Experimental and Analytical Assessment of the Fatigue Strength of Bolts with Large Dimensions under Consideration of Boundary Layer Effects

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Summary

High-strength bolt assemblies with large diameters between M36 and M72 are used in steel support structures for wind turbines as well as other applications in structural engineering. Protection against corrosion of the bolts is commonly achieved by hot-dip galvanizing. It has been shown that the zinc coating has an influence on the fatigue strength of bolts. However, due to high mean loads, the experimental prediction of the fatigue strength and the quantification of the boundary layer effect are very demanding for bolts with large diameters. Within the research project “Experimental and Analytical Assessment of the Fatigue Strength of Bolts with Large Dimensions under Consideration of Boundary Layer Effects” the fatigue behavior of large size, high-strength bolts is systematically investigated. One aspect of this investigation is the analysis of the mechanical phenomena, which lead to the reduced fatigue strength of the bolts caused by the zinc coating. The overall objectives of the investigations are the identification of the decisive mechanisms and the derivation of a suitable model for consideration of boundary layer effects in analytical fatigue predictions. Besides detailed metallurgical analyses of boundary layer and base material, the investigations comprise an experimental quantification of the boundary layer effect on the fatigue strength of notched specimens. Furthermore, extensive fatigue tests are performed directly on high-strength bolts with large diameters M36 and M64. In addition to the direct quantification of the boundary layer effect, the test results will be used to verify the applicability of an analytical assessment method based on the notch strain approach. The analytical fatigue life assessment method focuses on the inclusion of boundary layer effects and on the predictability of fatigue life under variable amplitudes. Hence, the outcome of the project will be an experimentally validated assessment method which can be used for the fatigue life prediction of hot-dip galvanized, large-size bolts under variable loading conditions.

Key Words

Hot-dip galvanizing, high-strength bolt assemblies (HV), fatigue, experimental testing

Introduction

Bolts with large diameters of size M36 to M64 are used in the wind energy industry but also in other areas of civil and mechanical engineering in the form of high-strength bolt assemblies (HV-sets). Bolts, used in these areas of application, are subjected to high cyclic loading at varying amplitudes. The corrosion protection of the threaded fasteners is often ensured by hot-dip galvanizing, which is an economical and long-lasting corrosion protection system. It is known, however, that hot-dip galvanizing has a negative influence on the cyclic load bearing capacity of components made of steel [1–3]. Since end of 2014, VDI 2230 explicitly takes into account the influence of the specific geometry of high-strength threaded fastener (HV-sets) with regard to the cyclic load bearing capacity [4]. Consequently, according to the guideline, the fatigue strength is to be reduced by a total of 30 % when using hot-dip galvanized HV-sets. The reduction according to VDI 2230 consists of a 20 % component due to the hot-dip galvanizing and a 10 % component due to the geometry of HV-sets. In Eurocode 3 (DIN EN 1993-1-9) [5], which is the applicable design standard in constructional engineering, bolts are allocated to detail category 50. An explicit consideration of the boundary layer condition is not included in Eurocode 3.

The “Guideline for the Certification of Offshore Wind Turbines“ from Germanischer Lloyd [6] recommends the application of detail category 71 for black, uncoated bolts and detail category 50 for the hot-dip galvanized version on the basis of the Eurocode. Thus, the technical user is given an opportunity to differentiate between a hot-dip galvanized and an uncoated version in the dimensioning of bolts on the basis of Eurocode 3.

In [3] the results of detailed investigations on the influence of normal temperature hot-dip galvanizing on the fatigue behavior of components made of structural steel are presented. Here a crossing over of micro-cracks in the δ_1– and ζ- phases in the base material is described as the cause of a premature fatigue crack initiation and therefore the negative effect of the normal temperature hot-dip galvanizing on the cyclic load capacity of the steel components (Figure 1).

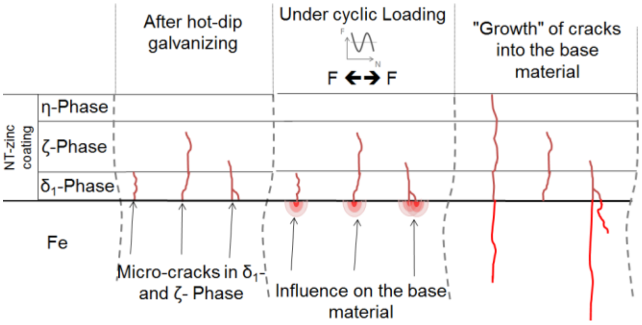

Figure 1: Fatigue crack initiation [3]

Until now, the described failure mechanism is not applied when evaluating the fatigue live of large-size bolts. An experimentally confirmed evaluation method that reliably detects an assured estimate of the fatigue strength of hot-dip galvanized bolts with large dimensions is yet to be developed.

