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EVOLUTION OF THE RESIDUAL STRESS STATE IN BTA DEEP DRILLED COMPONENTS UNDER QUASI-STATIC AND CYCLIC LOADING

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ABSTRACT

The Boring Trepanning Association (BTA) deep hole drilling process is frequently employed for machining bores with a high length-to-diameter ratio and diameters larger than 6 mm. Typical applications of BTA deep hole-drilled components include the production of drill collars, hydraulic cylinders and highly safety-critical parts like the landing gear of airplanes [1]. The production of these components tends to be complex and usually they are very cost-intensive. For this reason, the quality of bores not only concerning geometric aspects like roundness and straightness but also in terms of surface integrity is of major importance to ensure a component's performance throughout its entire lifetime. The residual stress state in the subsurface zone of the bores is a key aspect of the surface integrity, which has a major impact on fatigue performance [2,3]. In previous experimental studies and analytical modeling approaches, it was found that during BTA deep hole drilling elevated compressive residual stresses are built up in the subsurface zone of the bores [4]. In this study, the evolution of residual stresses under quasi-static and cyclic loading is analyzed, using X-ray diffractometry and magnetic Barkhausen noise (MBN) analysis. Both methods were employed intermittently in tests inspired by the tube-flattening test according to DIN EN ISO 8492. Compressive residual stresses, with medium intensity of approx. -300 MPa, can persist in the subsurface zone of the bores until a large number of cycles. Major drops in the intensity of compressive stresses were observed after macro crack initiation in fatigue tests.

Keywords: BTA (Boring Trepanning Association); Magnetic Barkhausen noise (MBN); Fatigue testing

1. Introduction

To guarantee the performance of components throughout their entire lifetime, their surface integrity state needs to be well known and if possible tailored to the specific applications. This also includes a precise understanding of the evolution of surface integrity during a component's lifetime, e.g. after components have been subjected to quasi-static or cyclic loads. BTA deep-drilled components are vital in various applications in fields like aerospace engineering or the petrol industry, however, up to this day, there is a vast gap in research on surface integrity of BTA deep-drilled components and in particular on the evolution of surface integrity during their lifetime. For this reason, methods are developed for quasi-static and cyclic compression testing

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of deep-drilled specimens, inspired by the tube flattening test (DIN EN ISO 8492). The methods developed include intermittent X-ray diffractometry (XRD) and magnetic Barkhausen noise (MBN) analyses, to investigate the evolution of residual stresses in the subsurface zone of bores after they have been subjected to quasi-static and cyclic loads.

2. Materials and methods

2.1. Materials

All analyses were performed analyzing deep-drilled AISI 4140 steel specimens (42CrMo4, 1.7225) in quenched and tempered condition (+QT; $T_{\text{tempering}} = 640\text{ }^{\circ}\text{C}$, $t_{\text{tempering}} = 3.25\text{ h}$). Mechanical properties of the material are displayed in **Table 1** and the chemical composition in **Table 2**. Round bars of $d = 80\text{ mm}$ were cut into segments of $l_{\text{bore}} = 250\text{ mm}$. The segments were drilled, using the BTA deep hole drilling machine Giana GBB 560 and a solid drill head with a diameter of $d_{\text{inner}} = 60\text{ mm}$, equipped with cemented carbide cutting edges and guide pads coated with TiN. Cutting speeds in the range of $v_c = 60\text{ to }100\text{ m/min}$ and feed rates in the range of $f = 0.150\text{ to }0.300\text{ mm}$ were used. During drilling, the deep drilling oil Berucut RMO TC 22 was supplied with a pressure of $p = 11\text{ bar}$ and a flow rate of $\dot{V} = 300\text{ l/min}$. After drilling, segments for quasi-static and cyclic testing with a length of $l_{\text{segment}} = 30\text{ mm}$ were extracted from the specimens and turned to a precise outer diameter of $d = 74\text{ mm}$ (**Fig. 1**). The start and the end of a bore exhibit peculiarities in surface integrity, resulting from the unsteady state of the process at these points [1]. Thus, segments were not taken from a distance below $\Delta l < 30\text{ mm}$ to the start and the end of the bore. The labeling of the specimens is done according to the following scheme: $Q_{X;Y;Z}$ for specimens for quasi-static testing; $C_{X;Y;Z}$ for constant amplitude testing and $M_{X;Y;Z}$ for multi amplitude testing, with the indices representing feed rate (X); cutting speed (Y) and segment number (Z).

