Materials Research Proceedings **6** (2018) 209-214 doi: http://dx.doi.org/10.21741/9781945291890-33

Analysis of Residual Stress State in Deep-Rolled HT-Bolts

Julian Unglaub[1,a,*], Jonas Hensel[2,b], Robert Wimpory[3,c], Thomas Nitschke-Pagel[2] Klaus Dilger[2] and Klaus Thiele[1]

[1]Inst. of Steel Structures, TU Braunschweig, Germany

[2]Institute of Joining and Welding. TU Braunschweig, Germany

[3]Helmholtz-Zentrum Berlin für Materialien und Energie, Germany

[a]j.unglaub@stahlbau.tu-braunschweig.de, [b]j.hensel@tu-braunschweig.de, [c]robert.wimpory@helmholtz-berlin.de

Keywords: HT-Bolts, Deep Rolling, Residual Stress Measurement, Neutron Diffraction

Abstract. Results of residual stress measurements of HT-bolts gained by neutron diffraction at HZB will be presented. The in-depth residual stress of different conditions of “rolled-before heat-treatment and galvanized” M24 HT-bolts made from 33MnCrB5-2 will be shown: As-manufactured, pre-stressed and fatigue loaded. Additionally, results of an unloaded, “rolled-after heat-treatment and hot-dipped” galvanized M36 HT-bolt will be presented. It will be shown that the manufacturing sequence “rolled-before heat-treatment and galvanized” can develop compressive residual stresses due to heat-treatment close to the surface and that “rolled-after heat-treatment and hot-dipped” shows a contraire residual stress path as “rolled-before heat-treatment and galvanized” with a maximum below the surface.

Introduction

Bolted joints are generally the most frequently used joining elements in mechanical and plant engineering. High-tensile (HT) bolts with large diameters (M30 up to M72) are heavily used in wind power plants both onshore and offshore. Bolted joints are made from hardened steels (for instance 33MnCrB5-2) and show high stress concentration in the thread. One of the fatigue strength governing parameters is the production method used to manufacture those threads, shown in Fig. 1. During the cold-rolling process compressive residual stresses are generated at the root of the thread in combination with strain hardening. The residual stress state can be significantly influenced by heat-treatment or loading.

The in-depth residual stresses of bolts in different conditions of “rolled before heat-treatment” and galvanized HT-bolts M24x130 10.9 tZn made from 33MnCrB5-2 have been investigated by neutron diffraction: As-manufactured, pre-stressed in tension and fatigue loaded. Additionally, an unloaded, “rolled after heat-treatment and hot-dipped galvanized” M36x235 10.9 tZn HT bolt has been examined. The mechanical properties are listed in Tab. 1.

The as-manufactured sample represents the residual stress condition induced by the manufacturing process. The pre-stressed condition reflects the in-situ stress state of a mounted bolt under pre-tension (about 70% of Rp0.2). This was achieved by mounting the bolt in an artificial restraint device. The pre-loaded bolt was pre-stressed and fatigue loaded at TU Braunschweig in the finite life regime until N = 100.000 load cycles which is assumed to correspond to a cyclically stabilized state after residual stress relaxation. The residual stress history can be used to further interpret given fatigue test results.

Materials Research Proceedings **6** (2018) 209-214 doi: http://dx.doi.org/10.21741/9781945291890-33