Thus, the objective of this research project is the development of an experimentally confirmed evaluation method for the fatigue strength of large-size bolts taking into account the influence of hot-dip galvanizing.

To achieve this objective, firstly the effects of normal temperature hot-dip galvanizing and high temperature hot-dip galvanizing on the cyclic load bearing capacity of notched specimens with enrolled single notch as well as on M36 bolt sets of strength class 10.9 are investigated. Based on fatigue tests and the material model of the bolt's base material, a design model for the assessment of the fatigue life is developed on basis of the notch strain approach. Our approach has been to consider the effect of the zinc coating by application of the “Thin Boundary Layer” [14] model. The model allows the simulation of the negative influence of the zinc coating by the employment of a virtual strain inherent to the zinc boundary layer. The assessment method will be verified using the results of the experimental investigations on large-size, high-strength bolts. In addition to fatigue tests at constant amplitudes on M36 HV-sets, these also include service load tests on M36 bolts at variable amplitudes as well as further fatigue tests at constant amplitudes on very large bolts M64.

Experimental investigations on the influence of hot-dip galvanizing on cyclic load bearing capacity

From both, literature as well as relevant normative standards, it is evident that hot-dip galvanizing negatively influences the fatigue strength of threaded fasteners. New research describes the basic failure mechanism [3]. To develop an assessment model, first of all the influence of hot-dip galvanizing on notched specimens and high-strength bolts M36 is analyzed. The isolated effect of a normal temperature zinc coating and a high temperature zinc coating is examined using comparative S-N tests on specimens made of high strength steel 32CrB4 with an enrolled notch (Figure 2, left). The notched specimens are adjusted for strength class 10.9 in accordance with DIN EN ISO 898-1 [7]. Since the results arising from the free single notch of the notched specimen cannot readily be transferred to a high-strength HV-set, fatigue tests are also performed on hot-dip galvanized M36 HV-sets (DIN EN 14399 [8]) of strength class 10.9 of the same material (Figure 2, right).

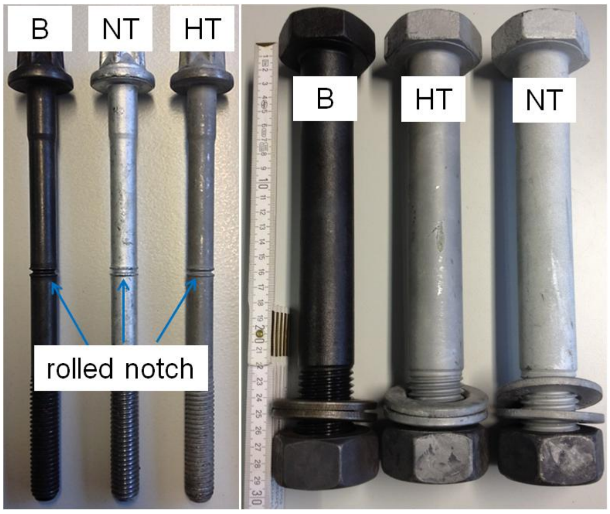

Figure 2: Notched specimen and bolt specimen; black (B), normal temperature hot-dip galvanized (NT) and high temperature hot-dip galvanized (HT)

Notched specimens and HV-sets are examined in their quenched and tempered, black oxide condition (B) as well as normal temperature hot-dip galvanized (NT) and high temperature hot-dip galvanized (HT). At this point it must be noted that according to DSV-GAV guideline for hot-dip galvanized bolts [9] the technical application of HT hot-dip galvanizing is currently limited to threaded fasteners ≤ M24. Thus, high temperature hot-dip galvanizing is not permissible for bolts diameter M36 because of the potential risk of liquid metal assisted cracking (LMAC).

The near-surface area of the black oxide, NT and HT-hot-dip galvanized specimens in the area of the enrolled notch is shown in Figure 3. A slight surface oxidation is visible in the black specimens. The NT hot-dip galvanizing shows a typical 3-phase composition; the HT hot-dip galvanizing is composed completely of the δ_1 phase.

