Monitoring of the fatigue state of single-lip deep-drilled specimens made of the quenched and tempered steel AISI 4140 using micromagnetic methods

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Abstract

Fatigue is one of the main causes for the failure of technical components. Therefore, the monitoring of fatigue-related material degradation is a target-oriented way to extend the lifetime of safety-relevant components. In terms of sustainability and resource conservation, the implementation of reliable fatigue monitoring is of crucial importance. Fatigue damage is manifested by a variety of microstructural and micromechanical property changes such as grain refinement, relaxation of residual stresses, increase of dislocation density and hardness change. An application of micromagnetic techniques is very promising, since it is known that Barkhausen noise analysis and eddy current testing are sensitive to these parameters.

This work deals with the separation of the micromagnetic parameters with respect to fatigue-induced changes. This separation is necessary to identify, quantify and evaluate the relevant fatigue damage mechanisms and thereby assess the remaining lifetime of the monitored components. In this work, multiple amplitude fatigue tests were performed on specimens drilled under different conditions and as a consequence partly feature a white etching layer. Under these aspects the capability of Barkhausen noise analysis and eddy current testing was compared and assessed.

1 Introduction

The surface integrity is crucial for the fatigue performance of machined mechanical components. For example, the drilling parameter and cooling strategy of single lip deep-drilling processes have a main influence on the subsurface microstructure, hardness and residual stresses [1–3]. Therefore, the validation and monitoring of the machining induced surface integrity aspects during fatigue tests are a promising approach for the development of a condition monitoring system. It was shown, that the magnetic Barkhausen noise technique (MBN) is suitable to detect the hardness [4,5], microstructure [6,7] and residual stresses [7] and as a consequence is capable to fulfill the requirements for the monitoring tasks. In machining operations the formation of white etching layers (WEL) is often associated with unfavorable mechanical conditions like brittleness and tensile residual stresses [8,9], moreover it was shown that these layers inhibit the characterization of the surface integrity by MBN [10], therefore besides MBN eddy current measurements were conducted.

2 Materials and methods

The specimens (*Fig. 1*) were produced from low-Sulphur AISI 4140 (42CrMo4+QT, 1.7225) in quenched and tempered condition. The material has a tensile strength of 965 MPa and a hardness of 316 HV10 [11]. The chemical composition comply the limits defined in EN 10083-3 and can be found in *Tab. 1*.

Tab. 1: Chemical composition [11]

C	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Fe**
0.41	0.18	0.85	0.011	0.011	1.01	0.18	bal.

The drilling experiments were performed using two different cooling strategies, both using solid carbide single-lip drill tools by Botek Praezisionsbohrtechnik (Riederich, Germany) with a diameter of 5 mm. Firstly using the conventional deep drilling oil ISOCUT T 404 (oil) for cooling and lubrication on an IXION TLF 1004 (Wedel, Germany). Secondly using a minimum quantity lubrication approach (MQL) using a Shell Garia SL201 with $\dot{V}_{Oil}$ = 50 ml/h and $\dot{V}_{Air}$ = 10 m³/h on a Grob BZ 600 (Mindelheim, Germany). Both processes were performed with a cutting velocity of v_c = 50 m/min and a feed rate of f = 0.05 mm.

The light microscopic images were taken at cross sections in cutting direction as displayed in *Fig 1*. The cross sections were etched in Nital and investigated using a Keyence VHX-7000 digital microscope (Osaka, Japan).

