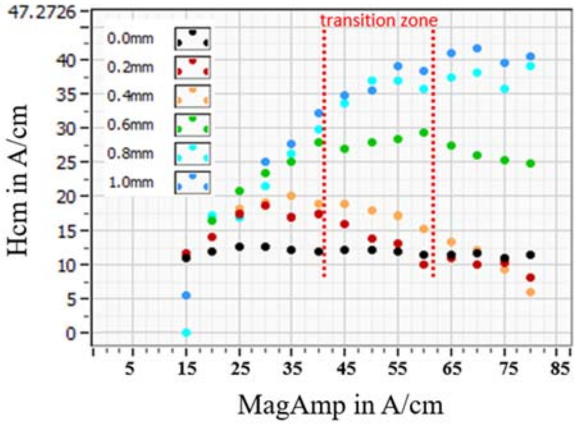

Fig. 3. Comparison of Hcm at MagFreq 352Hz marked transition zone for 0.6mm in red.

Due to similarity of the curves for higher LiftOff it can be said that maximum detectable signal to noise ratio for the 3MA probe head due to magnetic field strength and skin depth δ is reached by a LifOff greater than 0.8mm.

$$\delta = \frac{1}{\sqrt{\pi*\sigma\ \mu_0*\mu_r*MagFreq}} \qquad (1)$$

It is well known from formulas (1) and [4, 5] that the magnetic permeability μ_r of the material which can be measured by the 3MA-system via $\mu_{r,apparently}$ is depending on set up parameter MagAmp, MagFreq, LiftOff and geometry effects G_e of the sample with non-linear behavior, like described in equation (2).

$$\mu_{r,apparently} = (MagAmp, MagFreq, LiftOff, G_e) \qquad (2)$$

Since the aim for a 3MA-system setup is a high measuring frequency and low penetration depth enabling high sensitivity in surface near zones, MagAmp should be chosen for high $\mu_{r,apparently}$.

Indeed [4, 5] describe that high $\mu_{r,apparently}$ is represented by the turning point of Hcm in transition zone where measured data presented in Fig 3 for 0.6mm LiftOff reaches Hc=28A/cm and changes from linear gradient to asymptotic behavior. Respectively for MagAmp 40A/cm to 60A/cm.

In the following the parameters LiftOff 0.6mm, MagFreq 352Hz were chosen to proof if it is possible to distinguish between base material before the turning process and after turning process, see Fig. 4., indicated by micromagnetic parameter Hcm of the 3MA-system.

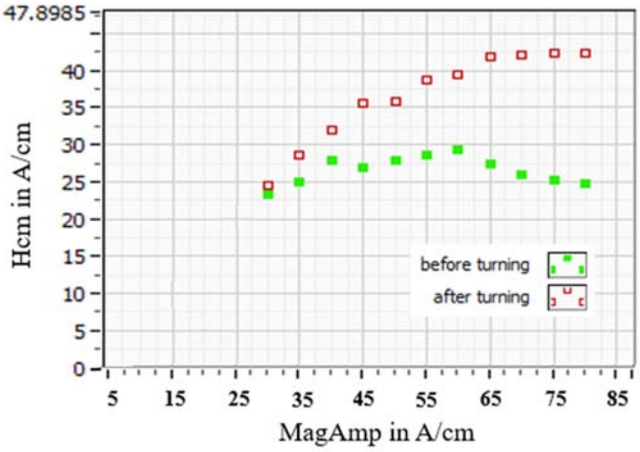

Fig. 4. Comparison of Hcm for AISI4140 QT300 before (without WL) and after (with WL on surface) the turning process at different MagAmp values.

Fig. 4 clearly shows a significant difference between AISI4140 QT300 before the turning process and after the turning process by variation of MagAmp from 30A/cm to 80A/cm and measuring of Hcm. A transition zone as depicted in Fig. 3 develops whereby in this case for the working point after turning a shift takes place to higher MagAmp. Therefore 60A/cm would be most suited for highest sensitivity (difference in Hcm) of approximately 10 A/cm.