Table 1. Mechanical properties of investigated AISI 4140+QT steel.

AISI 4140+QT			
Tensile strength R_m in MPa	972	Elongation at break A in %	17.8
Yield strength $R_{p0.2}$ in MPa	877	Reduction of area Z in %	63

Table 2. Chemical composition of investigated AISI 4140+QT steel (wt. %) [5].

C	Mn	Si	Cr	Ni	Mo	Cu	P	Ti
0.430	0.740	0.294	1.048	0.095	0.224	0.071	0.009	0.008

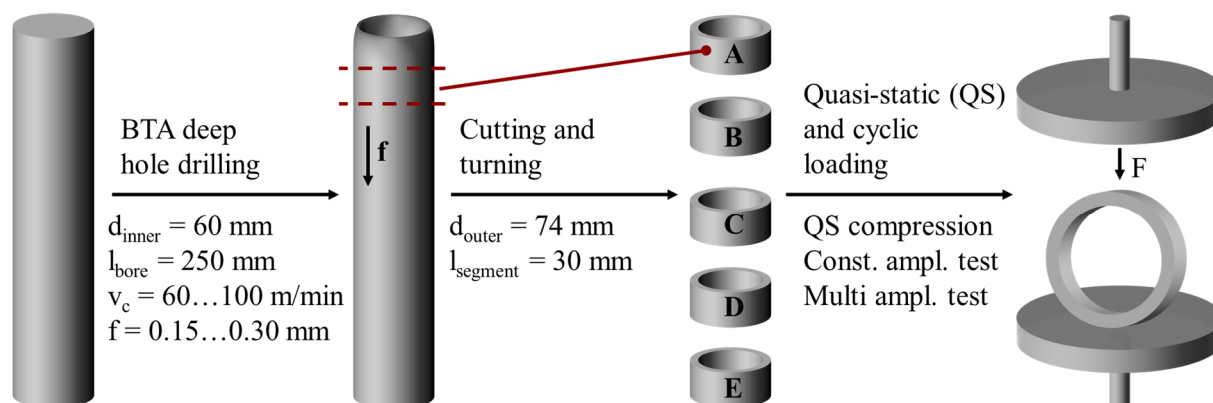


Fig. 1. Preparation of the specimens for quasi-static and cyclic tests, based on [6].

2.2. Quasi-static and cyclic compression tests

The instrumented quasi-static and cyclic compression tests developed are based on the tube-flattening test according to DIN EN ISO 8492. Specimens were mounted between compression plates and subjected to quasi-static compression (QS), cyclic constant amplitude tests (CCA) and cyclic multi amplitude tests (CMA) on the servohydraulic testing system Schenck PSB100 with Instron 8800 controller (Instron, Illinois Tool Works Inc., Norwood, MA, United States) (Fig. 2 a).