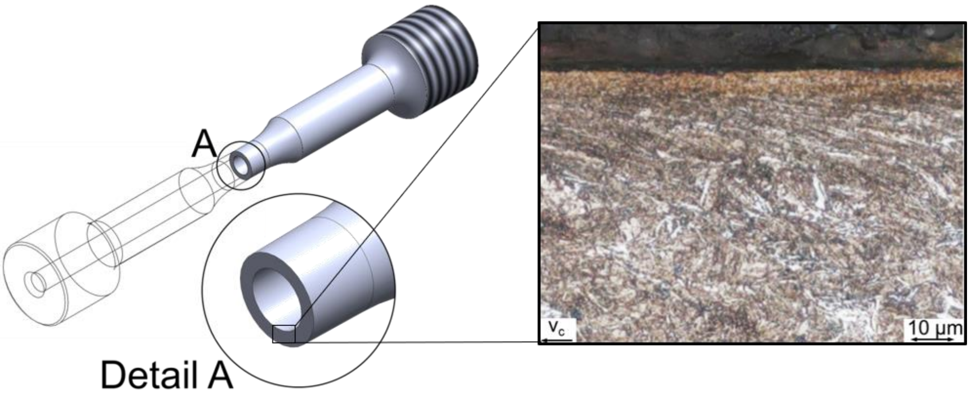
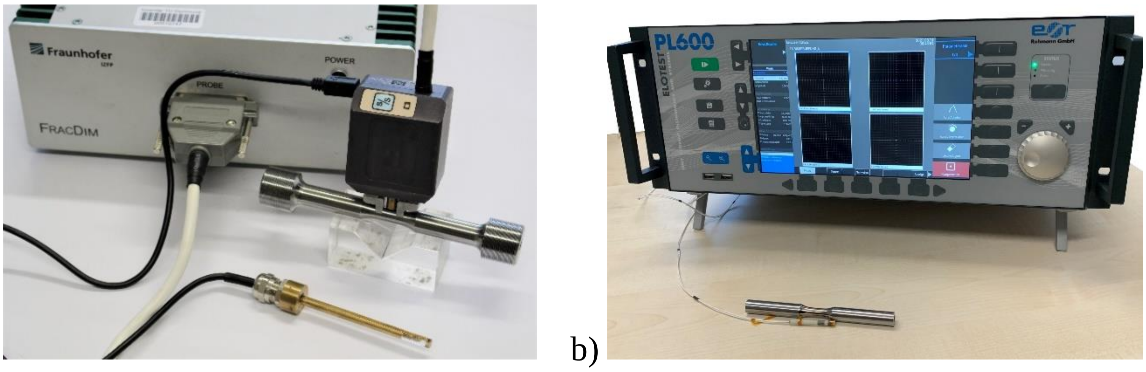


Fig 1: Position of the microstructural examinations [12]

Fatigue experiments were carried out using a Shimadzu EHF-EV050 (Kyoto, Japan) equipped with hydraulic clamps. The tests were performed with a test frequency of f = 10 Hz and a stress ration of R = -1. For the time-efficient and reliable comparison of different drilling parameters, a multiple amplitude test approach was used. The fatigue tests started at a non-damaging stress amplitude $\sigma_{a,start}$ = 250 MPa and were increased by $\Delta\sigma_a$ = 10 MPa each $\Delta N = 10^4$ cycles until the final fracture.

The non-destructive evaluations were performed with a FracDim Barkhausen noise testing system by Fraunhofer IKTS (Dresden, Germany) and a PL-600 eddy current system by Rohmann (Frankenthal, Germany). For the MBN investigations a custom-made inner-surface sensor shown in ***Fehler! Verweisquelle konnte nicht gefunden werden.*** *a)* was used. The magnetization of the specimens occure from the outside with an adapted standard sensor, the detection of the MBN parameters were made on the crucial inside of the bores. The magnetization frequency was set to f_{mag} = 30 Hz and the magnetization voltage was adjusted to a max. magnetic flux of Φ_{max} = 10 µVs. For the evalutation of the maximum Barkhausen noise amplitude (M_{max}) and the coercive field strength Φ_{cm}, a band pass filter of f_{BP} = 10-200 kHz was applied. The fatigue tests were interrupted every two steps to measure the MBN parameters. Also for the eddy-current measurements a tailored sensor was used.



a) b)

Fig. 2: Experimental setup for a) Barkhausen noise [11] and b) eddy-current [2] measurements with customized inner-surface sensors

The diameter of the sensor was 4 mm and therefore the sensor can remain in the bore during fatigue tests without beeing damaged. For that reason the tests did not have to be interrupted for the eddy current measurements. The eddy current frequency was set to f_{EC} = 1.2 MHz. For the assesment of the degradation during the multiple amplitude fatigue tests the eddy current amplitude in the complex impedace plane at the moment of the maximum tensile stress $A_{U,EC}$ was evaluated.

3 Results and discussion

The light microscopy investigations shown in *Fig3* revealed different microstructures in the surface zone. While both images exhibit an in drilling direction deformed microstructure, the influenced zone in case of the oil cooled process is much thinner, which can be explained by the much lower thermomechanical loads during the drilling process [13]. The most apparent distinction between the two investigated strategies is the formation of a white etching layer (WEL) in case of the MQL approach. These layers are known to consist of a very fine grained microstructure and tend to generate tensile residual stresses [14]. For drilling processes was shown that the WEL contain severe compressive stresses [15]. The fine microstructure has a major influence on the micro-magnetic investigations, it was shown that the formation of an WEL inhibits the detection of other mechanical features by MBN investigations [10].