To evaluate the radial change in WL thickness in the microsection of the cutted sample shown in Fig.1 (a) (b) and to proof the behavior of the previous mentioned micromagnetic behavior, a radial testing of a round specimen 0.5cm in axial position prior to the microsection with thick WL formation was conducted contact based. 3MA-system and pyramid probe head with MagAmp 60A/cm and MagFreq 352Hz in angle steps of π/360 was performed. Coercive magnetic field Hcm derived from BN and coercive magnetic field Hcu derived from IP over measurement angle are shown in Fig. 5. Furthermore, the zones of thick and thin WL appearance out of microsection with proper radian are shown. Hcu shows less noise compared to Hcm whereby both have an even oscillation with highest peak for an angle of approximately 0.8π and lowest at 1.8π. Noticeable is the proven microsection for thin WL appearance in the zone of lowest values of Hcm and Hcu and thick WL appearance for higher values of Hcm.

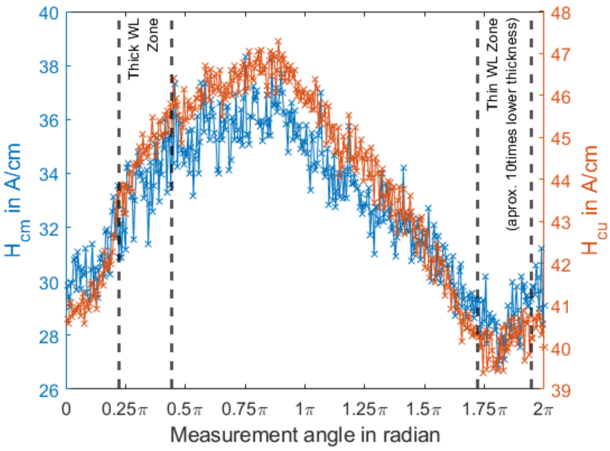

Fig. 5. Comparison of Hcm and Hcu for radial sample surface measurement of AISI4140 QT300 with thick WL- and thin WL-formation.

5. Conclusion

Experimental laboratory investigations on AISI4140 QT300 were done to examine high sensitivity and less disturbances in 3MA setup and to allow fast measurements by high magnetization frequency with low penetration depth.

It is shown that maximum detectable signal to noise ratio for the 3MA probe head is reached by a LifOff greater than 0.8mm.

An investigation based on micromagnetic parameters via 3MA to distinguish between AISI4140 QT 300 base material before the turning process and after turning process with the formation of 750HV of WL 10µm in thickness in surface near zones compared to 600HV in bulk material with no WL formation is possible. High values of Hcm (derived from BN) with sensitivity of approximately 10 A/cm have been measured. Furthermore, radial testing of the round sample surface with thin WL appearance in the zone of lowest values of Hcm and Hcu (derived from IP) compared to high hardness and thick WL appearance for higher values of Hcm occurred. Although there is a clear tendency in micromagnetic data for hardness increase combined with WL formation in surface near zones these findings cannot be generalized. For a greater view, residual stress analysis needs to be done in future and a comparison of its profile to the remaining and unanalyzed micromagnetic data in order to increase the predictive significance.

In next steps this feasibility analysis will be transferred to other tempering stages of AISI4140. Depicted experimental laboratory investigations can be transferred directly into the machining process with an automated positioning to fix the LiftOff position in-process by 0.6mm and hence to proof the applicability.

3MA uses a correlation between the measured micro-magnetic properties of the material and its mechanical or microstructural properties. Based on destructively determined reference values in the next step a polynomial function by a regression analysis, which describes the mathematical relation, needs to be calculated for micromagnetic properties. The calibrated 3MA-system shall be used in future to measure absolute hardness and residual stress profiles during the turning process indicating WL formation.

The described 3MA-system opens up the possibility of a quality assurance with 100%-inspection during machining via nondestructive determination of mechanical and microstructural properties and will reduce the amount of microsections. Furthermore, an observation of the measurement uncertainty creates the prerequisites for an industrial application of the NDT-techniques. In terms of Industry 4.0 the combination of 3MA with further production integrated NDT methods such as acoustic-emission techniques combined with real-time analysis, could enable an in-line monitoring and closed-loop control for the optimization of the production process turning.

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