Medium to high cycle fatigue investigation on hot dip galvanized structural steel welded joints

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ABSTRACT

Hot dip galvanization offers stable and lasting corrosion protection to steel structure, both acting as a barrier for external agents and inducing galvanic protection, through the deposition of a thin layer of zinc on the steel structure by submersion in a molten bath of the metal. Current standards for welded steel structures subjected to fatigue loads do not allow the use of the technique, while the cost for maintenance, repair or failure due to corrosion has an elevated worldwide impact. A series of hot dip galvanized structural steel welded specimens was tested with the aim of increasing the understanding of the damage and failure of a structure that has undergone such treatment. The goal is to define whether the use of hot dip galvanization poses a threat to structural safety and if this is eventually accountable for with the use of a certain corrective coefficient for the fatigue classes reported in the regulations. A revision of old fatigue data is here reported to critically discuss the new results presented.

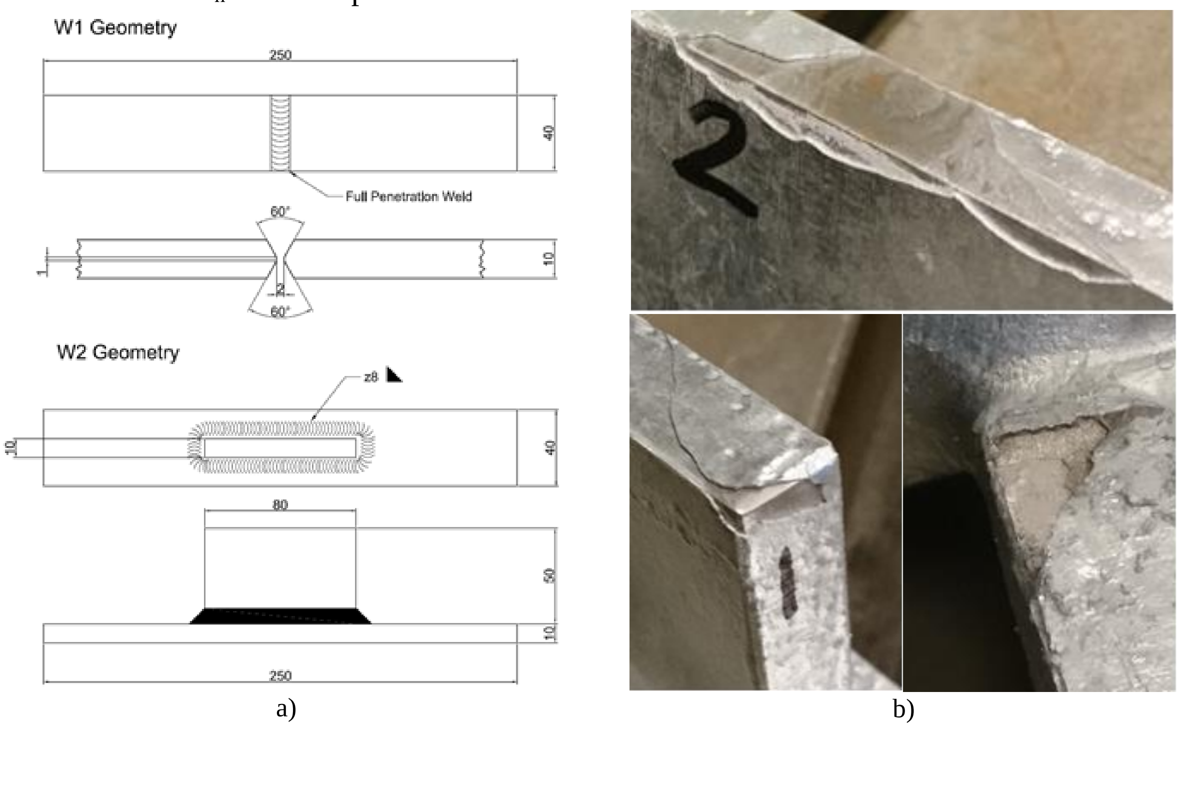
Keywords: hot dip galvanized, structural steel, welded joints, fatigue, corrosion