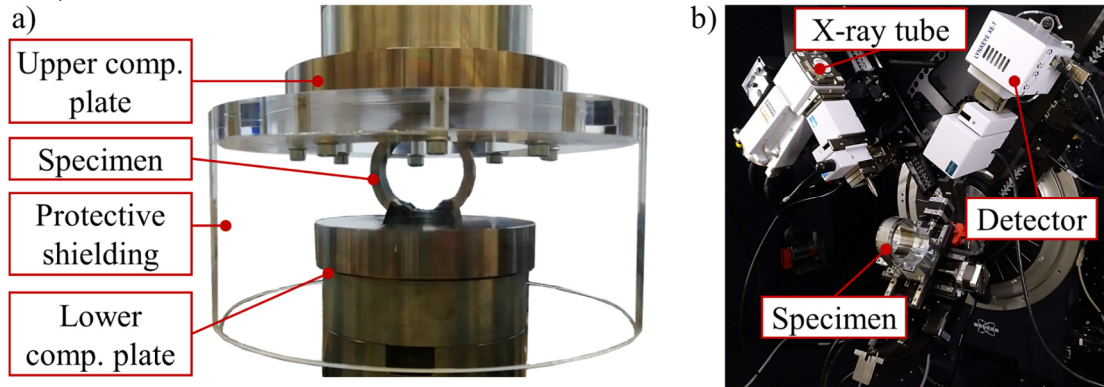


Fig. 2. a) Setup employed for quasi-static and cyclic testing; b) setup for X-ray diffractometry.

The method employed for quasi-static testing of BTA deep-drilled specimens was first developed in previous investigations [6]. Testing was performed by lowering the upper compression plate with a constant velocity of $v = 5$ mm/min. DIC-based investigations of spatial strain distribution during quasi-static compression of BTA deep-drilled specimens revealed that during compression, the highest deformation occurs at the top position and at the bottom position of the inner side of BTA deep-drilled specimens [6]. Thus, these positions of the bores were considered as crucial spots for the initiation and growth of cracks and they were analyzed by means of MBN and X-ray diffractometry intermittently to compression. Based on this method and the results of quasi-static compression tests, methods for cyclic testing with pulsating compression loads were developed. Constant amplitude testing with intermittent XRD and MBN analysis was performed with the same experimental setup, applying a mean force of $F_m = -13.75$ kN and a force amplitude of $F_a = 11.25$ kN with a frequency of $f_{cyc} = 10$ Hz and a stress ratio of $R = 10$ (compression-compression loading) for constant amplitude testing. For multi amplitude testing, the identical frequency and stress ratio were applied. A starting force amplitude of $F_{a,start} = 0.45$ kN and a stepwise increase of the amplitude of $\Delta F_a = 0.45$ kN every $\Delta N = 10^4$ cycles was used.

2.3. Micromagnetic, diffractometric and metallographic analyses

Intermittently to quasi-static and cyclic investigations, MBN and XRD (Fig. 2 b) analyses were performed. For this, the testing was paused and the specimens removed. MBN analyses were carried out using the device FracDim (Fraunhofer IKTS, Dresden, Germany) with a multipurpose sensor. MBN is based on the observation of the expansion of magnetic domains when an external magnetic field is applied to a ferromagnetic material. Since this is affected by material properties like grain size, residual stresses and hardness of the material, MBN is an adequate means to holistically characterize these properties. A detailed description of the MBN method and the equipment used can be found in [7] alongside a summary of correlations that were discovered in the past between the micromagnetic properties and surface integrity. The parameters employed for MBN analysis are depicted in detail in [5].

The diffractometer D8 Discover (Bruker Corporation, Billerica, MA, USA) was used for XRD investigations according to the $\sin^2\psi$ -method. The parameters employed are displayed in Table 3. The relatively low Bragg angle of $2\Theta = 106.027^\circ$ which transgresses the common

standard of only using angles greater than 130° for more precise measurements [8], was selected to avoid the shading of radiation by specimens. The standard Bragg angle of 156.08° could not be used due to the shape of the specimens, the Bragg angle of 106.03° in contrast allows the X-rays to reach the inside of the bores and the diffracted radiation to reach the detector. The Young's modulus E and the Poisson's ratio ν for the calculation of residual stresses were chosen according to the studies of Eigenmann and Macherauch [9]. All investigations were performed according to the χ -method, rotating the specimens mounted on an Eulerian cradle. For depth profiles of residual stresses, electropolishing was performed using the electrolytic polishing and etching machine Kristall 650 (ATM Qness GmbH, Neuhausen, Germany).