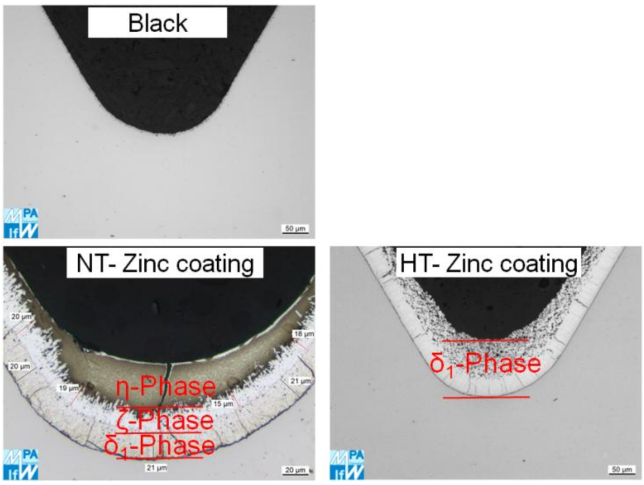

Figure 3: Metallographic sections of the notched specimen

The quasi-static testing of the specimens has shown that NT hot-dip galvanizing has no significant effects on strength values. In HT hot-dip galvanizing, however, a slight decrease of all strength values was observed. This decline is caused by the temperature loading during the high temperature hot-dip galvanizing process. The notched specimens were tempered at approx. 500°C. The high temperature hot-dip galvanizing was carried out at higher temperatures. This means that a renewed tempering of the specimens took place in the galvanizing process.

The results of the comparative fatigue tests in accordance with DIN 969 [10] on the notched specimens at a mean stress $\sigma_m = 0.7 \cdot R_{p0,2\%}$ show that both the NT hot-dip galvanized as well as the HT hot-dip galvanized notched specimens have a lower fatigue strength compared to the uncoated reference condition (Figure 4).

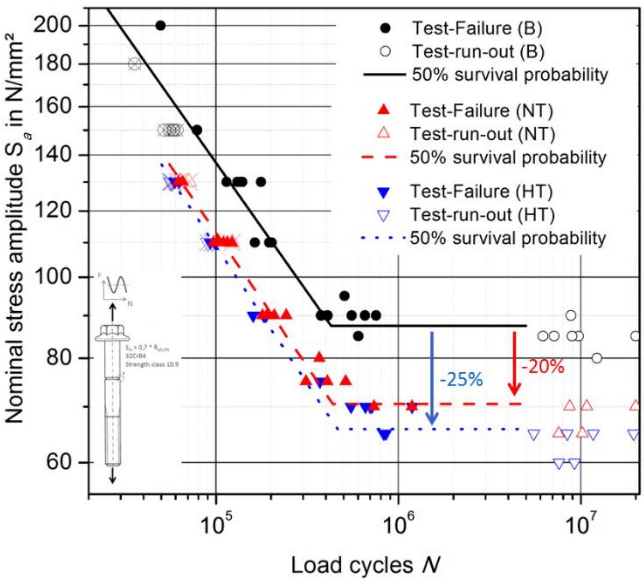

Figure 4: Comparison of fatigue lives of black oxidized an NT galvanized with HT galvanized notched specimens

To examine the cause of the reduction of fatigue strength, NT hot-dip galvanized notched specimens from aborted fatigue tests were analyzed in metallographic tests. To this end, the fatigue tests were aborted at varying load cycles and the fatigue crack initiation was documented in metallographic sections. Figure 5 shows the aborted fatigue tests.

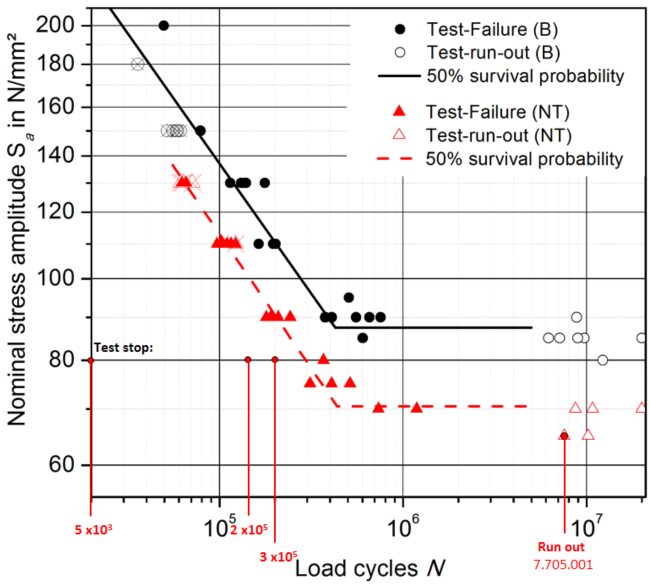

Figure 5: Fatigue tests aborted at varying load cycles

From the metallographic analysis can be concluded (Figure 6) that fatigue cracks in the base material are initiated from micro-cracks in the zinc coating.