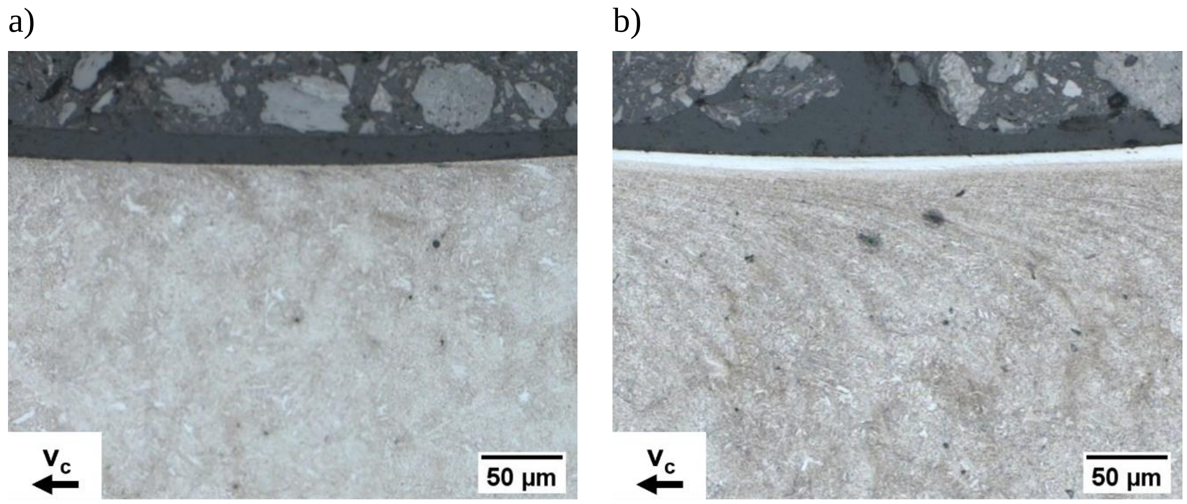


Fig3: Nital-etched cross sections of the surface layer in light microscopy using a) deep hole drilling oil and b) minimum quantity lubrication (MQL)

In *Fig.* 4 the evolution of the MBN parameters coercive field strength Φ_{cm} and maximum Barkhausen noise amplitude M_{max} during multiple amplitude fatigue tests are shown. It can be seen, that Φ_{cm} and M_{max} in case of the oil cooled process are good indicators for the increasing fatigue damage. While Φ_{cm} increases continuingly with the ongoing tests, M_{max} remains constant until σ_a = 400 MPa. After reaching this threshold, M_{max} decreases quadratically. In the case of the MQL approach Φ_{cm} remains constant until the very end of the fatigue test. M_{max} of the MQL specimens shows a slight decrease over the entire course of the fatigue test. These behaviors can be explained by the formation of the WEL in MQL process and the associated decreasing magnetic permeability.

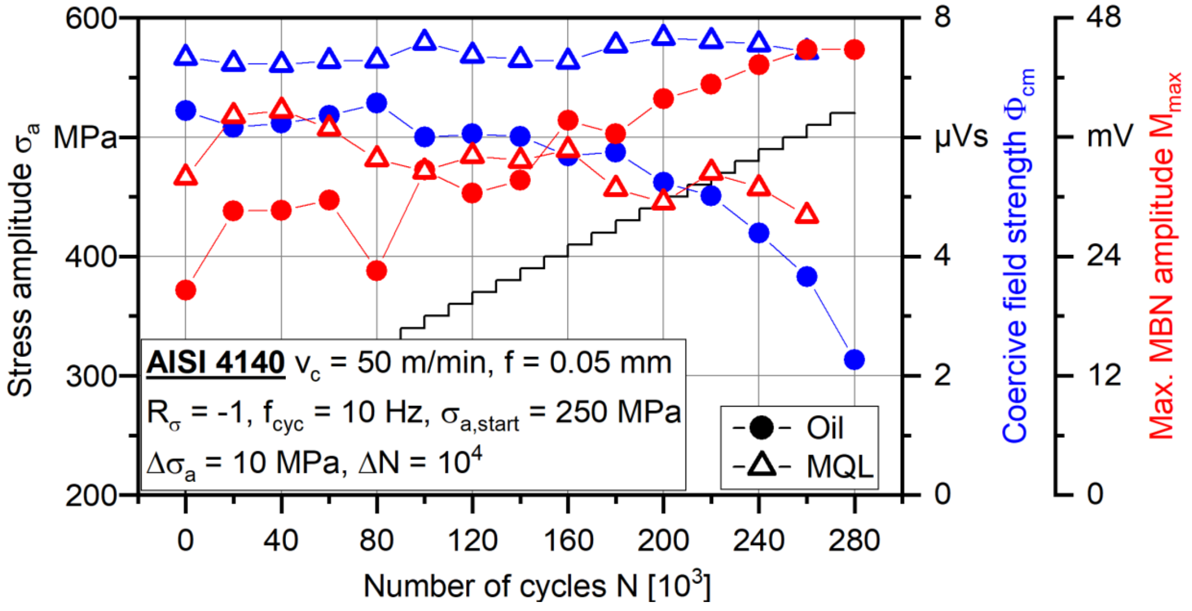


Fig. 4: Evolution coercive field strength and max. MBN amplitude in multiple amplitude tests depending on the cooling strategy