1 INTRODUCTION

In the service life of steel structures corrosion is a very important issue, which causes significant economic losses and may lead to accelerated deterioration of the structure and consequently poses a serious threat to safety. Different techniques have been developed to help reducing the negative impact of corrosion, such as alloying, painting, coating and cathodic protection. In particular the deposition of a thin layer of zinc on the component by submersion in a molten metal bath, hot dip galvanization (HDG), is able to provide an effective barrier against external agents. Due to the cathodic protection generated by the zinc this coating remains effective against corrosion even if spalling is caused by impact or rough handling and part of the base material is exposed. Due to its beneficial properties and low overall cost HDG is a common process, but its application is not contemplated by the regulations in the case of welded joints subjected to fatigue loads [1]. In fact, the coating layer might influence the fatigue life of the joint causing early crack initiation. A correlation between the thickness of the zinc layer and a reduced fatigue life has been individuated for un-notched specimens made of high strength steel [2], effect not systematically experienced in other research [3]. Testing on un-notched geometries of hot dip galvanized structural steels found no effect of the zinc coating on the fatigue life if the layer does not exceed a thickness of 60 µm [4]. Steel wires have been tested [5, 6] with focus on the corrosion fatigue response of the material. The influence of pre-straining on the fatigue resistance of hot dip galvanized steel has also been investigated [7]. All these results regard un-notched non welded components. Some further research has already been performed for welded details, finding a modest deviation from the uncoated specimens, but no worse performance than the minimum S-N class for most details [8-11]. The present work aims to present new tests regarding hot dip galvanized welded structural steel in different geometries subjected to fatigue loading and integrate the discussion with the results already available to contribute building knowledge on the real influence on the fatigue behavior of hot dip galvanized welded joints.