For the analysis of the microstructure in the subsurface zones of the bores, metallographic analyses were performed. For this, segments were extracted in the transverse direction. After embedding, grinding, polishing and etching by Nital, optical microscopy was used.

Table 3. Parameters for XRD investigations according to [4] and [9].

AISI 4140+QT					
Target	-	Cr	Poisson's ratio ν	-	0.33
Wave length $k\text{-}\alpha_1$	Å	2.2897	Young's modulus E	GPa	165
Bragg angle 2Θ	°	106.027	Voltage V	kV	30
Collimator \varnothing	mm	1	Current I	mA	40

3. Results and discussion

3.1. Residual stress depth profiles

To analyze the residual stress state introduced by the cutting edges and guide pads into the subsurface zone during BTA deep hole drilling, residual stress depth profiles were recorded at different lengths of the bore ($l_b = 157$ mm and $l_b = 173$ mm). The results are displayed in Fig. 3. For specimen characterization in axial direction and for electrochemical polishing, accessibility of the inner surface of the bores needs to be allowed. For this reason, the top part of the specimens was removed by cutting the specimens into half-shells. In order to analyze the impact of cutting on the residual stress state, residual stresses were analyzed before (Fig. 3 I) and after cutting (Fig. 3 II). It was found that no major alteration of residual stresses occurs during cutting. Analyzing the residual stress depth profiles recorded (Fig. 3 III), it can be concluded that close to the surface of the bore, high compressive residual stresses are built up during drilling in axial and tangential directions.

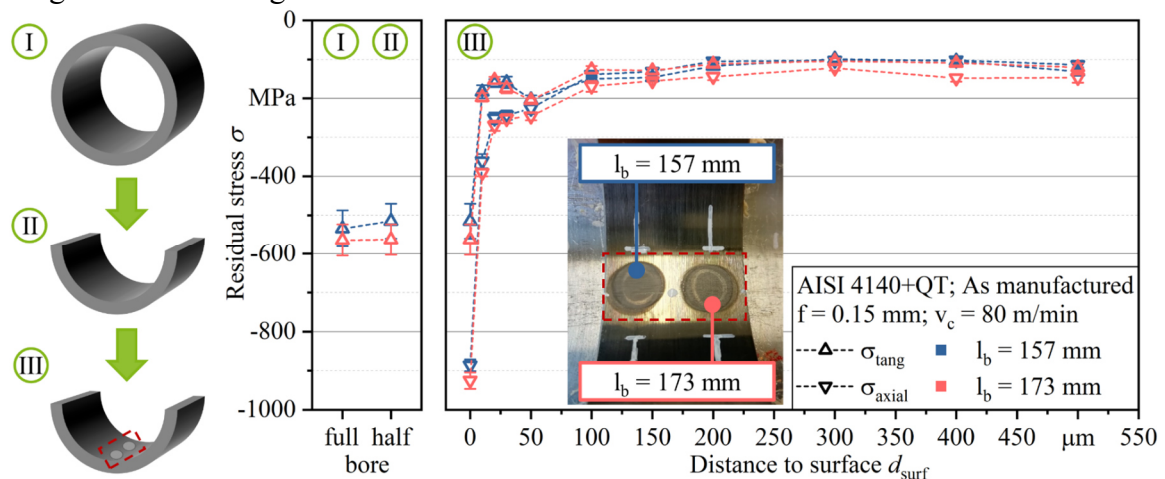


Fig. 3. Residual stress depth profiles in axial and tangential directions at various positions of the bore (l_b) before (I) and after cutting (II) and after electrochemical polishing (III).