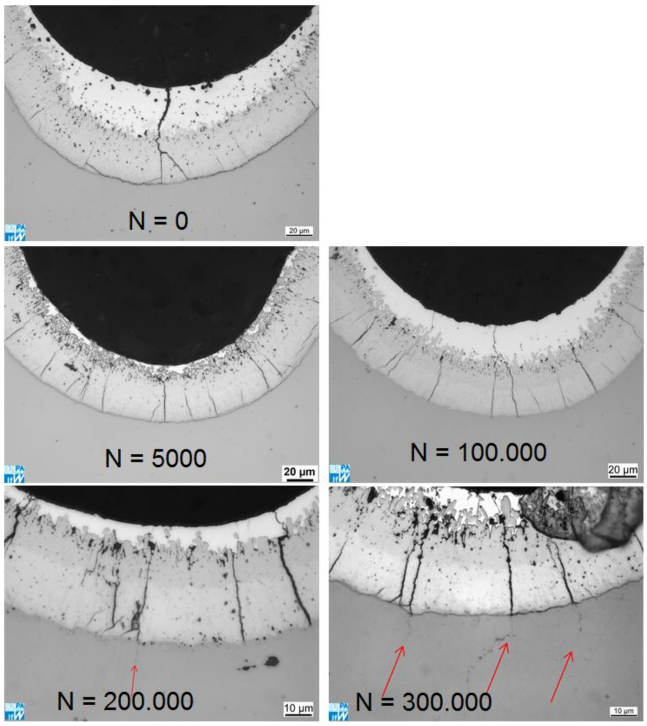

Figure 6: Documentation of fatigue crack initiation by Micro-cracks in the zinc coating

Fatigue tests at constant amplitudes on high-strength bolts M36 and M64

The direct experimental determination of the influence of hot-dip galvanizing on the fatigue resistance of large-size HV-sets is initially carried out using detailed fatigue tests at constant amplitudes on bolt sets M36 of strength class 10.9 [16]. The experimental test series was carried out in a high frequency pulsator (1 MN MOT) in the newly established Test Center for Support Structures in Hannover (TTH) at a constant mean stress level of $\sigma_m = 0{,}7 \cdot R_{p0,2\%}$. This corresponds to the nominal preload of 515 kN for M36 HV-sets. The test frequency was approximately 50 Hz. Under application of standardized statistical evaluation procedures in accordance with DIN 969 [10] three complete S-N curves for the conditions "black bolt" (B), "high temperature hot-dip galvanized" (HT) and "normal temperature hot-dip galvanized" (NT) were determined. S-N curves include the statistical estimation of the endurance limit as well as the fatigue strength in the high cycle fatigue regime. In total over 100 tests on high-strength bolt sets M36 were carried out within the test series.

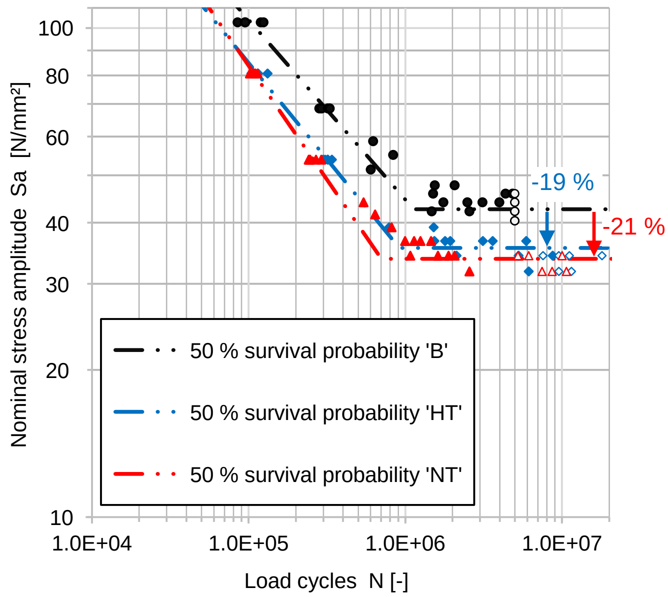

Figure 7: Fatigue test results for high-strength HV-sets M36 with different boundary layer configuration (filled marker (●): failure of specimen; empty marker (○): run-out)