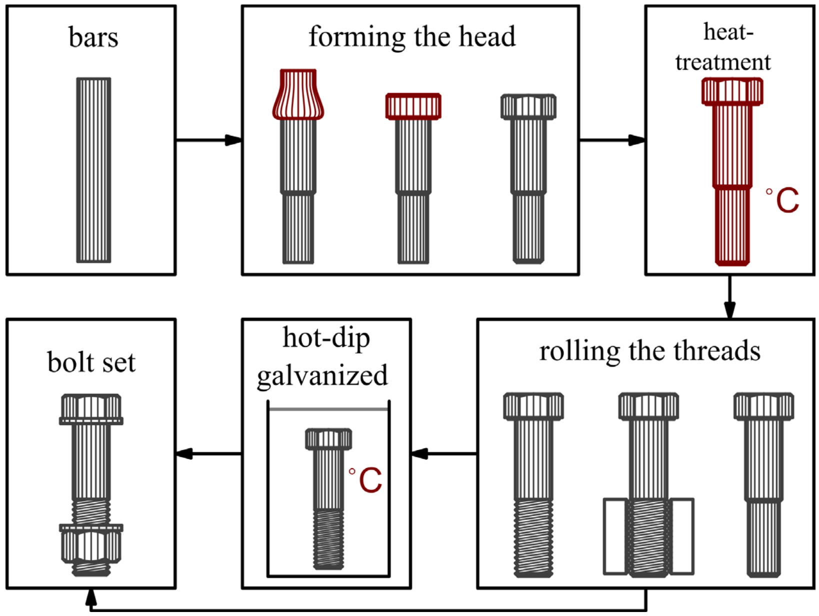

Figure 1: Manufacturing process of rolled after heat-treatment and hot dipped galvanized HT bolts, [4]

Table 1 Mechanical properties

	$R_{p0,2}$ [MPa]	R_m [MPa]	E [MPa]	ν -	θ_0 [rad]
M24	969	1081	198400	0,28	77,882
M36	912	1050	194400	0,28	77,882

Setup

The measurement setup at experiment E3 at Helmholtz-Zentrum Berlin für Materialien und Energie (Berlin) for the M24 bolts is shown in Fig. 2 and Fig. 3. The setup shown in Fig. 2 was used for the measurement of the radial, tangential directions for the M24 bolts. Two sections of the bolts have been examined: the first load bearing thread and the shank. In order to cancel out the surface effect the measurements have been carried out in pairs 180° to each other.

The measurement of the axial direction is shown in Fig. 3. With this setup the shank and the first load bearing thread was investigated.

The gauge volume was 2x2x2 mm^3 which was defined by the primary slit of the neutron beam and radial collimator as a secondary optic. Along the cross section of the measuring path, from the center of the bolt to the surface, the volume distance was equidistant with overlapping volumes close to the surface.

The corresponding measurement setup for the M36 bolts is shown in Fig. 4. and follows the same principles as the setup for the M24 bolts. Because of the sample size and density only the unloaded sample of the M36 bold has been scanned. Due to time constraints solely measurements close to the surface have been made.

The reference Bragg-angel θ_0 of the base material was determined from a cut out sample of the shank of an unloaded bolt. The same material reference sample was used for both bolt diameters. The measurement uncertainties were estimated by the method proposed by Wimpory et. al. [3].

Materials Research Proceedings **6** (2018) 209-214 doi: http://dx.doi.org/10.21741/9781945291890-33

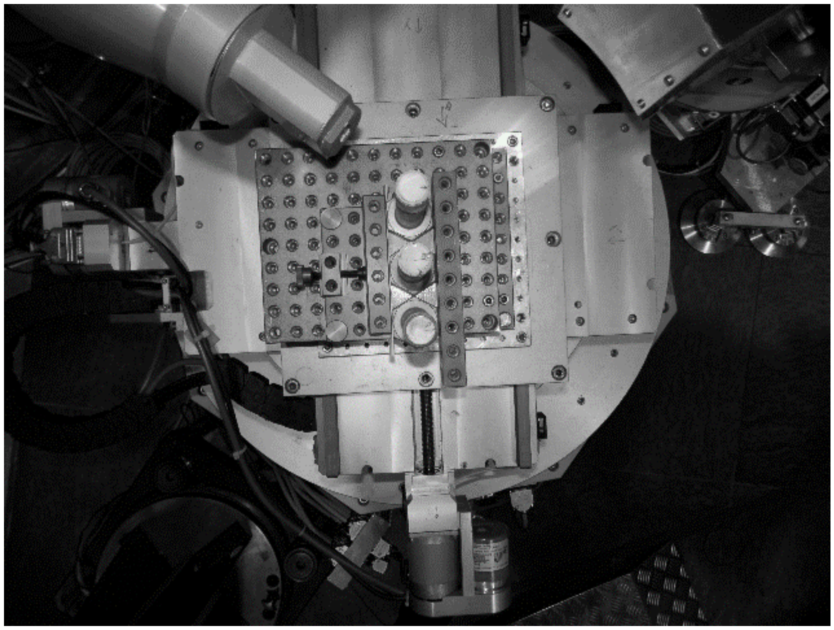

Figure 2: Setup M24, top view for radial, tangential, in measurement pairs '0° and 180°'