In axial direction compressive residual stresses with an intensity of $|\sigma| \approx 900$ MPa were recorded. In tangential direction, they have an intensity of $|\sigma| \approx 550$ MPa. A significant drop in the intensity of compressive residual stresses was already observed after the first step of electrochemical polishing at a distance of $d_{\text{surf}} = 10 \mu\text{m}$. Below a distance of $d_{\text{surf}} < 100 \mu\text{m}$, residual stresses stay on a relatively constant level in axial and tangential direction (Fig. 3). No major difference was observed between the residual stress states at the different lengths of the bore analyzed. The findings presented are in good agreement with the results of previous studies, in which it was shown by means of XRD and a novel analytical modeling approach based on eigenstrain theory that during BTA deep hole drilling elevated compressive residual stresses are built up [4]. However, the intensity of the residual stresses recorded in this study surpasses the intensity of the modeled stresses. Reasons for this might be found in the parameters employed for modeling.

3.2. Quasi-static compression

The results of XRD and MBN investigations after quasi-static compression of a specimen to an elastic displacement of $s_{\text{QS}} = 2$ mm are displayed in **Fig. 4**, for various positions along the length of the bore l_b . The displacement of $s_{\text{QS}} = 2$ mm was selected, based on the results of previous investigations, to ensure that no plastic deformation occurs [6]. Before compression, residual stresses were in the range of $\sigma_{\text{tang}} \approx -370$ MPa to $\sigma_{\text{tang}} \approx -910$ MPa. After compression of the specimen, residual stresses in the range of $\sigma_{\text{tang}} \approx -90$ MPa to $\sigma_{\text{tang}} \approx -360$ MPa were detected. Thus, it can be concluded that a major relaxation of residual stresses occurs during quasi-static elastic deformation of the deep-drilled specimens. In addition to this, the variation of the intensity of residual stresses along the length of the bore is significantly reduced and a more homogenous residual stress state is established in the subsurface zone of the deep-drilled specimens. MBN measurements were performed at the same positions as XRD investigations, leaving out the edges of the specimen ($127 \text{ mm} \leq l_b \leq 143 \text{ mm}$), to avoid geometrical influences. Initially, the MBN amplitude M_{max} was relatively low, about $M_{\text{max}} \approx 6$ mV. After compression, it increased up to $M_{\text{max}} \approx 18$ mV. The reason for this increase in M_{max} might be found in the reduction of compressive residual stresses in the subsurface zone during compression. This correlation between MBN amplitude and residual stress state is well-reported in [7]. The analysis of MBN seems to be an adequate means for quickly and non-destructively assessing the relaxation of residual stress states in BTA deep-drilled specimens, e.g. in compression tests.