As for the tested notched specimens, the test results of the M36 HV-sets (Figure 7) show a reduction of the endurance limit by approximately 20 % for the hot-dip galvanized bolts. Furthermore, a clear reduction of fatigue strength is also present in the high cycle fatigue range. In contrast to the notched specimens, the determined fatigue resistance of the high temperature hot-dip galvanized bolts tends to lie slightly above the resistance of the normal temperature hot-dip galvanized bolts. However, the scatter bands of both series overlap considerably. Thus, no essential, measurable difference can be assumed. The conclusion is thus reached that, for normal temperature as well as for high temperature hot-dip galvanizing, a comparable reduction of fatigue resistance is implied.

Figure 8 shows the comparison of test results on hot-dip galvanized bolts M36 with the normative S-N curves of VDI 2230 [4] and of Eurocode 3 [5]. If the influence of the specific geometry of HV-sets in accordance with the recommendation of the most current revision of VDI 2230 is taken into account, the calculation method of the endurance limit of hot-dip galvanized bolts given by the guideline provides a conservative estimation. However, in the high cycle fatigue range fractures of specimens lie partially below the corresponding fatigue curve.

The comparison of the test results with the S-N curve of Eurocode 3 confirms an allocation of hot-dip galvanized HV-sets to the detail category 50 under consideration of a thickness reduction factor for large diameters (50red). The test results also revealed that an allocation of black, non-galvanized bolts to the detail category 71red is justified, as suggested in the GL-Guideline [6].

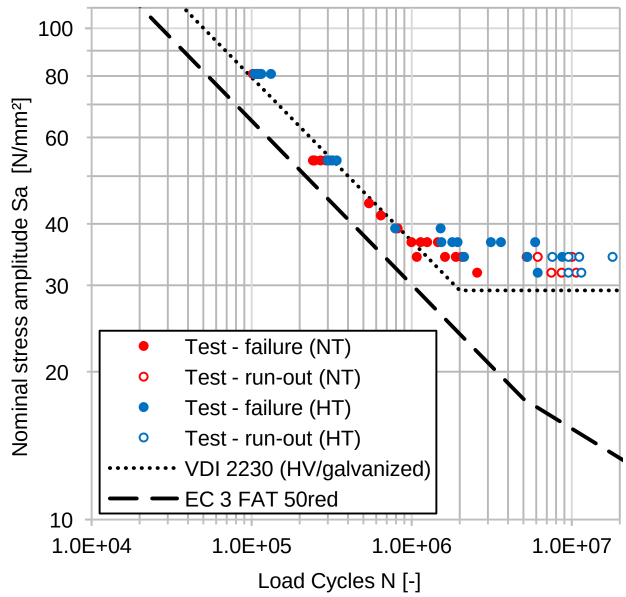

Figure 8: Comparison between test results of hot-dip galvanized bolts M36 and relevant normative S-N curves

Based on the results of the fatigue tests on high-strength bolts M36, further tests will be carried out on HV-sets with very large diameter M64. In this way, the influence of the diameter on the fatigue resistance of black and hot-dip galvanized bolts will be determined. Furthermore, the experiments enable a validation of the aspired numerical fatigue assessment method for very large bolt diameters. For the realization of a representative mean stress level of $\sigma_m = 0{,}7 \cdot R_{p,0,2\%}$ the tests are carried out in a high-strength servo-hydraulic testing machine. Due to the significantly longer test duration and the high testing costs, the aim of the experiments on bolts M64 is the validation of the findings, archived so far, on a limited number of specimens. Thereby tests will mainly be carried out in the high cycle fatigue range. As in the previously described test series, comparative tests will be performed on black as well as NT hot-dip galvanized bolts.

Development of an analytical evaluation method for the fatigue strength of hot-dip galvanized bolts

The objective of the research project is the development of a secured calculation method for the fatigue strength of large-size bolts taking into account the influence of hot-dip galvanizing. This method can then be used for further examination of the fatigue resistance of large-size, hot-dip galvanized bolts instead of expensive experimental tests. The aspired calculation method is developed based on the notch strain approach. In the first step load cycles with constant amplitudes up to the initial crack are computed for bolts M36. In accordance with a recommendation by Schneider [11] monotonic material behavior is considered for the initial load application in the cyclic hysteresis in order to take into account the static preloading process of the bolts. Afterwards cyclic material properties under consideration of Masing-behavior are used. Evaluating the pathway of the cyclic hysteresis, load cycles until initial crack of the bolts can be calculated with the strain-S-N curve of the base material under application of an appropriate damage parameter P.