Because the MBN measurements were not capable to generate adequate indicators for the material degradation when WEL occur, a further promising non-destructive measurement technique was used. *Fig. 5* shows the evolution of the eddy current amplitude at the reversal point at maximum tensile strength in multiple amplitude tests. It can be seen, that the sensitivity of the upper eddy current amplitude $A_{U,EC}$ regarding the fatigue damage process is inversed in comparison to the MBN investigations. An increase of $A_{U,EC}$ was detected much earlier for the MQL process, in comparison to the oil cooled process. The increase started approx. 70 MPa below the fracture stress amplitude, where the increase started for the oil cooled process 30 MPa below the fracture stress amplitude.

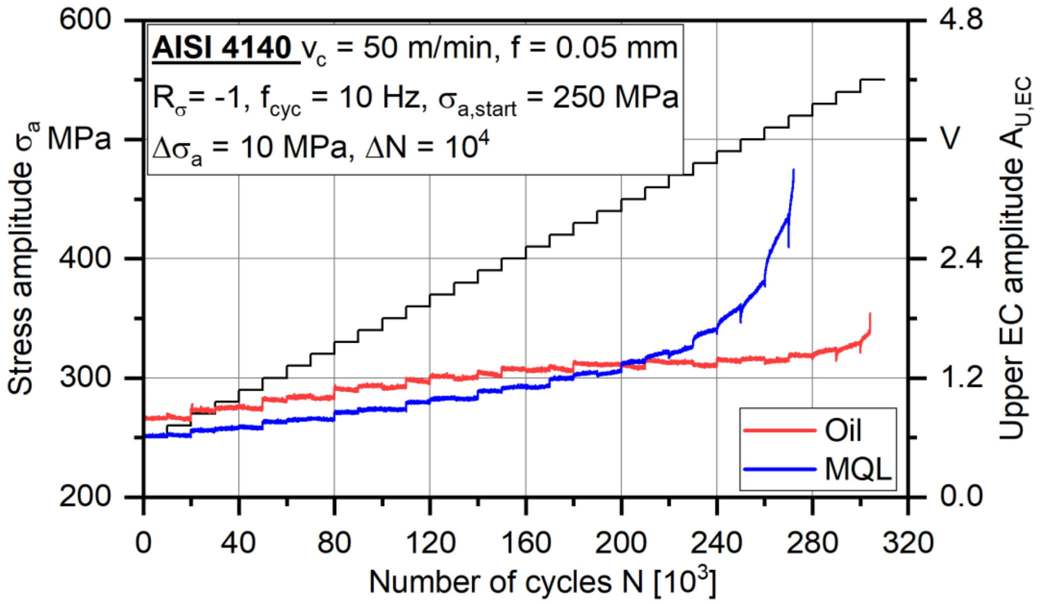


Fig. 5: Evolution of the upper eddy current amplitude in multiple amplitude tests depending on the cooling strategy

4 Conclusion and outlook

The formation of white etching layers, which occur under high drilling parameters and low cooling and lubrication conditions, have a major influence on the evaluation of the fatigue damage by micromagnetic non-destructive measurement techniques. Although Barkhausen noise measurements shows sensitivity to fatigue induced damages when no white etching layers can be found, eddy current just indicates the final failure approx. 30 MPa before reaching the fracture stress amplitude. On the other hand, in case of white etching layer affected specimens the behavior changes. The Barkhausen noise measurement isn't capable to detect changes reliably and the eddy current investigations prove to be much more sufficient for condition monitoring. The failure could be predicted roughly 70 MPa before reaching the failure stress amplitude.

Upcoming studies have to separate the mechanisms which lead to these fundamentally different behaviors. Therefore, an evaluation residual stress behavior, by means of X-ray diffraction investigations in combination with magnetic microstructure examinations with light microscopes using magnetooptical Kerr effect and magnetic force microscopy should be performed. These investigations can reveal the correlation between the micromechanical and micromagnetical behavior of the surface and sub-surface zone of machined specimens and components.

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