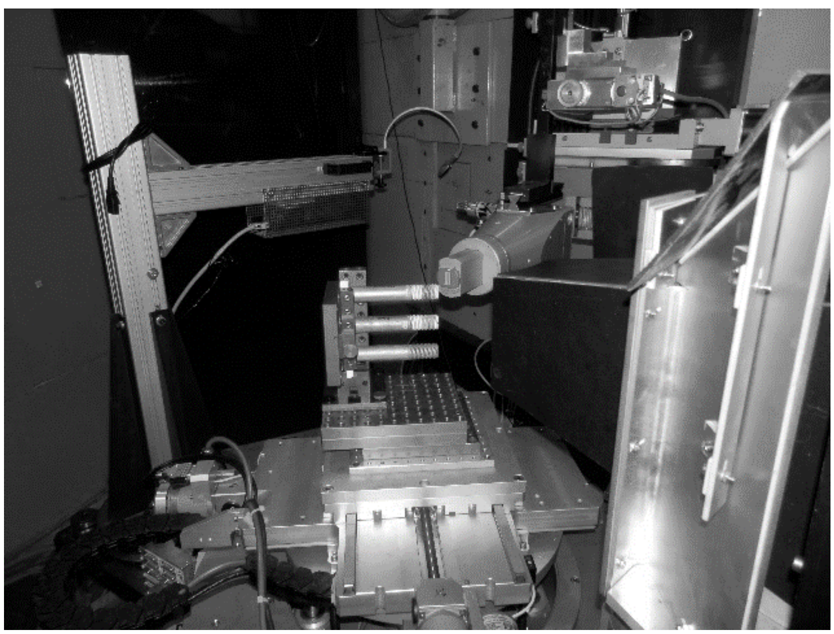

Figure 3: Setup M24, side view for axial, in measurement pairs 0° and 180°

Results

The results of the measurement of the "rolled after heat-treatment", hot dipped galvanized M36 HT-bolt is shown in Fig. 4. As expected, compressive residual stresses in the axial and tangential direction are present in the thread root. The maximum of the compressive residual stresses is located below the surface.

Materials Research Proceedings **6** (2018) 209-214 doi: http://dx.doi.org/10.21741/9781945291890-33

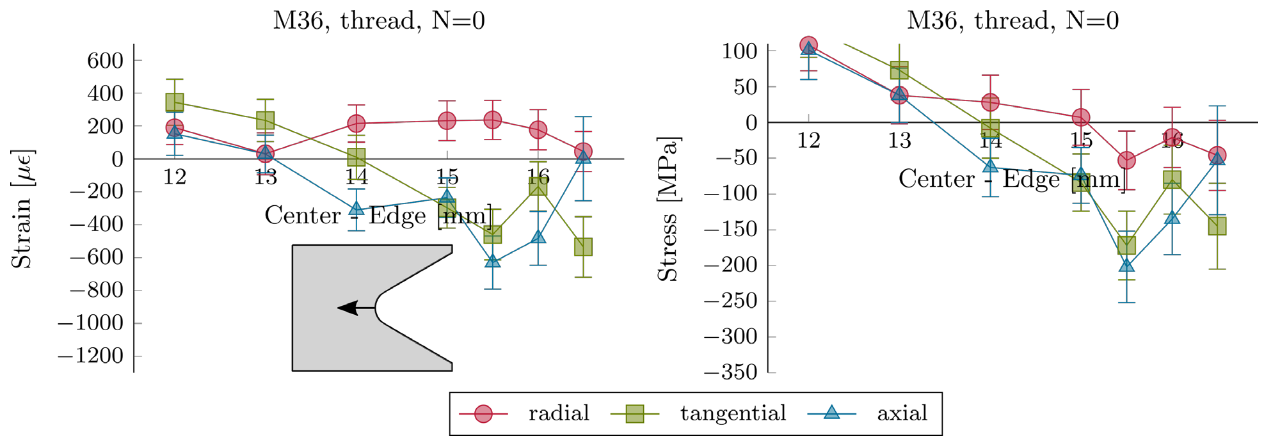

Figure 4: Residual Strain and Stresses of "rolled after heat-treatment" and hot dipped galvanized M36x235 10.9 tZn HT-bolt, threat root, unloaded

The results of the measurements of the M24 HT-bolts are shown in Fig. 5. The unloaded, "rolled after heat-treatment", hot dipped galvanized M24 HT-bolt shows minor compressive residual stresses very close to the surface. The axial stress component of the Sample M24, N=1 is calculated from the radial and tangential strain component under the assumption of zero radial stress. This stress state is influenced by the loading and can be seen in the results of the measurements of the loaded sample with N=1 and N=100.000 load cycle.