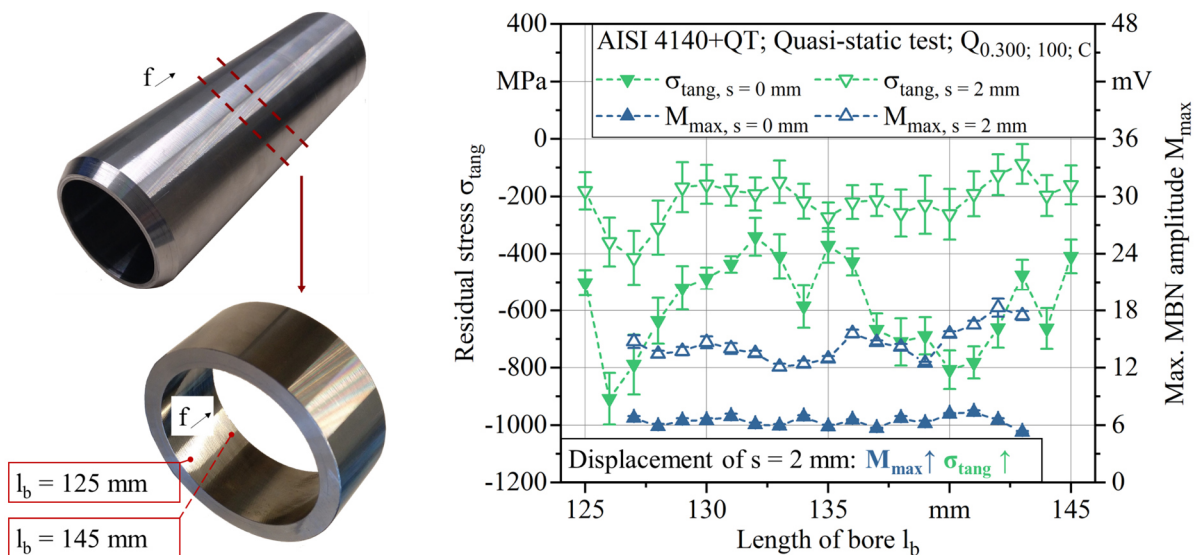


Fig. 4. Tangential residual stresses σ_{tang} and max. MBN amplitudes M_{max} before and after compression of the specimens to a displacement of $s_{\text{QS}} = 2$ mm.

Fig. 5 displays detailed results of MBN analyses (Fig. 5 a), metallographic investigations (Fig. 5 b) and quasi-static performance (Fig. 5 c) of deep-drilled specimens. In previous investigations, it was found that when using relatively high feed rates and cutting speeds during drilling, white etching layers (WEL) form at the surface of the bore, which can be detected by MBN analysis [5]. The discovered correlation agrees well with the findings in this study. Four specimens show relatively high values (Fig. 5 a, vertical shading) and are thus suspected to have no WEL, three of the specimens have low MBN amplitudes (Fig. 5 a, horizontal shading) and are consequently suspected to have a WEL. Based on the data presented in this study and [5], a possible threshold for WEL detection might be $M_{\max} \approx 6$ mV with the setup and parameters used for MBN analysis. In metallographic investigations, the hypothesis could be confirmed (Fig. 5 b). WEL layers tend to be hard and brittle and their presence is often associated with a negative impact on quasi-static and fatigue performance [6,10]. This agrees well with the finding that specimens that had WEL showed crack initiation at significantly lower displacements compared to specimens without WEL (Fig. 5).