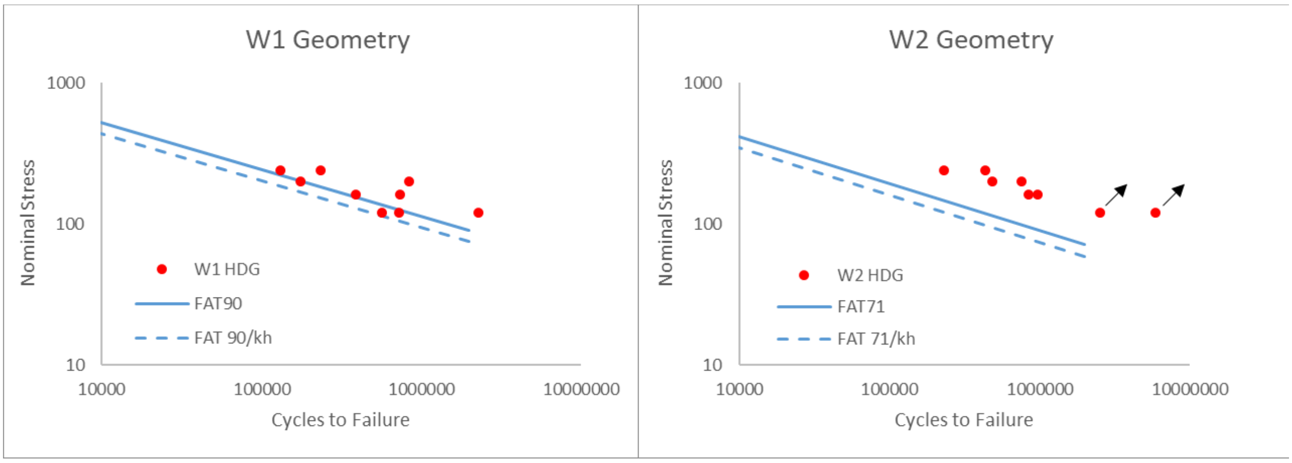
2 FATIGUE TESTING MATERIAL AND RESULTS

The fatigue testing presented in this work was performed on two different geometries (Figure 1) of hot dip galvanized structural steel welded joints. The specimens were produced in S355J2+N structural steel welded by MAG process. After welding the specimens were galvanized by submersion in an molten zinc bath obtaining an average coating thickness between 350 and 450 µm. The cohesive layer between the base material and the zinc coating is subject to fragile fracture in case of impact. Figure 1b shows some areas of the specimens where the protective layer was removed due to rough handling and transport of the samples. The areas of base material uncovered have not been heavily corroded due to the galvanic protection generated by the surrounding zinc. This property constitutes a great advantage of the adoption of hot dip galvanization as a protection from external agents. According to the International Institute of Welding Recommendations [12] the samples have an S-N fatigue curve for nominal stress characterized by a stress range of 90 and 71 MPa at 2E6 cycles for geometries W1 and W2 respectively and a reverse slope k=3. The fatigue classes reported by IIW consider a failure probability of 2.3 % and a load ratio R=0.5. No enhancement of the fatigue class is to be performed for the load ratio R=0 adopted in the fatigue testing in case of non-stress relieved or three dimensional welded joints. The samples were tested at four load levels in the number of 9 and 8 samples for geometry W1 and W2 respectively at a frequency f=10 Hz in a servo-hydraulic system equipped with a 100 kN load cell. The clamping length was of 30 mm on both ends of the specimens. A certain degree of misalignment is induced in the specimens by the welding process. Due to the use of a rigid clamping system, additional stress is induced in the specimens and has to be considered in the fatigue analysis. In order to do so, the procedure followed was to multiply the stress range applied by the testing machine by a corrective factor km as indicated by IIW p. 136 [13], obtaining an equivalent corrected nominal stress. Sample failure was detected as complete fracture. All the failures have originated in the area of local stress intensification at the weld toes and propagated orthogonally to the load applied until the final plastic collapse of the residual ligament. The results of the fatigue testing are summarized in the plots Figure 2 and 3, both in terms of nominal stress range and corrected nominal stress range. The dashed line indicates the detail's fatigue class divided by a safety factor k_h=1.2 proposed by the authors as corrective measure for obtaining a safe estimate of the fatigue resistance of hot deep galvanized structural steel welded joints from the fatigue class reported in the regulations. This correction is not necessary if the deformation is considered because the S-N curves result extremely conservative, but this might not always be possible or economically feasible for a real structure. The choice of the value k_h=1.2 is explained in section 4.



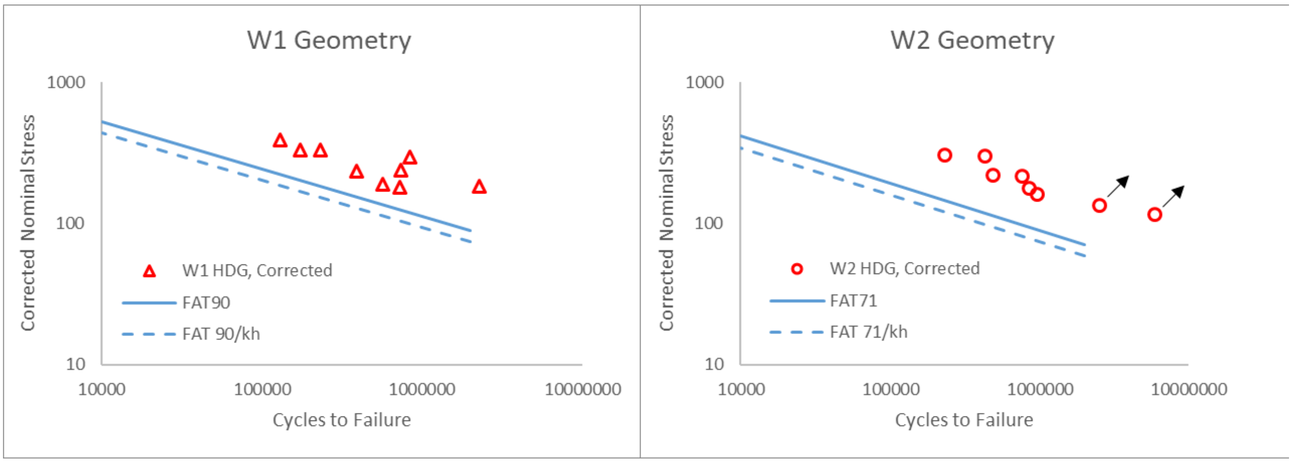
a) b)

Fig. 1. a) Geometries of the samples tested, scales not unified; b) Spalling of the coating due to rough handling. No corrosion detected due to galvanic protection



a) b)

Fig. 2. Synthesis of the fatigue results in terms of nominal stress range for geometry W1 (a) and W2 (b)



a) b)