Discussion

Unfortunately, there are only a few publications with in depth residual stress measurements on hot-dip galvanized bolts available. These investigations mainly investigate small bolt diameters.
Stephens et. al. [2] investigates the influence of "rolled after heat-treatment" and "rolled before heat-treatment". A residual stress measurement by help of x-ray diffraction shows residual stresses close to the surface of the thread root up to 500 MPa (compression) in axial and -1000 MPa (tension) in tangential direction for rolled after heat-treatment bolts. Residual stresses in "rolled before heat-treatment" bolts are close to zero.
The measured residual stresses of M 36 bolts differ from those in the literature. However, the general path of the residual stresses resembles those from Stephens et. al. [2] quite well. A smaller distance between the measured volumes could capture the maximum better.
The results for the unloaded M24 shows contrary behavior to the investigations of Stephens et. al. [2] for "rolled before heat-treatment" bolts. However, after the heat-treatment process (900 °C) of the bolts the temperature drops rapidly, compressive residual stresses can develop due to the change of the material from cubic face-centred to body-centred cubic.
The change of stress from N=1 to N=100.000 under loading conditions can be led back to cyclic softening, as described by Panic et. al. [1].

Materials Research Proceedings **6** (2018) 209-214 doi: http://dx.doi.org/10.21741/9781945291890-33