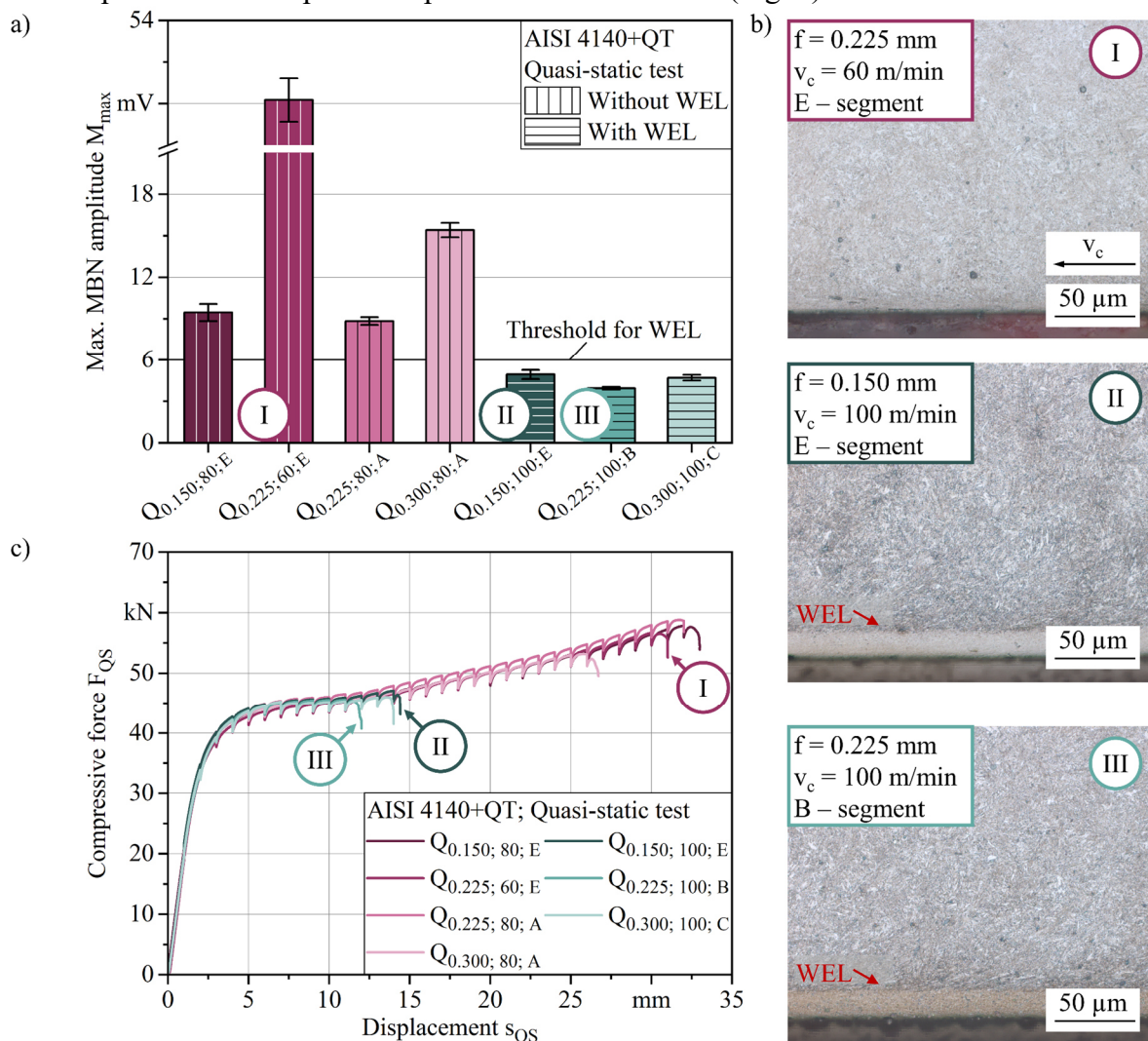


Fig. 5. a) Micromagnetic investigations of specimens for compression tests, b) metallographic investigations of specimens for compression tests and c) compressive force and displacement in quasi-static compression.

3.3. Cyclic compression

Besides quasi-static testing, methods were developed for instrumented cyclic testing by means of constant amplitude and multiple amplitude testing with intermittent MBN and XRD analysis. Exemplary results of the constant amplitude tests are depicted in **Fig. 6**. Both XRD and MBN indicate a reduction in compressive residual stresses already after the first cycles.

The residual stress state then remains constant at $\sigma \approx -300$ MPa until the main relaxation is observed by XRD after 60,000 cycles (Fig. 6 a). In dye penetration testing, evidence was provided that cracks formed at the top and bottom of the bore and most likely account for the relaxation of residual stresses at this point (Fig. 6 b). MBN analysis indicates that these cracks might already have initiated at 50,000 cycles, leading to a reduction of compressive residual stresses and subsequently increasing max. MBN amplitudes.