Fig. 3. Synthesis of the fatigue results in terms of corrected nominal stress range for geometry W1 (a) and W2 (b)

3 SEM FRACTURE INVESTIGATION

The fractures where investigated with the aid of a scanning electron microscopy to better understand the influence of the zinc coating on crack initiation. Figure 4 represents the initiation site of a fatigue crack for a Geometry W1 specimen subjected to a nominal stress range of 240 MPa. In the capture can be clearly distinguished the zinc layer and its different metallographic phases (on the left) and the base material (on the right). It can be seen that the bonding between the two is good and a fatigue crack propagates inside the steel plate from the boundary line. Figure 5 represents instead a Geometry W2 specimen subjected to a nominal stress range of 160 MPa. In this figure no bonding between the two materials is seen. The smoothness of the contact surface of the steel suggests that the hot bath did not depose the zinc in the desired way, probably due to contamination of the surface, rather than a de-cohesion happened subsequently to failure.

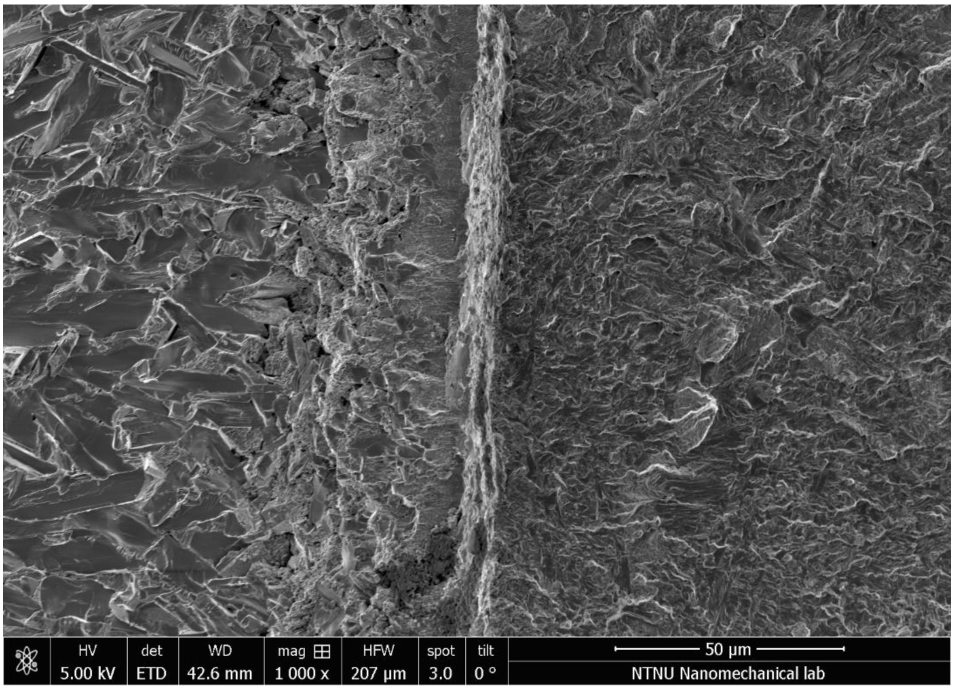


Fig. 4. Crack initiation at the zinc-base material boundary in an area of good bonding