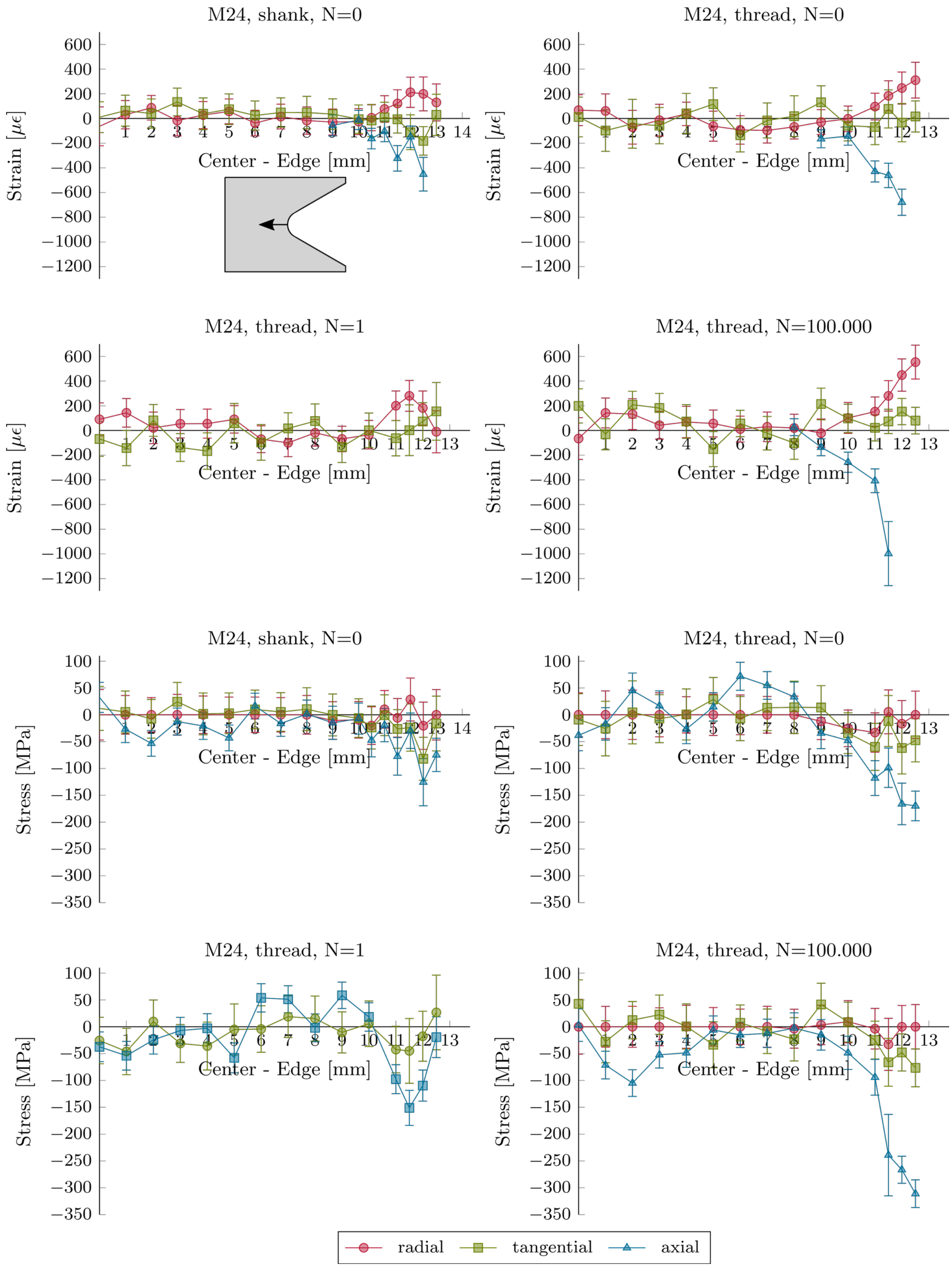

Figure 5: Residual Strain and Stresses of "rolled before heat-treatment" and hot dipped galvanized M24x120 10.9 tZn HT-bolts, threat root, unloaded, load N=1 and load N=100.000.

Materials Research Proceedings **6** (2018) 209-214 doi: http://dx.doi.org/10.21741/9781945291890-33

Summary

For the first time, "rolled after heat-treatment", hot-dipped galvanized M24 HT-bolts with different loading situations have been investigated with neutron diffraction. It can be seen that the heat-treatment process can produce small compressive residual stresses close to the surface. Theses stresses are subject to cyclic softening. Additionally, "rolled after heat-treatment", hot-dipped galvanized M36 HT-bolts have been examined and show promising results for the unloaded sample. It is evident that the maximum of the compressive residual stresses is below the surface. Future research has to be performed to describe the residual stress relaxation due to loading. For this purpose, all three strain components need to be measured.

The measurements have been performed within a subproject of the DFG Graduiertenkolleg 2075 Models for the description of aging of construction materials and structures. One topic is the investigation of the influence of residual stresses on the fatigue life of large bolt diameters M24, M36 and M48.

Acknowledgements

Measurements were carried out at the E3 instrument station at the Helmholtz-Zentrum Berlin. We thank HZB for the allocation of neutron beam time.

We thank Peiner Umformtechnik GmbH und August Friedberg GmbH for providing test samples.

References

[1] Panic, D., Beier, T., Vormwald, M.: Damage Assessment of Threaded Connections based on an Advanced Material Model and Local Concepts. Procedia Engineering 74 (2014), S. 119–128. https://doi.org/10.1016/j.proeng.2014.06.235

[2] Stephens, R., Bradley, C., Horn, N., Gradman, J., Arkema, J., Borgwardt, C.: Fatigue of High Strength Bolts Rolled Before or After Heat Treatment with Five Different Preload Levels. 2005 SAE World Congress (2005). https://doi.org/10.4271/2005-01-1321

[3] Wimpory, R. C.; Ohms, C.; Hofmann, M.; Schneider, R.; Youtsos, A. G. (2009): Statistical analysis of residual stress determinations using neutron diffraction. In: International Journal of Pressure Vessels and Piping 86 (1), S. 48–62. https://doi.org/10.1016/j.ijpvp.2008.11.003

[4] Unglaub, J., Reininghaus, M., Thiele, K.: The fatigue behaviour of bolts with large diameters under overloading. In: The Eighth International Conference on Low Cycle Fatigue (LCF8) 27.-29.06 2017 Dresden (2017).