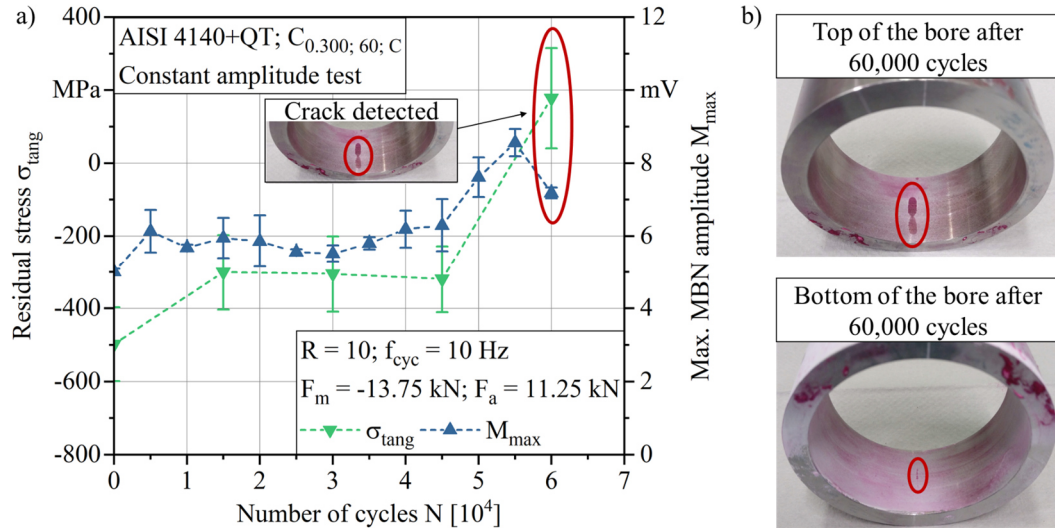


Fig. 6. a) Residual stress and max. MBN amplitude in constant amplitude testing and b) dye penetration testing after $N = 60,000$ cycles.

Fig. 7 displays the results of an exemplary multi amplitude test with intermittent XRD analyses. It can be observed that residual stress intensity initially increases, until approx. 150,000 cycles. The explanation of this phenomenon is complex and requires further investigation. After this number of cycles intensity of residual stresses slightly decreases. However, an elevated intensity of $|\sigma_{\text{tang}}| > 450$ MPa remains until crack initiation occurs. The reason for this might be found in the relatively low mean displacement during multi amplitude testing (Fig. 7).

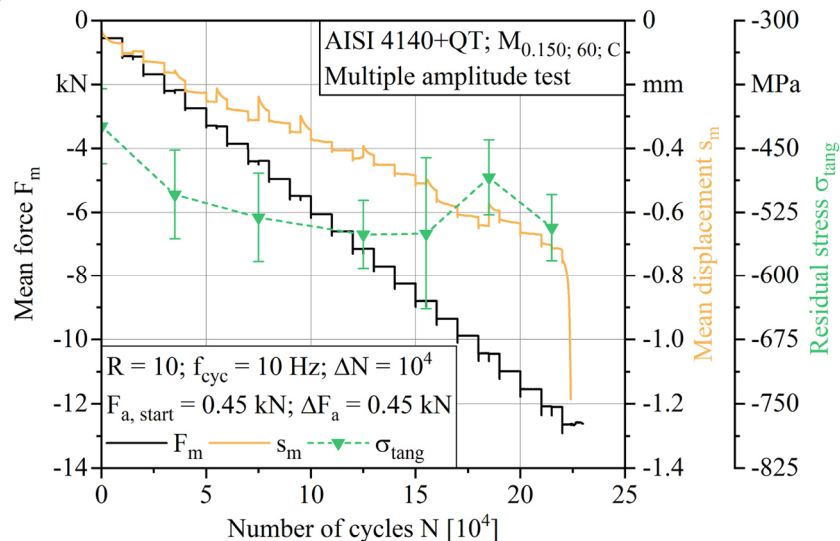


Fig. 7. Mean force, mean displacement and residual stress in multi amplitude testing.

4. Conclusions and outlook

BTA deep hole drilling introduces high compressive residual stresses of up to $\sigma \approx -900$ MPa into the subsurface zones of bores. Residual stress depth profiles provide evidence that the intensity of these stresses steeply declines below the surface of the bore. Depending on the

selection of cutting parameters WEL form. These can be detected reliably by micromagnetic analyses. The presence of WEL has a significant impact on the quasi-static performance of the specimens. Compressing the bores elastically to a displacement of $s = 2$ mm leads to a relaxation of residual stresses from up to $\sigma_{\text{tang}} \approx -910$ MPa to $\sigma_{\text{tang}} \approx -360$ MPa. In constant amplitude testing and multiple amplitude testing, evidence was provided, that elevated compressive residual stresses can remain in the subsurface zone of bores until a large number of cycles ($N = 45,000$). After crack initiation occurred, a relaxation of residual stresses was observed, leading to tensile residual stresses of approx. $\sigma_{\text{tang}} \approx 200$ MPa. Further research will target further identifying and understanding the complex interrelations between the loads applied to the specimens, the resulting displacement and the relaxation of residual stresses.

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