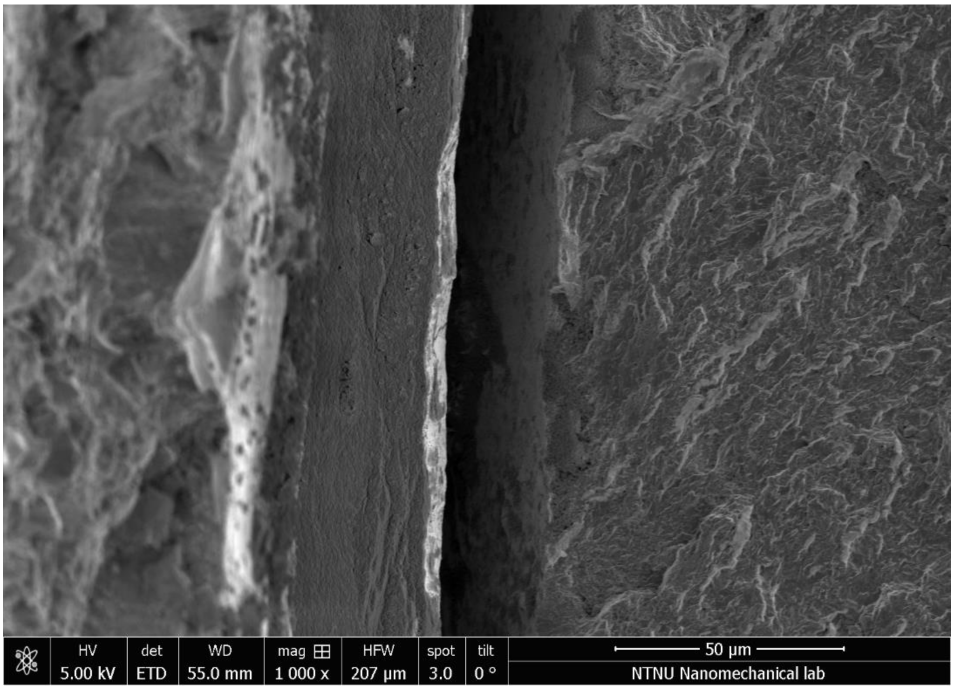


Fig. 5. Area of poor zinc-base material bonding

4 DISCUSSION

Oechsner et al. [10] tested different series of specimens, small and large scale specimens, both in untreated and in hot dip galvanized conditions. In the four cases, all the specimens respected the minimum detail's fatigue resistance, although the galvanized ones where weaker than the correspondent non-galvanized ones. The reduction of fatigue strength was of 16.4% and 14.6% for the small and large-scale specimens respectively, considering a 97.7% survival probability. Rademacher et al. [11] performed several tests on non and galvanized steel welded joints finding all results in agreement with the resistance indicated by the regulations. Their investigation of the zinc layer and the boundary region with the base material evidenced several small-scale cracks in the δ_1 phase of the coating, which constitute defects at the interface ready to propagate in the base material. The test performed by Berto et al. [8] on non-load carrying cruciform joints show a reduction of the fatigue resistance by 9.43% if a 50% survival probability is considered. The 90%

survival probability curves differ by a mere 1MPa in correspondence of the 2E6 cycles life. The reverse slopes of the two fatigue curves are of 2.94 and 3.33 for the uncoated and galvanized respectively. That is, the former slightly outperform the latter for a number of cycles inferior to 2E6. However, all the results respect the relative detail's category as suggested by Hobbacher [12]. Viespoli et al. [9] presented the results of tests on load carrying and non-load carrying welded joints. The coating process caused no severe reduction of the resistance of the samples, but some of the load carrying specimens failed at the weld toe, indicating a weakening of the same that competes with the weld root for the final failure of the samples. In the present contribution, the results of the fatigue testing of two series of galvanized welded joints are reported. Geometry W1, a load carrying full penetration double-V butt joint and geometry W2, a non-load carrying joint constituted by a plate stiffened by a longitudinal attachment. Geometry W1 results slightly weaker than the relative fatigue class, but if the nominal stress is corrected to account for the distortion introduced by the welding process as described by Hobbacher [12], it fully respects the minimum strength requirement. Geometry W2 is considerably stronger than its class also if this correction is not performed. In virtue of all the results considered, the authors consider the use of hot dip galvanization safe. To account for the slight reduction in fatigue life caused by the process in most cases, a safety coefficient k_h=1.2 is proposed. This coefficient is to be used to reduce the details' fatigue classes reported by the regulation for the design of a hot dip galvanized welded structure. No conclusion is so far possible of the long-term fatigue behaviour.

5 CONCLUSIONS

In the present work the results of a series of fatigue testing results on hot dip galvanized welded S355 structural steel are reported. In light of the present investigation and of the literature review executed the main conclusions are the following:

- The use of hot dip galvanization is an effective method for protecting steel structures from the corrosive aggression of external agents, which does not reduce significantly the fatigue resistance of welded components.
- On the base of the present testing and of the literature review executed an additional safety coefficient k_h=1.2 is proposed in case the coating process is performed.
- Further investigation is necessary in the high to very high cycle fatigue range to determine whether the treatment affects the position of the fatigue curve knee point, fixed to 1E7 cycles without coating, and the slope of the fatigue curve at higher cycles.

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