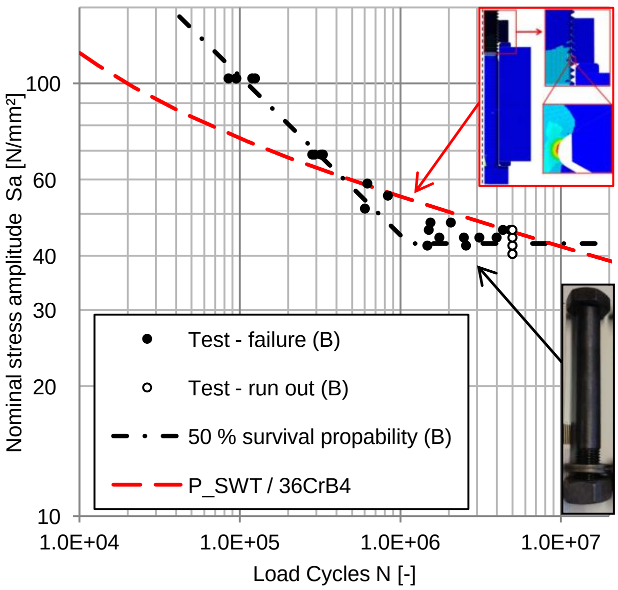

Figure 9: Comparison of S-N curves calculated with the notch strain approach and test results of black bolts M36

Figure 9 shows the comparison of analytical calculation results under application of the damage parameter P_{SWT} [12] with the test results of the black M36 bolts. For this initial analytical calculation, cyclic material data of a high-strength bolt material 36CrB4 published in [11] has been used. In further calculations, experimentally determined material parameter of the actual bolt material 32CrB4, derived directly from the base material of the bolts, will be applied.
The numerical calculations generally show a good approximation to the experimental results. A further improvement is expected through the use of the more accurate damage parameters P_j [13] and by consideration of cyclic relaxation processes of the bolt material. To this end respective tests under high mean strains will be carried out on the bolt's base material.
In order to enable the calculation of the entire fatigue life until rupture, the assessment method will be extended by the application of the crack propagation method of the FKM-Guideline [14]. The calculation of fatigue life under variable amplitudes will be included by application of the Memory-Model. Finally, the negative influence of hot-dip galvanizing on the fatigue resistance of the bolts is to be considered within the calculation method. This will be achieved with the assistance of the "Thin Boundary Layer" [15] model. In the model, a virtual strain caused by the influence of the boundary layer is added to the numerically determined strain in the cyclic hysteresis. An applicable methodology of this model, which is suitable for the fatigue life calculation of hot-dip galvanized bolts, will be investigated in the framework of the presented research project.
Based on the elaborated calculation method and the performed experiments, recommendations for a simplified, practically implementable verification method on basis of the nominal stress approach will be developed.

Conclusions

The objective of the research project presented in this paper is the development of an experimentally confirmed evaluation method for the fatigue strength of large-size bolts taking into account the influence of hot-dip galvanizing. It was possible to demonstrate that normal temperature hot-dip galvanizing and high temperature hot-dip galvanizing have a significant influence on the cyclic load bearing capacity of notched specimens. The origin of the influence of normal temperature hot-dip galvanizing lies within premature fatigue crack initiation caused by microcracks in the zinc coating. It was possible to document the fatigue crack initiation by means of aborted fatigue tests. In fatigue tests a significant influence of hot-dip galvanizing was also demonstrated on the fatigue resistance of high-strength bolt M36. The reduction of fatigue strength caused by the boundary layer is for both, notched specimens as well as bolts M36 in a range of approximately 20 %. This result confirms the corresponding recommendation of VDI 2230. With the application of an additional reduction, taking into account the specific geometry of HV-sets, the endurance limit is appropriately estimated in VDI

2230. In regard to Eurocode 3, the allocation of hot-dip galvanized HV-sets to detail category 50 provides a secure design basis. First calculations with the notch strain approach as basis for an analytical evaluation method show a good approximation to the experimental results. The further development of the assessment method especially involves the consideration of the influence of the zinc coating by use of the “Thin Boundary Layer” model.

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